MOTION + POWER MANUFACTURERS ALLIANCE™

American Gear Manufacturers Association®

ABMA® American Bearing Manufacturers Association

Technical Publications Catalog

Contents

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Motion + Power Manufacturers Alliance

The Motion and Power Manufacturers Alliance (MPMA) is a voluntary association of companies, consultants and academicians with a direct interest in the design, manufacture, and application of gears, flexible couplings, and bearings. MPMA was created by a merger between the American Gear Manufacturers Association (AGMA) and the American Bearing Manufacturers Association (ABMA). It delivers value through standards creation under the AGMA and ABMA brands, robust education and workforce development programs, a strong connection of the supply chain via face-to-face events, two industry publications, and advocacy at the federal government. MPMA is a member- and market-driven organization that provides a wide variety of services to the gear and bearing industries and its customers and conducts numerous programs that support these services. Some services and programs are:

- **EVENTS:**
  - **FALL TECHNIAL MEETING (FTM)** – MPMA's annual Fall Technical Meeting (FTM) is the perfect forum in which to share this cutting-edge research and to disperse knowledge for the benefit of the industry. It provides engineers with the opportunity to communicate ideas with other experts in the industry making innovation fundamental to the rise of modern mechanical technology.
  - **MOTION + POWER TECHNOLOGY (MPT) EXPO** – the MPT Expo connects the top manufacturers, suppliers, buyers, and experts in the mechanical, electrical, and fluid power industries.
- **STANDARDS:** MPMA develops all U.S. gear-related standards (AGMA) and bearing-related standards (ABMA) through an open process under the authorization of the American National Standards Institute (ANSI).
- **ISO PARTICIPATION:** AGMA is Secretariat to TC60, the technical committee responsible for developing all international gear standards. Also, ABMA is involved in TC4, the technical committee responsible for developing international rolling bearing standards TC60 and TC4 are International Organization of Standardization (ISO) committees.
- **WEBINARS:** We offer a range of engaging gear- and bearing-related webinars throughout the year. You can view webinars live as they happen, or you can browse our archive and watch them on-demand.
- **TECHNICAL COMMITTEE MEETINGS**: MPMA's technical committee meetings are the core of the open AGMA and ABMA standard writing process, keeping members abreast of new developments while ensuring these standards are kept current.
- **EDUCATION:** MPMA supports the professional development of the gear and bearing manufacturing workforce that, in turn, will enhance the manufacturing and distribution of member company products. We offer face-to-face, online, and webinar formats; leading the industry in gear education and training, while embracing the expanded use of technology to reach our learners anytime, anywhere.
- **MPMA's E-NEWSLETTERS**: Offers timely and useful information to engage members and non-members alike.

If you would like additional information about our programs, or on how to become a member of MPMA, please contact MPMA headquarters.

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Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
AGMA	900-M25	IS	Style Manual for the Preparation of Standards and Information Sheets	This information sheet is a compilation of the AGMA and ISO editorial style manuals. This document provides guidelines for the way that the AGMA Brand is presented from both a graphic and language perspective in publications of the Technical Division, specifically standards and information sheets. It is intended for use ensuring multiple contributors create a clear and cohesive way that reflects the corporate style and ensures brand consistency. These standards will be applied either for general use or individual publication. Revision of AGMA 900-L24.		35	8/19/2025	Published
AGMA	901-A92	IS	A Rational Procedure for the Preliminary Design of Minimum Volume Gears	Presents a simple, closed-form procedure as a first step in the minimum volume spur and helical gearset design. It Includes methods for selecting geometry and dimensions, considering maximum pitting resistance, bending strength, and scuffing resistance, and methods for selecting profile shift. Reaffirmed August 2025.	1-55589-579-4	37	8/26/2025	Reaffirmation
AGMA	905-A17	IS	Inspection of Molded Plastic Gears	Due to their specification, design, and manufacture, plastic gears have unique issues that can affect the measurement methods and results obtained. This information sheet describes industry accepted practices to inspect molded plastic gears. It identifies the unique characteristics of molded plastic gears that influence the accuracy and/or repeatability of gear measurements. Reaffirmed August 1, 2022.	1-55589-735-2	84	8/1/2022	Reaffirmation
AGMA	908-B89	IS	Geometry Factors for Determining the Pitting Resistance and Bending Strength of Spur Helical and Herringbone Gear Teeth	Gives the equations for calculating the pitting resistance geometry factor, I, for external and internal spur and helical gears, and the bending strength geometry factor, J, for external spur and helical gears that are generated by rack-type tools (hobs, rack cutters or generating grinding wheels) or pinion-type tools (shaper cutters). Includes charts which provide geometry factors, I and J, for a range of typical gear sets and tooth forms. Reaffirmed November 11, 2020.	1-55589-525-5	78	11/11/2020	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
AGMA	909-A06	IS	Specifications for Molded Plastic Gears	The objective of this information sheet is to inform the plastic gear designer of the importance to clearly and thoroughly define the gear specifications to the plastic gear producer. It discusses the specifications for gear tooth geometry, inspection, other gear features and manufacturing considerations for involute external and internal spur and helical gears. Suggested data forms are provided in the annexes. Reaffirmed April 3, 2023.	1-55589-889-8	25	4/3/2023	Reaffirmation
AGMA	910-D12	IS	Formats for Fine-Pitch Gear Specification Data	This information sheet consists of a series of printed forms for gear drawings that contain the appropriate data to be tabulated by the gear designer for the gear manufacturer. It also includes a series of definitions of the various tabulated items. Replaces AGMA 910-C90. Reaffirmed August 1, 2022.	1-55589-999-8	32	8/1/2022	Reaffirmation
AGMA	911-B21	IS	Guidelines for Aerospace Gearing	This information sheet covers current gearbox design practices as they are applied to air vehicles and spacecraft. The material included goes beyond the design of gear meshes and presents the broad spectrum of factors which combine to produce a working gear system, whether it be a power gearbox or special purpose mechanism. Although a variety of gear types, such as wormgears, face gears and various proprietary tooth forms are used in aerospace applications, this document covers only spur, helical, and bevel gears. Replaces AGMA 911-A94.	978-1-64353-094-9	140	5/1/2021	Published
AGMA	913-A98	IS	Method for Specifying the Geometry of Spur and Helical Gears	Provides information to translate tooth thickness specifications which are expressed in terms of tooth thickness, center distance or diameter into profile shift coefficients. It describes the effect that profile shift has on the geometry and performance of gears. Annexes are provided which contain practical examples on the calculation of tool proportions and profile shift. Reaffirmed May 2021.	1-55589-714-2	25	5/1/2021	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
AGMA	914-B04	IS	Gear Sound Manual - Part I: Fundamentals of Sound as Related to Gears; Part II: Sources Specifications and Levels of Gear Sound; Part III: Gear Noise Control	This information sheet discusses how noise measurement and control depend upon the individual characteristics of the prime mover, gear unit, and driven machine, as well as their combined effects in a particular acoustical environment. It indicates certain areas that might require special attention. This document is a revision of AGMA 299.01 to include updated references and a discussion of Fast Fourier Transform analysis. Replaces AGMA 299.01. Reaffirmed April 3, 2023.	1-55589-820-3	37	4/3/2023	Reaffirmation
AGMA	915-2-B20	IS	Inspection Practices - Part 2: Cylindrical Gears - Radial Measurements	This information sheet discusses inspection of cylindrical involute gears using the radial (double flank) composite method, with recommended practices detailed. Also included is a clause on runout and eccentricity measurement methods. This information sheet is a supplement to the standard ANSI/AGMA 2015-2. It replaced AGMA ISO 10064-2 and replaces double flank composite measurement section of AGMA 2000-A88. Reaffirmed April 14, 2025.	978-1-64353-067-3	52	4/14/2025	Reaffirmation
AGMA	915-3-A99	IS	Inspection Practices - Gear Blanks Shaft Center Distance and Parallelism	Provides recommended numerical values relating to the inspection of gear blanks, shaft center distance and parallelism of shaft axes. Discussions include such topics as methods for defining datum axes on components; the use of center holes and mounting surfaces during manufacturing and inspection; and, recommended values of in-plane and out-of-plane deviations of shaft parallelism. Modified adoption of ISO/TR 10064-3:1996. Reaffirmed October 2022.	1-55589-738-3	9	8/1/2022	Reaffirmation
AGMA	916-A19	IS	Face Gears with Intersecting Perpendicular Axes	Describes design calculations for spur pinions and face gears that intersect with perpendicular axes. The procedure described in this document will result in a face gear tooth geometry that is defined by the generating action of a reciprocating spur gear cutter which incorporates certain essential features of the mating pinion. The method described applies to all modules and profile angles. Reaffirmed March 13, 2024.	978-1-64353-038-3	93	3/13/2024	Reaffirmation
AGMA	917-B97	IS	Design Manual for Parallel Shaft Fine-Pitch Gearing	Provides guidance for the design of spur and helical gearing of 20 through 120 diametral pitch including internal and rack forms. Manual contains such specialized subjects as inspection, lubrication, gear load calculation methods, materials, including a wide variety of plastics. Replaces AGMA 370.01. Reaffirmed August 2022.	1-55589-694-4	84	8/1/2022	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
AGMA	918-A93	IS	A Summary of Numerical Examples Demonstrating the Procedures for Calculating Geometry Factors for Spur and Helical Gears	Provides numerical examples for calculating the pitting resistance geometry factor, I, and bending strength geometry factor, J, for typical gearsets that are generated by rack-type tools (hobs, rack cutters or generating grinding wheels) or pinion-type tools (disk-type shaper cutters). Supplement to AGMA 908-B89. Reaffirmed April 14, 2025.	1-55589-617-0	42	4/14/2025	Reaffirmation
AGMA	919-1-A14	IS	Condition Monitoring and Diagnostics of Gear Units and Open Gears: Part 1 - Basics	The new information sheet provides basic overviews of key approaches to establishing a condition monitoring and diagnostics program for open gearing and enclosed gear units. This information sheet attempts to inform the reader of the common techniques used and parameters measured for condition monitoring of a gear unit allowing the reader to build a program based on individual needs. Reaffirmed April 14, 2025.	978-1-61481-087-2	20	4/14/2025	Reaffirmation
AGMA	920-B15	IS	Materials for Plastic Gears	The purpose of this document is to aid the gear designer in understanding the unique physical, mechanical and thermal behavior of plastic materials. The use of plastic materials for gear applications has grown considerably due to cost and performance issues. Growing markets include the automotive, business machine, and consumer-related industries. Topics covered include general plastic material behavior, gear operating conditions, plastic gear manufacturing, tests for gear related material properties, and typical plastic gear materials. There are no quantitative details on material properties or any comparative evaluations of plastic types. Such specific information is left to be provided by material suppliers and gear manufacturers. Revision of AGMA 920-A01. Reaffirmed April 14, 2025.	1-55589-048-3	50	4/14/2025	Reaffirmation
AGMA	922-A96	IS	Load Classification & Service Factors for Flexible Coupling	This Information Sheet provides load classifications and related service factors that are frequently used for various flexible coupling applications. Typical applications using smooth prime movers and special considerations involving unusual or more severe loading are discussed. Replaces AGMA 514.02. Reaffirmed April 14, 2025.	1-55589-680-4	6	4/14/2025	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
AGMA	923-C22	IS	Metallurgical Specifications for Steel Gearing	This document identifies metallurgical quality characteristics which are important to the performance of steel gearing. The AGMA gear rating standards identify performance levels of gearing by heat treatment method and grade number. For each heat treatment method and AGMA grade number, acceptance criteria are given for various metallurgical characteristics identified in this document. Revision of AGMA 923-B05. NOTE: AGMA 923-C22 has two errata included at the end of the document.	978-1-64353-119-9	56	8/1/2022	Published/Errata
AGMA	925-B22	IS	Effect of Lubrication on Gear Surface Distress	AGMA 925-B22 covers lubricant-related damage modes in gear teeth. Various methods of gear surface distress are included, such as scuffing and wear, and micro- and macropitting. This document contains additional information about lubricant viscometric data, Dudley's regimes of lubrication theory, surface roughness measurements, EHD theory, FZG lubricant test rigs, Gaussian theory, flow charts, and example calculations. Replaces AGMA 925-A03.	978-1-64353-116-8	113	4/1/2022	Published
AGMA	926-C99	IS	Recommended Practice for Carburized Aerospace Gearing	Establishes recommended practices for material case and core properties, microstructure and processing procedures for carburized AISI 9310 aerospace gears. This document is not intended to be a practice for any gears other than those applied to aerospace. Replaces AGMA 246.02a. Reaffirmed October 20, 2017.	1-55589-758-4	9	10/20/2017	Reaffirmation
AGMA	927-A01	IS	Load Distribution Factors - Analytical Methods for Cylindrical Gears	Describes an analytical procedure for the calculation of face load distribution factor. The iterative solution that is described is compatible with the definitions of the term face load distribution of AGMA standards and longitudinal load distribution of the ISO standards. The procedure is easily programmable and flow charts of the calculation scheme, as well as examples from typical software are presented. Supplement to ANSI/AGMA 2001-D04. Reaffirmed April 3, 2023.	1-55589-779-7	31	4/3/2023	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
AGMA	929-B22	IS	Calculation of Bevel Gear Top Land and Guidance on Cutter Edge Radius	This information sheet supplements ANSI/AGMA ISO 23509-A08 with calculations for bevel gear top land and guidance for selection of cutter edge radius for determination of tooth geometry. It integrates various publications with modifications to include face hobbing. It adds top land calculations for non-generated manufacturing methods. It is intended to provide assistance in completing the calculations requiring determination of top lands and cutter edge radii for gear capacity in accordance with ANSI/AGMA 2003-C10. Revision of AGMA 929-A06. (Errata included).	978-1-64353-120-5	71	8/1/2022	Published/errata
AGMA	930-A05	IS	Calculated Bending Load Capacity of Powder Metallurgy (P/M) External Spur Gears	This information sheet describes a procedure for calculating the load capacity of a pair of powder metallurgy external spur gears based on tooth bending strength. Two types of loading are considered: 1) repeated loading over many cycles; and 2) occasional peak loading. It also describes an essentially reverse procedure for establishing an initial design from specified applied loads. As part of the load capacity calculations, there is a detailed analysis of the gear teeth geometry, including tooth profiles and various fillets. Reaffirmed August 2022.	1-55589-845-9	78	8/1/2022	Reaffirmation
AGMA	932-A05	IS	Rating the Pitting Resistance and Bending Strength of Hypoid Gears.	This information sheet provides a method by which different hypoid gear designs can be compared. The formulas are intended to establish a uniformly acceptable method for calculating the pitting resistance and bending strength capacity of both curved and skewed tooth hypoid gears. They apply equally to tapered depth and uniform depth teeth. Annexes contain graphs for geometry factors and a sample calculation to assist the user. Supplement to ANSI/AGMA 2003-B97. Reaffirmed August 15, 2024.	1-55589-869-6	18	8/15/2024	Reaffirmation
AGMA	933-B03	IS	Basic Gear Geometry	This information sheet illustrates important geometrical relationships which provide a sound basis for a thoroughly logical and comprehensive system of gear geometry. Replaces AGMA 115.01. Reaffirmed February 2022.	1-55589-814-9	18	2/1/2022	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
AGMA	937-A12	IS	Aerospace Bevel Gears	This information sheet covers aerospace bevel gears for power, accessory and actuation applications. It provides additional information on the design, manufacturing and quality control unique to the aerospace environment. The new information sheet was developed to fill the void following the withdrawal of AGMA 431.01. It expands the scope to include all applications of aerospace bevel gearing. Reaffirmed August 2022.	1-61481-030-8	142	8/1/2022	Reaffirmation
AGMA	938-A05	IS	Shot Peening of Gears	This information sheet provides a tool for gear designers interested in the residual compressive stress properties produced by shot peening and its relationship to gearing. It also discusses shot media materials, delivery methods and process controls. Reaffirmed April 3, 2023.	1-55589-847-5	14	4/3/2023	Reaffirmation
AGMA	939-A07	IS	Austempered Ductile Iron for Gears	This information sheet gives the background and basic guidelines to consider the feasibility of austempered ductile iron (ADI) for gear applications. It contains experimental, experiential and anecdotal information to assist in the specification, purchase and manufacture of ADI components. The metallurgy of ADI, relevant factors in its production, allowable stress numbers, and stress cycle curves are reviewed. It also has references, relevant standards, and evaluation methods used in the manufacture of ADI components. Reaffirmed January 30, 2018.	1-55589-901-1	10	4/3/2023	Reaffirmation
AGMA	940-A09	IS	Double Helical Epicyclic Gear Units	This information sheet addresses epicyclic gear drives which utilize double helical type gearing on the planetary elements. It is intended to be a supplement to and used in conjunction with ANSI/AGMA 6123-B06, Design Manual for Enclosed Epicyclic Gear Dives. It covers only those topics which are unique to double helical gear arrangements in epicyclic gear drives. Reaffirmed August 2022.	1-55589-953-0	28	8/1/2022	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
AGMA	942-A12	IS	Metallurgical Specifications for Powder Metallurgy PM Steel Gearing	This information sheet recommends powder metallurgy, PM, steel materials and metallurgical quality characteristics for use in specifying PM gearing. It identifies specifications and requirements for various PM steel materials for as-sintered, through hardened or sinter hardened, carburized case hardened, and induction hardened gearing. Requirements are coded by process and class number, the latter based on the density of the PM gear teeth. Characteristics covered include material composition, density, sinter processing (conventional, high temperature and sinter hardening), secondary heat treatments and post heat treatment processing, and their associated inspections. Reaffirmed August 2022.	1-61481-031-5	17	8/1/2022	Reaffirmation
AGMA	943-A22	IS	Tolerances for Spur and Helical Racks	This information sheet establishes a tolerance classification system relevant to manufacturing and conformity assessment of tooth flanks of a single piece spur or helical rack. It specifies definitions for rack flank tolerance terms, the structure of the flank tolerance class system, and allowable values.	978-1-64353-117-5	22	2/1/2022	Published
AGMA	944-A19	IS	Mechanisms of Powder Metal PM Gear Failures	This information sheet describes many of the ways in which powder metal, PM, gear teeth can fail and recommends methods for reducing PM gear failures. It provides basic guidance for those attempting to analyze PM gear failures. The information sheet should be used in conjunction with ANSI/AGMA 1010 in which the gear tooth failure modes are defined. Similar definitions can also be found in ISO 10825 [1]. Although these standards are primarily focused on steel parts, they help investigators understand failures and investigate remedies. Reaffirmed March 13, 2024.	978-1-64353-036-9	30	3/13/2024	Reaffirmation
AGMA	945-1-B20	IS	Splines - Design and Applications	This information sheet covers parallel straight sided and involute splines. It provides information relating to geometry, fit types, materials, manufacturing, rating, inspection, lubrication, and failure of splined elements. Revision of AGMA 945-A18. Reaffirmed November 6, 2025.	978-1-64353-076-5	79	11/6/2025	Reaffirmation
AGMA	945-2-B20	IS	Splines - Design and Applications (Inch Edition)	This information sheet covers parallel straight sided and involute splines. It provides information relating to geometry, fit types, materials, manufacturing, rating, inspection, lubrication, and failure of splined elements. For metric based splines, see AGMA 945-1-B20. Reaffirmed November 6, 2025.	978-1-64353-077-2	79	11/6/2025	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
AGMA	946-A21	IS	Test Methods for Plastic Gears	This information sheet describes test methods and recommended documentation practices for determining load carrying capacity and wear performance of plastic gears. It describes test methods for plastic gears related to dynamic testing where two gears rotate against each other under controlled load and velocity, as well as static testing where a gear is held stationary while a load is applied to one or more of the gear's features, or pulsator testing where the test gear is not rotating, but the load is pulsed repeatedly until fatigue failure occurs. Reaffirmed April 14, 2025.	978-1-64353-091-8	18	4/14/2025	Reaffirmation
AGMA	947-A23	IS	Gear Reducers - Thermal Capacity	This information sheet utilizes an analytical heat balance model to provide a means of calculating the thermal transmittable power of a single- or multiple-stage gear drive lubricated with mineral oil. The calculation is based on standard conditions of 25°C maximum ambient temperature and 95°C maximum oil sump temperature in a large indoor space but provides modifiers for other conditions. Replaces AGMA ISO 14179-1.	978-1-64353-145-8	71	6/1/2023	Published
AGMA	955-A22	IS	Guidance for Industrial Gear Lubrication	This information sheet provides lubrication guidelines for enclosed and open gearing installed in general industrial power transmission applications. It is not intended to supplant specific instructions from the gear manufacturer.	978-1-64353-118-2	73	8/1/2022	Published
AGMA	999-E25	IS	Operating Instructions for MPMA Technical Division	The AGMA Technical Division developed this Information Sheet to assist Project Working Groups in the efficient administration of their respective projects.		26	8/19/2025	Published
AGMA ISO	10064-1-A21	IS	Code of Inspection Practice - Part 1: Measurement of cylindrical gear tooth flanks	This information sheet provides a code of practice dealing with measurements on flanks of individual cylindrical involute gears, i.e. with the measurement of pitch, profile, helix and tangential composite characteristics. It describes measuring equipment, provides advice for gear measuring methods and for the analysis of measurement results, and discusses the interpretation of results. Replaces AGMA 915-1-A02. Identical adoption of ISO TR 10064-1:2019. Reaffirmed April 14, 2025	978-1-64353-089-5	91	4/14/2025	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
AGMA ISO	10064-5-A06	IS	Code of Inspection Practice - Part 5: Recommendations Relative to Evaluation of Gear Measuring Instruments	This information sheet provides methods and examples to support the implementation of ANSI/AGMA ISO 18653-A06. It includes evaluation and calibration procedures for involute, helix, runout, and tooth thickness measurement processes. Methods are given for the evaluation of condition and alignment of instrument elements such as centers, guideways, probe systems, etc. Recommendations include statistical data evaluation procedures. Guidance is given on the application of measurement processes to the inspection of product gears, including fitness for use and the recommended limits of U95 uncertainty based on the accuracy tolerances of product gears to be inspected. Many of its recommendations could be applied to the measurement of worms, worm wheels, bevel gears and gear cutting tools. Replaces AGMA 931-A02. Identical to ISO/TR 10064-5:2005. Reaffirmed April 14, 2025.	1-55589-881-5	62	4/14/2025	Reaffirmation
AGMA ISO	10064-6-A10	IS	Code of Inspection Practice - Part 6: Bevel Gear Measurement Methods	This document provides information on measuring methods and practices of unassembled bevel and hypoid gears and gear pairs. Tolerances are provided in ISO 17485:2006, for calculating the maximum values allowed by the specific tolerance grade. These methods and practices are intended to promote uniform inspection procedures which are accurate and repeatable to a degree compatible with the specified tolerance grade. Replaces ANSI/AGMA 2009-B01. Reaffirmed April 14, 2025.	1-55589-994-3	28	4/14/2025	Reaffirmation
AGMA ISO	10828-2024	Std	Worm gears — Worm profiles and gear mesh geometry			0		Adoption
AGMA ISO	22849-A12	IS	Design recommendations for bevel gears	This information sheet provides information for the application of bevel and hypoid gears using the geometry in ANSI/AGMA ISO 23509, the capacity as determined by ISO 10300 (all parts), or ANSI/AGMA 2003-C10 and AGMA 932-A05, and the tolerances in ANSI/AGMA ISO 17485. This information sheet provides additional information on the application, manufacturing, strength and efficiency of bevel gears for consideration in the design stage of a new bevel gear set. Replaces ANSI/AGMA 2005-D03. Reaffirmed April 14, 2025.	1-61481-029-2	40	4/14/2025	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI ABMA	10A-2001	Std	Metal Balls for Unground Bearings and Other Uses	This standard establishes the requirements for metal balls for unground rolling contact bearings and other uses. The requirements for finished balls for roiling contact bearings are contained in ANSI/ABMA/ISO 3290.		32	9/3/2020	Reaffirmation
ANSI ABMA	11-2014	Std	Load Ratings and Fatigue Life for Roller Bearings	This standard specifies the method of calculating the basic dynamic load rating of rolling bearings within the size ranges shown in the relevant ANSI/ABMA standards, manufactured from contemporary, commonly used, good quality hardened bearing steel in accordance with good manufacturing practice and basically of conventional design as regards the shape of rolling contact surfaces. This standard also specifies the method of calculating the basic rating life, which is the life associated with 90% reliability, with commonly used high quality material, good manufacturing quality and with conventional operating conditions. In addition, it specifies the method of calculating adjusted rating life, in which various reliabilities, special bearing properties and specific operating conditions are taken into account by means of life adjustment factors. Furthermore, this standard specifies the method of calculating the basic static load rating and the static equivalent load for roller bearings within the size ranges shown in the relevant ANSI/ABMA Standards, manufactured from good quality hardened bearing steel, in accordance with good manufacturing practice and basically of conventional design as regards the shape of rolling contact surfaces.		28	11/2/2020	Reaffirmation
ANSI ABMA	12.1-1992	Std	Instrument Ball Bearings – Metric Design	This standard covers the characteristics that define metric design instrument ball bearings, their boundary dimensions, tolerances, internal clearances, classification for selective assembly, and recommended practices for gaging, friction torque determination, load rating, operational life prediction and yield rate limitation.		52	5/19/2020	Stabilized
ANSI ABMA	12.2-1992	Std	Instrument Ball Bearings – Inch Design	This standard covers the characteristics that define inch design instrument ball bearings, their boundary dimensions, tolerances, internal clearances, classification for selective assembly, and recommended practices for gaging, friction torque determination, load rating, operational life prediction and yield rate limitation.		53	5/19/2020	Stabilized

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ANSI ABMA	14-1995	Std	Housings for Bearings with Spherical Outside Surfaces	This standard specifies boundary dimensions and tolerances for ball bearings with spherical outside surfaces and extended inner ring width. The feature of mating housing and bearing spherical surfaces is intended to provide initial self-alignment at mounting. Included are pillow block, flanged and take-up unit housings.		20	5/19/2020	Stabilized
ANSI ABMA	15-1991	Std	Ball Bearings with Spherical Outside Surfaces and Extended Inner Ring Width (Includes Eccentric Locking Collars)	This Standard specifies boundary dimensions and tolerances for bearings with spherical outside surfaces and extended inner ring width and eccentric locking collars. These bearings are frequently mounted in housings having mating internal spherical surfaces to provide alignment at mounting.		19	5/19/2020	Stabilized
ANSI ABMA	18.1-1982	Std	Needle Roller Bearings Radial – Metric Design	This standard for Metric Design Industrial Radial Needle Roller Bearings and components includes:- Identification Code- Boundary Dimensions- Bearing Tolerances- Fitting and Mounting PracticeAirframe Needle Roller Bearings, Needle Roller Thrust Bearings, and bearings of other types are covered in separate AFBMA-ANSI Standards.		46	1/10/2023	Stabilized
ANSI ABMA	18.2-1982	Std	Needle Roller Bearings Radial – Inch Design	This standard for Inch Design Industrial Radial Needle Roller Bearings and components includes:- Identification Code- Boundary Dimensions- Bearing Tolerances- Fitting and Mounting PracticeAirframe Needle Roller Bearings, Needle Roller Thrust Bearings, and bearings of other types are covered in separate AFBMA-ANSI Standards.		46	1/10/2023	Stabilized
ANSI ABMA	19.1-2011	Std	Tapered Roller Bearings – Radial Metric Design	This standard covers metric design radial tapered roller bearings of various types, part numbering systems, boundary dimensions, tolerances, and fitting practices. Tapered roller thrust bearings are covered in a separate ABMA standard.		62	6/20/2024	Reaffirmation
ANSI ABMA	19.2-2013	Std	Tapered Roller Bearings – Radial Inch Design	This standard covers inch design radial tapered roller bearings of various types, part numbering systems, boundary dimensions, tolerances, and fitting practices. Tapered roller thrust bearings are covered in a separate ABMA standard.		45	9/3/2020	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI ABMA	20-2025	Std	Radial Bearings of Ball, Cylindrical Roller and Spherical Roller Types – Metric Design	This standard includes:- Basic plan for the boundary dimensions of metric radial ball and roller bearings;- General rules for extension of the basic plans;- Dimensions and tolerances for snap ring groove and locating snap rings;- dimensions for radial ball bearings with flanged outer ring; and- Tolerances for boundary dimensions, chamfers, various runouts and internal clearance.		76	9/9/2025	Published
ANSI ABMA	21.1-1988	Std	Thrust Needle Roller and Cage Assemblies and Thrust Washers – Metric Design	This standard for metric thrust needle roller and cage assemblies and thrust washers includes:- Identification Code- Symbols and Nomenclature- Boundary Dimensions- Tolerances- Mounting Practice		17	5/19/2020	Stabilized
ANSI ABMA	21.2-1988	Std	Thrust Needle Roller and Cage Assemblies and Thrust Washers – Inch Design	This standard for inch thrust needle roller and cage assemblies and thrust washers covers:- Identification Code- Symbols and Nomenclature- Boundary Dimensions- Tolerances- Mounting Practice		20	5/19/2020	Stabilized
ANSI ABMA	22.2-1988	Std	Spherical Plain Radial Bearings, Joint Type – Inch Design	This standard for spherical bearings, joint type (without rolling elements) has been established for the purpose of defining the characteristics of these bearings such as boundary dimensions, tolerances and terminology. This style of bearing consists of an outer ring having an inner concave sphered sliding contact surface and an inner ring having a matched outer convex sphered sliding contact surface. Two general styles, related to manufacturing method are included, swaged (1.2) and fractured (1.3).		12	5/19/2020	Stabilized
ANSI ABMA	23.2-1988	Std	Thrust Bearings of Tapered Roller Type – Inch Design	This standard for thrust bearings of the tapered roller type of inch design covers:- Bearing Number and Type Identity- Symbols and Nomenclature- Boundary Dimensions- Tolerances- Mounting Dimensions		17	5/19/2020	Stabilized
ANSI ABMA	24.1-1989	Std	Thrust Bearings of Ball, Cylindrical Roller and Spherical Roller Types – Metric Design	This standard for thrust bearings of ball, cylindrical roller and spherical roller types of metric design covers:- Identification Code- Symbols and Nomenclature- Boundary Dimensions- Tolerances- Mounting Dimensions		72	5/19/2020	Stabilized
ANSI ABMA	24.2-1989	Std	Thrust Bearings of Ball and Cylindrical Roller Types – Inch Design	This standard for inch design thrust bearings of ball and cylindrical roller types covers:- Identification Code- Symbols and Nomenclature- Boundary Dimensions- Tolerance- Mounting Dimensions		68	5/19/2020	Stabilized

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI ABMA	25.2-1990	Std	Rolling Bearings, Linear Motion, Recirculating Ball, Sleeve Type – Inch Series	This Standard gives the general plan for boundary dimensions, tolerances and terminology for recirculating ball, sleeve type, linear motion bearings. This standard applies only to the size range covered by Table 1, Boundary Dimensions.		12	5/19/2020	Stabilized
ANSI ABMA	26.2-1994	Std	Thin Section Ball Bearings – Inch design	This standard specifies the boundary dimensions and the tolerances for boundary dimensions, running accuracies and internal clearances for thin section ball bearings of single row radial contact, angular contact and four-point angular contact types.		19	1/10/2023	Stabilized
ANSI ABMA	4-2025	Std	Tolerance Definitions and Gauging Practices for Ball and Roller Bearings	This standard includes:- Terms and definitions of tolerances for the boundary dimensions, running accuracy and internal clearance of ball and roller bearings listed in other ANSI/ABMA and ISO standards.- Description of methods of measuring, which are commonly used by bearing users and which, as a rule, give an accuracy sufficient for practical purposes.		60	9/9/2025	Published
ANSI ABMA	7-1995	Std	Shaft and Housing Fits for Metric Radial Ball and Roller Bearings (Except Tapered Roller Bearings) Conforming to Basic Boundary Plan	This standard covers the general selection of shaft and housing fits for metric radial ball and roller bearings of tolerance classes ABEC 1 - RBEC 1 as influenced by the type and extent of bearing loading and other design requirements. Other tolerance classes are not covered by this standard.		16	1/10/2023	Stabilized

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI ABMA	8.1-1990	Std	Ball and Roller Bearing Mounting Accessories – Metric Design	Mounting accessories covered in this standard are used for the location or fixing of ball and roller bearings to the shaft of a machine or mechanism. The purpose of the standard is to establish dimensions and minimum physical properties of these components consistent and compatible with ABMA, ANSI and ISO standards relating to ball and roller bearings. Products manufactured in accordance with this standard will fulfill the expected function when used with properly-designed shafts. This standard covers:- Locknuts and Removal Nuts — Locknuts and removal nuts for ball bearings and cylindrical, spherical, and tapered roller bearings.- Locking Devices — Lockwashers and locking clamps for ball bearings and cylindrical, spherical, and tapered roller bearings.- Mounting Sleeves — Adapter sleeves and withdrawal sleeves for ball bearings and spherical roller bearings.- Shaft Dimensions — Recommended dimensions for threads, keyways, and reliefs for shafts.- General Information — Symbols, definitions, part numbers, materials, tolerances, and threads.		73	5/19/2020	Stablized
ANSI ABMA	8.2-2023	Std	Ball and Roller Bearing Mounting Accessories – Inch Design / Rolling Element Bearings – Shaft Mounted – Locknuts, Sleeves, and Locking Devices – Inch Design	This standard establishes dimensions and minimum physical properties of mounting accessories used for location or fixing inch design ball and roller bearings to the shaft of a machine or mechanism. All components covered by this standard are designed to U.S. Customary (inch) dimensions. The purpose of the standard is to establish dimensions and minimum physical properties of these components consistent and compatible with ABMA, ANSI, and ISO Standards relating to ball and roller bearings. Products manufactured in accordance with this standard will fulfill the expected function when used with properly-designed shafts. This standard covers:- Locknuts and removal nuts, locking devices, and mounting sleeves for Rolling Element Bearings, REB.- Shaft dimensions: Required dimensions for threads, keyways, and reliefs for shafts.- General information: Symbols, definitions, part numbers, materials, tolerances, and threads.		39	7/19/2023	Published/Errata

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI ABMA	9-2015	Std	Load Ratings and Fatigue Life for Ball Bearings	This standard specifies the method of calculating the basic dynamic load rating of rolling bearings within the size ranges shown in the relevant ANSI/ABMA standards, manufactured from contemporary, commonly used, good quality hardened bearing steel in accordance with good manufacturing practice and basically of conventional design as regards the shape of rolling contact surfaces. This standard also specifies the method of calculating the basic rating life, which is the life associated with 90% reliability, with commonly used high quality material, good manufacturing quality and with conventional operating conditions. In addition, it specifies the method of calculating adjusted rating life, in which various reliabilities, special bearing properties and specific operating conditions are taken into account by means of life adjustment factors. Furthermore, this standard specifies the method of calculating the basic static rating and the static equivalent load for ball bearings within the size ranges shown in the relevant ANSI/ABMA Standards, manufactured from good quality hardened bearing steel, in accordance with good manufacturing practice and basically of conventional design as regards the shape of rolling contact surfaces.		30	11/2/2020	Reaffirmation/Errata
ANSI ABMA	B3.1-1992	Std	Rolling Element Bearings – Aircraft Engine, Engine Gearbox, and Accessory Applications – Eddy Current Inspection	This standard specifies a method for detection of discontinuities or nonhomogeneities in bearing components by means of eddy current interrogation. This standard is applicable to rolling element bearings used in aircraft engine, engine gearbox, and accessory applications.		8	5/19/2020	Stabilized
ANSI ABMA	B3.2-1992	Std	Rolling Element Bearings – Aircraft Engine, Engine Gearbox, and Accessory Applications – Surface Visual Inspection	This standard establishes a system for uniform visual acceptance criteria for aircraft engine, gearbox and accessory anti-friction bearings in continuous rotation applications made of the material listed in table 1. The standard requirements are in a flow chart format; the written text is supplementary and is used as support for the flow charts.		13	5/19/2020	Stabilized

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI ABMA	B3.3-1992	Std	Rolling Element Bearings – Aircraft Engine, Engine Gearbox, and Accessory Applications – Surface Temper Etch	This specification for temper etch inspection details the methods and controls for performing etching of ground surfaces for the detection, qualification, and control of altered metallurgical structures of various metallic alloys subjected to grinding. This specification presents two basic methods of etch, one of alcohol base and another of water base, in addition to use of a photo-graphic gray scale to control bath immersion times and part etching levels. This standard parallels MIL-STD-867 A (USAF), Military standard temper etch inspection.		11	5/19/2020	Stabilized
ANSI ABMA ISO	10285-2012	Std	Rolling Bearings – Sleeve Type Linear Ball bearings – Boundary Dimensions and Tolerances	This International Standard specifies the boundary dimensions, tolerances and definitions for sleeve type linear motion ball bearings. It is applicable to the size ranges covered by Table 1. Identical to ISO 10285:2007; includes ISO 10285:2007/Amd.1:2012		17	7/8/2025	Published
ANSI ABMA ISO	104-2016	Std	Rolling Bearings – Thrust Bearings – Boundary Dimensions, General Plan	This International Standard specifies preferred boundary dimensions for single-direction and double-direction thrust bearings with flat back faces. In addition, it gives the minimum bore diameters of housing washers and maximum outside diameters of shaft washers of bearings in dimension series 11, 12, 13, 14, 22, 23 and 24.		30	12/17/2024	Reaffirmation
ANSI ABMA ISO	12240-1-2021	Std	Spherical Plain Bearings – Part 1: Radial Spherical Plain Bearings	This part of ISO 12240 specifies dimension series, tolerances, and radial internal clearances for radial spherical plain bearings.		19	7/23/2021	Adoption
ANSI ABMA ISO	12240-2-2021	Std	Spherical Plain Bearings – Part 2: Angular Contact Radial Spherical Plain Bearings	This part of ISO 12240 specifies dimensions and tolerances for angular contact radial spherical plain bearings. The specified tolerance values apply to finished, angular contact radial spherical plain bearings before any coating or plating. Angular contact radial spherical plain bearings need not conform to the design illustrated but compliance is required as regards dimensions and tolerances specified. Note: Angular contact radial spherical plain bearings for airframe applications are not covered by this part of ISO 12240.		8	7/23/2021	Adoption

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI ABMA ISO	12240-3-2021	Std	Spherical Plain Bearings – Part 3: Thrust Spherical Plain Bearings	This part of ISO 12240 specifies dimensions and tolerances for thrust spherical plain bearings. The specified tolerance values apply to finished, thrust spherical plain bearings before any coating or plating. Thrust spherical plain bearings need not conform to the design illustrated but compliance is required as regards dimensions and tolerances specified. Note: Thrust spherical plain bearings for airframe applications are not covered by this part of ISO 12240.		8	7/23/2021	Adoption
ANSI ABMA ISO	12240-4-2021	Std	Spherical Plain Bearings – Part 4: Spherical Plain Bearing Rod Ends	This part of ISO 12240 specifies dimensions, tolerances and radial internal clearances for various dimension series of spherical plain bearing rod ends. The specified tolerance values apply for finished spherical plain bearing rod ends before any coating, plating, ring splitting or fracturing. Spherical plain bearing rod ends need not conform to the designs illustrated but compliance is required as regards dimensions, tolerances and radial internal clearances specified. Note: Spherical plain bearing rod ends for airframe applications and specific spherical plain baring rod ends for direct connection to hydraulic cylinders are not covered by this part of ISO 12240.		16	8/2/2021	Adoption/Corrigendum
ANSI ABMA ISO	15242-1-2016	Std	Rolling Bearings – Measuring Methods for Vibration – Part 1: Fundamentals	This part of ISO 15242 specifies measuring methods for vibration of rotating rolling bearings under established measuring conditions, together with calibration of the related measuring systems.		26	1/8/2025	Reaffirmation
ANSI ABMA ISO	15242-2-2016	Std	Rolling Bearings – Measuring Methods for Vibration – Part 2: Radial Ball Bearings with Cylindrical Bore and Outside Surface	This part of ISO 15242 specifies vibration measuring methods for single-row and double-row radial ball bearings, with a contact angle up to and including 45°. It covers radial ball bearings with cylindrical bore and outside surface, except bearings with filling slots and three- and four-point-contact ball bearings.		16	1/8/2025	Reaffirmation
ANSI ABMA ISO	15242-3-2018	Std	Rolling Bearings – Measuring Methods for Vibration – Part 3: Radial Spherical and Tapered Roller Bearings with Cylindrical Bore and Outside Surface	This document specifies vibration measuring methods for double-row radial spherical roller bearings and single-row and double-row radial tapered roller bearings, with cylindrical bore and outside surface and a contact angle up to and including 45°, under established measuring conditions.		16	1/8/2025	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI ABMA ISO	15242-4-2018	Std	Rolling Bearings – Measuring Methods For Vibration – Part 4: Radial Cylindrical Roller Bearings with Cylindrical Bore and Outside Surface	This document specifies vibration measuring methods for single-row and double-row radial cylindrical roller bearings with cylindrical bore and outside surface, under established measurement conditions.		20	1/8/2025	Reaffirmation
ANSI ABMA ISO	15243-2017	Std	Rolling bearings – Damage and Failures – Terms, Characteristics and Causes	This document classifies different modes of failure occurring in service for rolling bearings made of standard bearing steels. For each failure mode, it defines and describes the characteristics, appearance and possible root causes of failure. It will assist in the identification of failure modes based on appearance.		63	1/8/2025	Reaffirmed
ANSI ABMA ISO	3290-1-2014	Std	Rolling Bearings – Balls – Part 1: Steel Balls	This part of ISO 3290 specifies requirements for finished steel balls for rolling bearings.		22	12/17/2024	Reaffirmation
ANSI ABMA ISO	3290-2-2014	Std	Rolling Bearings – Balls – Part 2: Ceramic Balls	This part of ISO 3290 specifies requirements for finished silicon nitride balls for rolling bearings.		22	12/17/2024	Reaffirmation
ANSI ABMA ISO	5593-2023	Std	Rolling Bearings – Vocabulary	This International Standard establishes a vocabulary of terms, with their definitions, applied in the field of rolling bearings and their technology.		107	7/8/2025	Adoption
ANSI AGMA	1003-H07	Std	Tooth Proportions for Fine-Pitch Spur and Helical Gears	Tooth proportions for fine-pitch gearing are similar to those of coarse pitch gearing except in the matter of clearance. This standard is applicable to external spur and helical gears with diametral pitch of 20 through 120 and a profile angle of 20 degrees. It provides a system of enlarged pinions which use the involute form above 5 degrees of roll. Data on 14-1/2 and 25-degree profile angle systems, and a discussion of enlargement and tooth thicknesses are provided in annexes. In addition, it addresses, in a new annex, an analysis of comparative systems of selecting tooth thicknesses of pinions. Revision of ANSI/AGMA 1003-G93. NOTE: Errata issued April 2025. Reaffirmed April 21, 2025.	1-55589-902-8	25	4/21/2025	Errata

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA	1006-A97	Std	Tooth Proportions for Plastic Gears	Presents a new basic rack, AGMA PT, which, with its full round fillet, may be preferred in many applications of gears made from plastic materials. It contains a description, with equations and sample calculations, of how the proportions of a spur or helical gear may be derived from the design tooth thickness and the basic rack data. In several annexes, there are discussions of possible variations from the basic rack and also a procedure for defining tooth proportions without using the basic rack concept. Reaffirmed March 2023.	1-55589-684-7	47	3/9/2023	Reaffirmation
ANSI AGMA	1010-F14	Std	Appearance of Gear Teeth - Terminology of Wear and Failure	This standard provides nomenclature for general modes of gear tooth wear and failure. It classifies, identifies and describes the most common types of failure and provides information which will, in many cases, enable the user to identify failure modes and evaluate the degree or progression of wear. Revision of ANSI/AGMA 1010-E95. Reaffirmed April 23, 2025.	1-61481-089-6	81	4/23/2025	Reaffirmation
ANSI AGMA	1012-H23	Std	Gear Nomenclature Definitions of Terms with Symbols	This standard lists terms and their definitions with symbols for gear nomenclature. Revision of ANSI/AGMA 1012-G05.	978-1-61481-401-6	72	3/31/2023	Published
ANSI AGMA	1102-C19	Std	Tolerance Specification for Gear Hobs	The purpose of this standard is to provide specifications for nomenclature, dimensions, tolerances, and inspection of gear hobs, and thereby establish a basis for mutual understanding in this respect in the use and manufacture of these tools. Revision of ANSI/AGMA 1102-B13. Reaffirmed January 8, 2025.	978-1-64353-070-3	58	1/8/2025	Reaffirmation
ANSI AGMA	1103-H07	Std	Tooth Proportions for Fine-Pitch Spur and Helical Gearing (Metric Edition)	Tooth proportions for fine-pitch gearing are similar to those of coarse pitch gearing except in the matter of clearance. This standard is applicable to external spur and helical gears with diametral pitch of 1.25 through 0.2 and a profile angle of 20 degrees. It provides a system of enlarged pinions which use the involute form above 5 degrees of roll. Data on 14-1/2 and 25-degree profile angle systems, and a discussion of enlargement and tooth thicknesses are provided in annexes. In addition, it addresses, in a new annex, an analysis of comparative systems of selecting tooth thicknesses of pinions. Metric version of ANSI/AGMA 1003-H07. Reaffirmed April 21, 2025.	1-55589-903-5	25	4/21/2025	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA	1104-A09	Std	Tolerance Specification for Shaper Cutters	The purpose of this standard is to provide specifications for nomenclature, dimensions, tolerances, and inspection of shaper cutters, and thereby establish a basis for mutual understanding in this respect in the use and manufacture of these tools. Reaffirmed November 19, 2020.	1-55589-974-5	54	11/19/2020	Reaffirmation
ANSI AGMA	1106-A97	Std	Tooth Proportions for Plastic Gears	Presents a new basic rack, AGMA PT, which, with its full round fillet, may be preferred in many applications of gears made from plastic materials. It contains a description, with equations and sample calculations, of how the proportions of a spur or helical gear may be derived from the design tooth thickness and the basic rack data. In several annexes, there are discussions of possible variations from the basic rack and also a procedure for defining tooth proportions without using the basic rack concept. Metric edition of ANSI/AGMA 1006-A97. Reaffirmed March 2023.	1-55589-685-5	47	3/9/2023	Reaffirmation
ANSI AGMA	1107-A19	Std	Tolerance Specification for Form Milling Cutters	This standard provides specifications for nomenclature, dimensions, tolerances and inspection for form milling cutters. Included in these are involute type, straight sided for rack or worm thread generation, form relieved, indexable carbide insert (ICI), and special form. This standard establishes a basis for understanding the use and manufacture of these form types of milling cutters. Errata issued January 2025. Reaffirmed April 21, 2025.	978-1-64353-071-0	54	4/21/2025	Reaffirmation/Errata
ANSI AGMA	2002-D19	Std	Tooth Thickness and Backlash Measurement of Cylindrical Involute Gearing	Establishes the procedures for determining the specification limits for tooth thickness of external and internal cylindrical involute gearing. Includes equations and calculation procedures for the commonly used measuring methods. A specific tooth thickness specification limit can be established from the design thickness or from another tooth thickness measurement. The procedures can be used with an established design tooth thickness, or with actual tooth thickness dimensions. The effect of tooth geometric quality variations on tooth thickness dimensions is discussed. Calculations for backlash are included, and are based on the specified tooth thickness, center distance, and tolerances. Revision of ANSI/AGMA 2002-B88.	978-1-64353-068-0	145	12/2/2024	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA	2003-D19	Std	Rating the Pitting Resistance and Bending Strength of Generated Straight Bevel Zerol Bevel and Spiral Bevel Gear Teeth	This standard specifies a method for rating the pitting resistance and bending strength of generated straight bevel, zerol bevel and spiral bevel gear teeth. A detailed discussion of factors influencing gear survival and a calculation method are provided. Revision of ANSI/AGMA 2003-C10. (Errata included). Reaffirmed May 12, 2025.	978-1-64353-037-6	99	5/12/2025	Reaffirmation/Errata
ANSI AGMA	2004-C08	Std	Gear Materials Heat Treatment and Processing Manual	This standard provides information pertaining to ferrous and nonferrous materials used in gearing. Factors in material selection, including material forms, properties, and associated processing and heat treatments are discussed. Manufacturing procedures to prepare materials for machining and final heat treatment are included. Heat treating procedures used for gearing are covered in detail, including process description, product specifications, process controls, and characteristics of heat treated gearing. Post-heat treatment processes to meet gearing requirements are discussed. Product inspection methods and documentation are covered. Term definitions, test methods, distortion and residual stress, sources for additional information and bibliography are included. Revision of ANSI/AGMA 2004-B89. Reaffirmed April 21, 2025.	1-55589-904-2	68	4/21/2025	Reaffirmation
ANSI AGMA	2008-D11	Std	Assembling Bevel Gears	This Standard was prepared for the assembly man in the factory and for the service man in the field. Each definition, explanation, and instruction is directed toward the physical appearance of the gears as they are inspected and assembled by these personnel. The definitions are simple. The explanations are thorough. An Annex provides detailed instructions on performing contact pattern checks. Reaffirmed November 2021.	1-55589-998-1	49	11/1/2021	Reaffirmation
ANSI AGMA	2011-B14	Std	Cylindrical Wormgearing Tolerance and Inspection Methods	This standard describes and defines variations that may occur in unassembled wormgearing. It displays measuring methods and practices, giving suitable warnings if a preferred probe cannot be used. The applicability of single or double flank composite testing is discussed, using a reference gear. Tooth thickness measurement is shown using direct measurement as well as the use of measurements over wires or pins. Equations for the maximum variations are given for the stated ranges, as a function of size, pitch and tolerance grade. Revision of ANSI/AGMA 2011-A98. NOTE: Errata issued April 2025. Reaffirmed April 21, 2025.	1-61481-090-2	51	4/21/2025	Reaffirmation/Errata

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA	2101-E25	Std	Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth (Metric Edition)	This standard specifies a method for rating the macropitting resistance and bending strength of spur and helical involute gear pairs. A detailed discussion of factors influencing gear survival and calculation methods are provided.	978-1-64353-202-8	115	7/31/2025	Published
ANSI AGMA	2111-A98	Std	Cylindrical Wormgearing Tolerance and Inspection Methods (Metric Edition)	Establishes a classification system for the geometrical accuracy specification of wormgearing. It also provides uniform measurement procedures including discussions on single and double flank composite testing and tooth thickness measurements. The standard establishes ten accuracy grades, W3 through W12, based on the relative effect of geometrical errors on conjugate action for wormgear sets. Metric edition of ANSI/AGMA 2011-A98. NOTE: Errata issued April 2025. Reaffirmed November 20, 2025.	1-55589-717-7	43	11/20/2025	Reaffirmation/Errata
ANSI AGMA	2116-B24	Std	Evaluation of Double Flank Testers for Radial Composite Measurement of Gears	This standard provides the evaluation criteria for double flank testers. Recommended artifact sizes and geometry are provided along with measurement system conditions. Annex A provides a method for estimating calibration uncertainty. The withdrawn AGMA 935-A05 was incorporated into an annex. Revision of ANSI/AGMA 2116-A05.	978-1-64353-168-7	26	4/1/2024	Published
ANSI AGMA	6000-C20	Std	Specification for Measurement of Linear Vibration on Gear Units	This standard presents a method for the measurement of linear vibrations on a gear unit. Instrumentation, measuring methods, test procedures and discrete frequency vibration limits are recommended for acceptance testing to confirm integrity. An annex which lists system effects on gear unit vibration and responsibility is also provided. Revision of ANSI/AGMA 6000-B96.	1-55589-666-9	21	11/30/2020	Reaffirmation
ANSI AGMA	6001-F19	Std	Design and Selection of Components for Enclosed Gear Drives	This standard outlines the basic practices for the design and selection of components, other than gearing, for use in commercial and industrial enclosed gear drives. Fundamental equations provide for the proper sizing of shafts, keys, and fasteners based on stated allowable stresses. Other components are discussed in a manner to provide an awareness of their function or specific requirements. This standard applies to the following types of commercial and industrial enclosed gear drives, individually or in combination: spur, helical, herringbone, bevel and worm. Revision of ANSI/AGMA 6001-E08. Reaffirmed January 8, 2025.	978-1-64353-035-2	66	1/8/2025	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA	6002-D20	Std	Design Guide for Vehicle Spur and Helical Gears	This standard provides information on the design of spur and helical vehicle power transmission gears. Included are considerations for design, material and heat treatment, lubrication, determination of load capacity, mounting features, and typical design problems. Revision of ANSI/AGMA 6002-C15.	978-1-64353-074-1	65	2/6/2020	Published
ANSI AGMA	6006-B20	Std	Standard for Design and Specification of Gearboxes for Wind Turbines	This standard is intended to apply to wind turbine gearboxes. It provides information for specifying, selecting, designing, manufacturing, testing, procuring, operating and maintaining reliable speed increasing gearboxes for wind turbine generator system service. Annex information is supplied on wind turbine architecture, wind turbine load description, quality assurance, operation and maintenance, minimum purchaser gearbox manufacturer ordering data, lubrication selection and monitoring, determination of an application factor from a load spectrum using the equivalent torque, and bearing stress calculations. Revision of ANSI/AGMA/AWEA 6006-A03.	978-1-64353-073-4	46	2/11/2020	Published
ANSI AGMA	6008-B24	Std	Specifications for Powder Metallurgy Gears	This standard provides comprehensive details for the design, processing, and specifications of powder metallurgy (PM) steel gears that need to be agreed upon between the PM gear supplier and the purchaser. These include: definition of terms, gear tooth geometry considerations, inspection, PM gear materials, drawing specifications, heat treatment, and mechanical testing. Revision of ANSI/AGMA 6008-A98.	978-1-64353-167-0	77	4/2/2024	Published
ANSI AGMA	6011-K25	Std	Specification for High Speed Helical Gear Units	This standard includes design, lubrication, bearings, testing and rating for single and double helical external tooth, parallel shaft speed reducers or increasers. Units covered include those operating with at least one stage having a pitch line velocity equal to or greater than 35 meters per second or rotational speeds greater than 4500 rpm and other stages having pitch line velocities equal to or greater than 8 meters per second.	978-1-64353-201-1	83	9/2/2025	Published

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA	6013-B16	Std	Standard for Industrial Enclosed Gear Drives	This standard includes design, rating, lubrication, testing, and selection information for enclosed gear drives, including foot mounted, shaft mounted, screw conveyor drives, and gearmotors. These drives may include spur, helical, herringbone, double helical, or bevel gearing in single or multistage arrangements as either parallel, concentric, or right-angle configurations. Revision of ANSI/AGMA 6013-A06. Reaffirmed November 2021. NOTE: ANSI/AGMA 6013-B16 has an errata included at the end of the document.	978-1-55589-049-0	86	11/23/2021	Reaffirmed/Errata
ANSI AGMA	6014-B15	Std	Gear Power Rating for Cylindrical Shell and Trunnion Supported Equipment	This standard specifies a method for rating the pitting resistance and bending strength of open or semi-enclosed gearing for use on cylindrical shell and trunnion supported equipment such as grinding mills, kilns, coolers, and dryers. This includes spur, self-aligning spur, single helical, double helical, and herringbone gears made from steel, ductile iron, and austempered ductile iron. Annexes cover installation, alignment, maintenance, combination drives, and lubrication. Revision of ANSI/AGMA 6014-A06. Reaffirmed September 10, 2025.	1-55589-045-2	82	9/10/2025	Reaffirmation
ANSI AGMA	6015-A13	Std	Power Rating of Single and Double Helical Gearing for Rolling Mill Service	This Standard provides a method for determining the power rating of gear sets used in main mill drives, pinion stands, and combination units used for the reduction of material size in metal rolling mills. Applications include, but are not limited to, hot mills and cold mills, roughing and finishing stands: reducing, increasing, and 1:1 ratio sets. Auxiliary drives, including drives listed in ANSI/AGMA 6013-A06, such as bridles, coilers, uncoilers, edge trimmers, flatteners, loopers (accumulators), pinch rolls, scrap choppers, shears, and slitters are not covered by this document. This standard includes a method by which different gear tooth designs can be rated and compared at extended life cycles typical for these applications, up to 175 000 hours. Reaffirmed May 20, 2024.	1-61481-056-8	67	5/20/2024	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA	6022-D19	Std	Design Manual for Cylindrical Wormgearing	Covers the design of fine and coarse pitch cylindrical wormgearing operating at right angles and primarily made as gear sets to be incorporated into other machines and mechanisms. Many of the design procedures are also incorporated in enclosed drives. NOTE: Errata issued in July 2020 and January 2025 are included at the end of the document. Reaffirmed April 21, 2025.	1-55589-041-5	44	4/21/2025	Reaffirmation/Errata
ANSI AGMA	6025-E19	Std	Sound for Enclosed Helical Herringbone and Spiral Bevel Gear Drives	Describes a recommended method of acceptance testing and reporting of the sound pressure levels generated by a gear speed reducer or increaser when tested at the manufacturer’s facility. The results obtained through the use of this standard should represent only the sound of the gear unit, as other system influences, such as prime mover or driven equipment are minimized. Annexes to the standard present sound power measurement methods for use when required by specific contract provisions between the manufacturer and purchaser. Revision of ANSI/AGMA 6025-D98. Reaffirmed January 8, 2025.	978-1-64353-033-8	32	1/8/2025	Reaffirmation
ANSI AGMA	6032-B13	Std	Standard for Marine Gear Units: Rating and Application for Spur and Helical Gear Teeth	This document considers rating practices for marine main propulsion, power take-off and auxiliary propulsion service. Revision of ANSI/AGMA 6032-A94. Reaffirmed May 20, 2024	1-61481-084-1	52	5/20/2024	Reaffirmation
ANSI AGMA	6033-C08	Std	Materials for Marine Propulsion Gearing	This standard identifies commonly used alloy steels, heat treatments and inspection requirements for through hardened and surface hardened gearing for main propulsion marine service over 1500 hp. Forged and hot rolled alloy steel bar stock are specified to two metallurgical quality grades (1 and 2) according to cleanliness and test requirements. Cast steel gearing is specified to a single metallurgical quality level. Mechanical, metallurgical and nondestructive test requirements are provided for various heat treatment processes and metallurgical quality grades of gearing. Revision of ANSI/AGMA 6033-B98. Reaffirmed April 21, 2025.	1-55589-929-5	34	4/21/2025	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA	6034-C21	Std	Practice for Enclosed Cylindrical Wormgear Speed Reducers and Gearmotors	This standard gives a method for rating and design of specific enclosed cylindrical wormgear reducers and gear motors at speeds not greater than 3600 rpm or mesh sliding velocities not more than 6000 ft/min. It contains power, torque and efficiency equations with guidance on component design, thermal capacity, service factor selection, lubrication, and self-locking features of wormgears. Annexes are supplied on service factors, user recommendations. Replaces ANSI/AGMA 6034-B92.	978-1-64353-092-5	43	4/8/2021	Published
ANSI AGMA	6035-A02	Std	Design Rating and Application of Industrial Globoidal Wormgearing	This standard provides guidelines for the design, rating and application of globoidal wormgearing mounted at a 90-degree angle. Specific definitions for globoidal wormgearing terms are presented, along with formulas for determining the geometric sizes of the major features for the worm and gear. Design considerations, design procedures, gear blanks and self-locking conditions are also discussed. Procedures for rating the load capacity of globoidal wormgearing are included. Replaces ANSI/AGMA 6017-E86 and ANSI/AGMA 6030-C87. Reaffirmed April 21, 2025.	1-55589-792-4	45	4/21/2025	Reaffirmation
ANSI AGMA	6101-F19	Std	Design and Selection of Components for Enclosed Gear Drives (Metric Edition)	This standard outlines the basic practices for the design and selection of components, other than gearing, for use in commercial and industrial enclosed gear drives. Fundamental equations provide for the proper sizing of shafts, keys, and fasteners based on stated allowable stresses. Other components are discussed in a manner to provide an awareness of their function or specific requirements. This standard applies to the following types of commercial and industrial enclosed gear drives, individually or in combination: spur, helical, herringbone, bevel and worm. Metric Edition of ANSI/AGMA 6101-E08. Reaffirmed January 8, 2025.	978-1-64353-034-5	63	1/8/2025	Reaffirmation
ANSI AGMA	6102-D20	Std	Design Guide for Vehicle Spur and Helical Gears (Metric Edition)	This standard provides information on the design of spur and helical vehicle power transmission gears. Included are considerations for design, material and heat treatment, lubrication, determination of load capacity, mounting features, and typical design problems. Metric edition of ANSI/AGMA 6002-D20.	978-1-64353-075-8	65	2/6/2020	Published

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA	6113-B16	Std	Standard for Industrial Enclosed Gear Drives (Metric Edition)	This standard includes design, rating, lubrication, testing, and selection information for enclosed gear drives, including foot mounted, shaft mounted, screw conveyor drives, and gearmotors. These drives may include spur, helical, herringbone, double helical, or bevel gearing in single or multistage arrangements as either parallel, concentric, or right angle configurations. Metric version of ANSI/AGMA 6013-B16. Replaces ANSI/AGMA 6113-A06. Reaffirmed November 2021. NOTE: ANSI/AGMA 6113-B16 has an errata included at the end of the document.	978-1-55589-051-3	85	11/29/2021	Reaffirmation/Errata
ANSI AGMA	6114-B15	Std	Gear Power Rating for Cylindrical Shell and Trunnion Supported Equipment (Metric Edition)	This standard specifies a method for rating the pitting resistance and bending strength of open or semi-enclosed gearing for use on cylindrical shell and trunnion supported equipment such as grinding mills, kilns, coolers, and dryers. This includes spur, self-aligning spur, single helical, double helical, and herringbone gears made from steel, ductile iron, and austempered ductile iron. Annexes cover installation, alignment, maintenance, combination drives, and lubrication. Replaces 6114-A06. Metric edition of ANSI/AGMA 6014-B15. Reaffirmed September 10, 2025.	1-55589-047-6	82	9/10/2025	Reaffirmation
ANSI AGMA	6115-A13	Std	Power Rating of Single and Double Helical Gearing for Rolling Mill Service - Metric Edition	This Standard provides a method for determining the power rating of gear sets used in main mill drives, pinion stands, and combination units used for the reduction of material size in metal rolling mills. Applications include, but are not limited to, hot mills and cold mills, roughing and finishing stands: reducing, increasing, and 1:1 ratio sets. Auxiliary drives, including drives listed in ANSI/AGMA 6113-A06, such as bridles, coilers, uncoilers, edge trimmers, flatteners, loopers (accumulators), pinch rolls, scrap choppers, shears, and slitters are not covered by this document. This standard includes a method by which different gear tooth designs can be rated and compared at extended life cycles typical for these applications, up to 175 000 hours. Reaffirmed May 20, 2024.	1-61481-057-5	67	5/20/2024	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA	6123-C16	Std	Design Manual for Enclosed Epicyclic Gear Drives	This is a design manual for drives employing epicyclic gear arrangements. It includes descriptions of epicyclic drives, nomenclature, application information and design guidelines with reference to other AGMA standards. Replaces ANSI/AGMA 6123-B06. Reaffirmed October 2021. NOTE: ANSI/AGMA 6123-C16 has an errata included at the end of the document.	1-55589-059-9	136	10/7/2021	Reaffirmed/Errata
ANSI AGMA	6132-B13	Std	Standard for Marine Gear Units: Rating and Application for Spur and Helical Gear Teeth (Metric Edition)	This document considers rating practices for marine main propulsion, power take-off and auxiliary propulsion service. Metric edition of ANSI/AGMA 6032-B13. Reaffirmed May 20, 2024.	1-61481-085-8	52	5/20/2024	Reaffirmation
ANSI AGMA	6133-C08	Std	Materials for Propulsion Gearing (Metric Edition)	This standard identifies commonly used alloy steels, heat treatments and inspection requirements for through hardened and surface hardened gearing for main propulsion marine service over 1500 hp. Forged and hot rolled alloy steel bar stock are specified to two metallurgical quality grades (1 and 2) according to cleanliness and test requirements. Cast steel gearing is specified to a single metallurgical quality level. Mechanical, metallurgical and nondestructive test requirements are provided for various heat treatment processes and metallurgical quality grades of gearing. Metric version of ANSI/AGMA 6033-C08. Reaffirmed April 21, 2025.	1-55589-930-1	34	4/21/2025	Reaffirmation
ANSI AGMA	6134-C21	Std	Practice for Enclosed Cylindrical Wormgear Speed Reducers and Gearmotors (Metric Edition)	This standard gives a method for rating and design of specific enclosed cylindrical wormgear reducers and gear motors at speeds not greater than 3600 rpm or mesh sliding velocities not more than 30 m/s. It contains power, torque and efficiency equations with guidance on component design, thermal capacity, service factor selection, lubrication, and self-locking features of wormgears. Annexes are supplied on service factors, user recommendations. Metric version of ANSI/AGMA 6034-C21.	978-1-64353-093-2	43	4/9/2021	Published

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA	6135-A02	Std	Design Rating and Application of Industrial Globoidal Wormgearing (Metric Edition)	This standard provides guidelines for the design, rating and application of globoidal wormgearing mounted at a 90-degree angle. Specific definitions for globoidal wormgearing terms are presented, along with formulas for determining the geometric sizes of the major features for the worm and gear. Design considerations, design procedures, gear blanks and self-locking conditions are also discussed. Procedures for rating the load capacity of globoidal wormgearing are included. Replaces ANSI/AGMA 6017-E86 and ANSI/AGMA 6030-C87. Metric edition of ANSI/AGMA 6035-A02. Reaffirmed April 21, 2025.	1-55589-793-2	45	4/21/2025	Reaffirmation
ANSI AGMA	9000-D11	Std	Flexible Couplings - Potential Unbalance Classification	This standard defines classes of flexible coupling potential unbalance, one of which the user must select in order to meet the needs of their system. The classes are established using weight and speed and system sensitivity to arrive at a mass displacement value that defines the potential unbalance. The standard defines types of unbalance, provides a method of selecting balance class, identifies contributors to potential unbalance, and provides a method of determining potential coupling unbalance. The balance classes are derived from consideration of the potential unbalance of the coupling. Reaffirmed January 2022.	1-55589-995-0	0	1/6/2022	Reaffirmation
ANSI AGMA	9001-C18	Std	Flexible Couplings - Lubrication	This standard provides information on lubrication of gear couplings, chain couplings and metallic grid couplings. Types of lubricants and lubrication methods and practices are included. In addition, selection guides for grease and oil lubrication are provided. Revision of ANSI/AGMA 9001-B97. Reaffirmed May 20, 2024.	978-1-64353-003-1	0	5/20/2024	Reaffirmation
ANSI AGMA	9002-C14	Std	Bores and Keyways for Flexible Couplings Inch Series	This standard describes sizes and tolerances for straight and tapered bores and the associated keys and keyways, as furnished in flexible couplings. The data in the standard considers commercially standard coupling bores and keyways, not special coupling bores and keyways that may require special tolerances. Annexes provide material on inspection methods and design practices for tapered shafts. Revision of ANSI/AGMA 9002-B04. Reaffirmed December 1, 2025.	1-61481-091-9	0	12/1/2025	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA	9003-C17	Std	Flexible Couplings - Keyless Fits	This standard presents information on design, dimensions, tolerances, inspection, mounting, removal, and equipment that is in common use with keyless tapered and keyless straight (cylindrical) bore hubs for flexible couplings. Revision of ANSI/AGMA 9003-B08. Reaffirmed October 2022. (Errata included)	978-1-64353-000-0	0	10/28/2022	Reaffirmation/Errata
ANSI AGMA	9004-B08	Std	Flexible Couplings - Mass Elastic Properties and Other Characteristics	This standard provides calculation methods related to mass elastic properties of flexible couplings. Properties discussed include coupling mass, polar mass moment of inertia (WR2), center of gravity, axial stiffness, axial natural frequency, lateral stiffness, lateral natural frequency, and torsional stiffness. Calculation examples are provided in informative annexes. Revision of ANSI/AGMA 9004-A99. Reaffirmed April 2020.	1-55589-973-8	0	4/23/2020	Reaffirmation
ANSI AGMA	9005-F16	Std	Industrial Gear Lubrication	This standard provides lubrication guidelines for enclosed and open gearing installed in general industrial power transmission applications. It is not intended to supplant specific instructions from the gear manufacturer. Revision of ANSI/AGMA 9005-E02. Reaffirmed October 2021.	978-1-55589-052-0	0	10/5/2021	Reaffirmation
ANSI AGMA	9006-A16	Std	Flexible Couplings - Basis for Rating	This standard presents criteria and guidelines for the establishment of the basis for ratings of standard flexible couplings. Due to the diversity of coupling types, details of design such as formulas and analysis used to derive the stresses, etc. are often considered proprietary and are not considered in this standard. This standard is of importance to coupling manufacturers, users and equipment designers for the proper selection, comparison and application of flexible couplings. Reaffirmed January 2022.	978-1-55589-057-5	0	1/6/2022	Reaffirmed
ANSI AGMA	9008-B00	Std	Flexible Couplings - Gear Type - Flange Dimensions Inch Series	Defines the North American industry practice for the interface dimensions of the sleeve and rigid hubs of both shrouded and exposed bole, inch series, gear type couplings. Reaffirmed October 2022.	1-55589-736-3	0	10/28/2022	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA	9009-E20	Std	Flexible Couplings - Nomenclature for Flexible Couplings	This standard presents the nomenclature common to flexible couplings as used in mechanical power transmission drives. It does not address nomenclature for flexible shafts, quill shafts, universal joints or devices that exhibit slip such as clutches, fluid couplings, magnetic couplings or torque converters. The standard was prepared to reduce the language barriers that arise between designers, manufacturers and users when attempting to designate or describe various types of flexible couplings and their elements. Revision of ANSI/AGMA 9009-D02. Reaffirmed December 1, 2025.	978-1-64353-078-9	0	12/1/2025	Reaffirmation
ANSI AGMA	9103-C17	Std	Flexible Couplings - Keyless Fits (Metric Edition)	This standard presents information on design, dimensions, tolerances, inspection, mounting, removal, and equipment that is in common use with keyless tapered and keyless straight (cylindrical) bore hubs for flexible couplings. Metric version of ANSI/AGMA 9003-C17. Reaffirmed October 2022. (Errata included)	978-1-64353-001-7	22	10/28/2022	Reaffirmation/Errata
ANSI AGMA	9104-A06	Std	Flexible Couplings - Mass Elastic Properties and Other Characteristics (Metric Edition)	This standard provides calculation methods related to mass elastic properties of flexible couplings. Properties discussed include coupling mass, polar mass moment of inertia, center of gravity, axial stiffness, axial natural frequency, lateral stiffness, lateral natural frequency, and torsional stiffness. Calculation examples are provided in informative annexes. Metric edition of ANSI/AGMA 9004-A99. Reaffirmed October 2022.	1-55589-900-4	32	10/28/2022	Reaffirmation
ANSI AGMA	9110-A11	Std	Flexible Couplings - Potential Unbalance Classification (Metric Edition)	This metric standard defines classes of flexible coupling potential unbalance, one of which the user must select in order to meet the needs of their system. The classes are established using mass and speed and system sensitivity to arrive at a mass displacement value that defines the potential unbalance. The standard defines types of unbalance, provides a method of selecting balance class, identifies contributors to potential unbalance, and provides a method of determining potential coupling unbalance. The balance classes are derived from consideration of the potential unbalance of the coupling. Metric edition of ANSI/AGMA 9000-D11. Reaffirmed January 2022.	1-55589-996-7	69	1/6/2022	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA	9112-B15	Std	Bores and Keyways for Flexible Couplings (Metric Series)	This standard describes sizes and tolerances for straight and tapered bores and the associated keys and keyways, as furnished in flexible couplings. The data in the standard considers commercially standard coupling bores and keyways, not special coupling bores and keyways that may require special tolerances. Annexes provide material on inspection methods and design practices for tapered shafts. Metric edition of ANSI/AGMA 9002-C14. Reaffirmed December 1, 2025.	1-61481-092-6	36	12/1/2025	Reaffirmation
ANSI AGMA ISO	1328-1-B14	Std	Cylindrical Gears - ISO System of Flank Tolerance Classification - Part 1: Definitions and Allowable Values of Deviations Relevant to Flanks of Gear Teeth	This standard establishes a tolerance classification system relevant to manufacturing and conformity assessment of tooth flanks of individual cylindrical involute gears. It specifies definitions for gear flank tolerance terms, the structure of the flank tolerance class system, and allowable values. Replaces ANSI/AGMA 2015-1-A01. Reaffirmed September 18, 2024. (Errata included).	1-61481-114-5	47	9/18/2024	Reaffirmation/Errata
ANSI AGMA ISO	1328-2-A21	Std	Cylindrical Gears — ISO System of Flank Tolerance Classification — Part 2: Definitions and Allowable Values of Double Flank Radial Composite Deviations	This document establishes a gear tooth classification system relevant to double flank radial composite deviations of individual cylindrical involute gears and sector gears. It provides formulae to calculate tolerances for individual product gears when mated in double flank contact with a master gear. Identical to ISO 1328-2:2020. Reaffirmed September 2, 2025.	978-1-64353-115-1	26	9/2/2025	Reaffirmation
ANSI AGMA ISO	14104-A17	Std	Gears - Surface Temper Etch Inspection After Grinding Chemical Method	This document explains the materials and procedures necessary to determine, evaluate and describe localized overheating on ground surfaces. A system to describe and classify the indications produced during this inspection is included. However, specific acceptance or rejection criteria are not contained. An industry-wide survey was conducted to establish common solutions in time that were acceptable to the greatest number of users. The safety and environmental precautions were included therein for those not familiar with storage, handling, use and disposal of concentrated acids, alkalis and solvents. These precautions, however, do not supersede the latest applicable requirements. Replaces ANSI/AGMA 2007-C00. Reaffirmed August 20, 2024.	978-1-64353-032-1	23	8/20/2024	Reaffirmation

Accreditation	Document	Type	Title	Abstract	ISBN	Pages	Publish date	Pub type
ANSI AGMA ISO	17485-A08	Std	Bevel Gears - ISO System of Accuracy	This standard establishes a classification system that can be used to communicate geometrical accuracy specifications of unassembled bevel gears, hypoid gears, and gear pairs. It defines tooth accuracy terms, specifies the structure of the gear accuracy grade system, and provides allowable values. The standard provides the gear manufacturer and the gear buyer with a mutually advantageous reference for uniform tolerances. Ten grades are defined, numbered 2 to 11 in order of decreasing precision. Equations for tolerances and their ranges of validity are provided for bevel and hypoid gearing. Identical adoption of ISO 17485:2006. Replaces ANSI/AGMA 2009-B01. Reaffirmed March 2014.	1-55589-926-4	23	12/5/2024	Reaffirmation
ANSI AGMA ISO	18653-A06	Std	Gears - Evaluation of Instruments for the Measurement of Individual Gears	This International Standard specifies methods for the evaluation of measuring instruments used to measure cylindrical gear involute, helix, pitch and runout. It includes instruments that measure runout directly or compute it from index measurements. Of necessity, it includes the estimation of measurement uncertainty with the use of calibrated gear artifacts. It also gives recommendations for the evaluation of tooth thickness measuring instruments. The estimation of product gear measurement uncertainty is beyond its scope (see AGMA ISO 10064-5-A06 for recommendations). This standard is an identical adoption of ISO 18653:2006. Replaces ANSI/AGMA 2010-A94, ANSI/AGMA 2110-A94, ANSI/AGMA 2113-A97 and ANSI/AGMA 2114-A98. Reaffirmed September 4, 2024.	1-55589-882-3	14	9/4/2024	Reaffirmation
ANSI AGMA ISO	23509-B17	Std	Bevel and Hypoid Gear Geometry	This standard specifies the geometry of bevel gears. The term ‘bevel gears’ is used to mean straight, spiral, zerol bevel and hypoid gear designs. If the text pertains to one or more, but not all, of these, the specific forms are identified. This standard is intended for use by an experienced gear designer capable of selecting reasonable values for the factors based on his/her knowledge and background. It is not intended for use by the engineering public at large. Replaces ANSI/AGMA ISO 23509-A08. Reaffirmed August 19, 2024.	978-1-64353-002-4	143	8/19/2024	Reaffirmation

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AGMA 102	Concentric and Parallel Shaft Gearmotors	1943		
AGMA 110.04	Nomenclature of Gear Tooth Failure Modes	1979	ANSI/AGMA 1010-E95	Figure 5
AGMA 111.03	Letter Symbols and Abbreviations for Gear	1954	AGMA 112.04	Figure 6
AGMA 112.05	Gear Nomenclature (Geometry); Terms, Definitions, Symbols, and Abbreviations	1976	ANSI/AGMA 1012-F90	Figure 6
AGMA 113.01	Gear - Specification Drawings	1952	Withdrawn without replacement	--
AGMA 114.02	Formats for Fine-Pitch Gear Specification Data	1973	AGMA 910-C90	Figure 4
AGMA 115.01	Basic Gear Geometry	1959	AGMA 933-B03	--
AGMA 116.01	Glossary - Terms used in Gearing	1972	ANSI/AGMA 1012-F90	Figure 6
AGMA 118.01	Gear Tooth Surface Texture for Aerospace Gearing	1973	AGMA 906-A94	--
AGMA 120.01	Gear Cutting Tools; Fine and Coarse Pitch Hobs	1975	ANSI/AGMA 1102-A03	Figure 7
AGMA 121.02	Gear Cutting Tools; Single Thread Coarse Pitch	1956	AGMA 120.01	Figure 7
AGMA 122.02	Gear Cutting Tools; Single Thread Fine Pitch Hobs	1956	AGMA 120.01	Figure 7
AGMA 123.01	Gear Cutting Tools; Multiple Thread Coarse Pitch	1956	AGMA 120.01	Figure 7
AGMA 124.01	Gear Cutting Tools; Wormgear Hobs	1957	AGMA 120.01	Figure 7
AGMA 140.01	Molded Plastics Gearing; A report on the state of	1972	Withdrawn without replacement	--
AGMA 141.01	Plastics Gearing; Molded, Machined, and Other	1984	Withdrawn without replacement	--
AGMA 150.03	Application Classification for Spur, Helical, Herringbone, and Bevel Gear Gearmotors	1968	AGMA 460.05	Figure 3
AGMA 151.02	Application Classification for Helical, Herringbone, and Spiral Bevel Gear Speed Reducers	1963	AGMA 420.04	Figure 3
AGMA 152.02	Application Classification for Spur, Helical, and Herringbone Gear Shaft Mounted Speed Reducers	1960	AGMA 420.04	Figure 3
AGMA 161.02	Splines; Side Bearing Involute Splines	1947	Withdrawn without replacement	--
AGMA 170.01	Design Guide for Vehicle Spur and Helical Gears	1976	ANSI/AGMA 6002-B93	Figure 10
AGMA 201.02	Tooth Proportions for Course Pitch Involute Spur Gears	1968	Withdrawn without replacement	--
AGMA 202.03	System for Zerol Bevel Gears	1965	ANSI/AGMA 2005-B88	Figure 19

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AGMA 203.03	Fine Pitch On Center Face Gears for 20 degree Involute Spur Pinions	1973	AGMA 916-A19	--
AGMA 206.03	Fine Pitch Straight Bevel Gears		AGMA 208.02	Figure 19
AGMA 207.06	Tooth Proportions for Fine Pitch Involute Spur and Helical Gears	1977	ANSI/AGMA 1003-G93	Figure 4
AGMA 208.03	System for Straight Bevel Gears	1979	ANSI/AGMA 2005-B88	Figure 19
AGMA 209.04	System for Spiral Bevel Gears	1982	ANSI/AGMA 2005-B88	Figure 19
AGMA 210.02	Surface Durability (Pitting) of Spur Gear Teeth	1965	AGMA 218.01	Figure 2
AGMA 211.02	Surface Durability (Pitting) of Helical and Herringbone Gear Teeth	1969	AGMA 218.01	Figure 2
AGMA 211.02A	Design Practice Rating for the Durability of Helical and Herringbone Gears for Enclosed Drives	1966	AGMA 420.04	Figure 3
AGMA 211.02B	Design Practice Rating for the Durability of Helical and Herringbone Gears for Gearmotors		AGMA 460.05	Figure 3
AGMA 212.02	Surface Durability (Pitting) Formulas for Stright Bevel and Zerol Bevel Gear Teeth	1964	ANSI/AGMA 2003-A86	Figure 2
AGMA 213.02	Surface Durability of Cylindrical Worm Gearing	1952	Withdrawn without replacement	--
AGMA 214.02	Rating for Surface Durability of Double Enveloping Worm Gearing		AGMA 441.03	Figure 15
AGMA 215.01	Information Sheet for Surface Durability (Pitting) of Spur, Helical, Herringbone, and Bevel Gear Teeth	1966	AGMA 218.01 & ANSI/AGMA 2003-B97	Figure 2
AGMA 216.01	Surface Durability (Pitting) Formulas for Spiral Bevel Gear Teeth	1964	ANSI/AGMA 2003-A86	Figure 2
AGMA 216.01A	Rating for Surface Durability of Spiral Bevel Gears for Enclosed Drives	1966	AGMA 420.04	Figure 3
AGMA 217.01	Gear Scoring Design Guide for Aerospace Spur and Helical Power Gears	1965	Withdrawn without replacement	--

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AGMA 218.01	Rating the Pitting Resistance and Bending Strength of Spur and Helical Involute Gear Teeth	1982	ANSI/AGMA 2001-B88 & AGMA 908-B89	Figure 2
AGMA 220.02	Rating the Strength of Spur Gear Teeth	1966	AGMA 218.01	Figure 2
AGMA 221.02	Rating the Strength of Helical and Herringbone Gear Teeth	1965	AGMA 218.01	Figure 2
AGMA 221.02A	Rating the Strength of Helical and Herringbone Gears for Enclosed Drives	1966	AGMA 420.04	Figure 3
AGMA 221.02B	Rating the Strength of Helical and Herringbone Gears for Gearmotors	1963	AGMA 440.05	Figure 3
AGMA 221.02C	Rating the Strength of Helical and Herringbone Gears for Shaft-Mounted Speed Reducers	1965	Withdrawn without replacement	--
AGMA 221.02D	Rating the Strength of Helical and Herringbone Gears for Rolling Mill Drives	1966	Withdrawn without replacement	--
AGMA 222.02	Rating the Strength of Straight Bevel and Zerol Bevel Gear Teeth	1964	AGMA 226.01 & ANSI/AGMA 2003-A86	Figure 2
AGMA 223.01	Rating the Strength of Spiral Bevel Gear Teeth	1964	ANSI/AGMA 2003-A86	Figure 2
AGMA 223.01A	Deisgn Practice: Rating the Strength of Spiral Bevel Gears for Enclosed Drives	1966	AGMA 420.04	Figure 3
AGMA 223.01B	Spiral Bevel Gears for Gearmotors		AGMA 460.05	Figure 3
AGMA 224.01	Gear Materials Manual		AGMA 240.01	Figure 8
AGMA 225.01	Strength of Spur, Helical, Herringbone, and Bevel Gear Teeth	1967	AGMA 226.01	Figure 2
AGMA 226.01	Geometry Factors for Determining the Strength of Spur, Helical, Herringbone, and Bevel Gear Teeth	1970	AGMA 908-B89	Figure 2
AGMA 229.07	Spur and Helical Gear Geometry Factors		Withdrawn without replacement	Figure 2
AGMA 230.01	Surface Temper Inspection Process	1968	ANSI/AGMA 2007-B92	Figure 18
AGMA 231.02	Inspection of Coarse Pitch Spur and Helical Gears	1956	Withdrawn without replacement	--
AGMA 231.52	Pin Measurement Tables for Involute Spur Gears	1966	ANSI/AGMA 2002-B88	--

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AGMA 232.02	Inspection of Coarse Pitch Bevel and Hypoid Gears	1956	Withdrawn without replacement	--
AGMA 234.01	Inspection of Coarse Pitch Cylindrical Worms and Wormgears	1956	AGMA 390.02	Figure 1
AGMA 235.02	Master Gears	1964	AGMA 390.03	Figure 1
AGMA 236.04	Inspection of Fine Pitch Gears	1956	AGMA 390.03	Figure 1
AGMA 237.01	Data Gears Accuracy Specifications	1964	AGMA 390.03	Figure 1
AGMA 239.01	The Span System of Measuring Involute Gear Tooth Size	1965	AGMA 390.03	Figure 1
AGMA 239.01A	Measuring Methods and Practices Manual for Control of Bevel and Hypoid Gears	1966	AGMA 390.03	Figure 1
AGMA 240.01	Gear Materials Manual	1972	ANSI/AGMA 2004-B89	Figure 8
AGMA 241.02	Specification for General Industrial Gear Materials - Steel (Drawn, Rolled, and Forged)	1965	AGMA 240.01	Figure 8
AGMA 242.02	Materials; Cast Iron Gear Blanks	1946	AGMA 240.01	Figure 8
AGMA 243.01	Materials; Cast Bronze Gear Blanks	1954	AGMA 240.01	Figure 8
AGMA 243.51	Specification for Wormgear Bronze		AGMA 240.01	Figure 8
AGMA 243.61	Specification for Aluminum Bronze (Castings, Barstock, and Forgings)	1964	AGMA 240.01	Figure 8
AGMA 243.71	Specification for Manganese Bronze (Castings, Barstock, and Forgings)	1964	AGMA 240.01	Figure 8
AGMA 244.01	Materials; Nodular Iron Gear Materials	1959	AGMA 240.01	Figure 8
AGMA 245.01	Specification for Cast Steel Gear Materials	1964	AGMA 240.01	Figure 8
AGMA 246.01	Recommended Procedure for Carburized Industrial Gearing		AGMA 240.01	Figure 8
AGMA 246.02A	Practice for carburized Aerospace Gearing	1983	Replaced by 926-C99	--
AGMA 247.01	Recommended Procedure for Nitriding, Materials and Process	1965	AGMA 240.01	Figure 8
AGMA 248.01	Recommended Procedure for Induction Hardened Gears and Pinions	1964	AGMA 240.01	Figure 8
AGMA 249.01	Recommended Procedure for Flame Hardening	1964	AGMA 240.01	Figure 8

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AGMA 250.02a	Typical Manufacturer's Oils Meeting Standard AGMA 250.02	1956	AGMA 250.03	Figure 17
AGMA 250.04	Lubrication of Industrial Enclosed Gear Drives	1981	ANSI/AGMA 9005-D94	Figure 17
AGMA 251.02	Lubrication of Industrial Open Gearing	1974	ANSI/AGMA 9005-D94	Figure 17
AGMA 252.01	Mild Extreme Pressure Lubricants for Industrial Enclosed Gearing	1959	AGMA 250.03	Figure 17
AGMA 254.01	Basic Information on Lubricating Oils	1955	AGMA 250.04	Figure 17
AGMA 254.04	Data on Extreme Pressure Lubricants	1944	AGMA 251.02	Figure 17
AGMA 255.02	Bolting - Allowable Tensile Stress for Gear Drives	1964	AGMA 260.02	Figure 9
AGMA 260.02	Design of Components - Enclosed Gear Drives - Bearings, Bolting, Keys, and Shafting	1974	ANSI/AGMA 6001-C88	Figure 9
AGMA 261.02	Keys, Keyways in Bores and Keyseats in Shafts for General Industrial Practice	1966	Withdrawn without replacement	--
AGMA 265.01	Bearings - Allowable Loads and Speeds	1953	AGMA 260.02	Figure 9
AGMA 271.03	Ratios for Helical, Herringbone, and Combination Spiral Bevel Gear Speed Reducers	1963	AGMA 420.04	Figure 3
AGMA 279.01	How to Construct Ratio and Efficiency Formulas for Planetary Gear Trains	1969	Withdrawn without replacement	--
AGMA 290.03	Marking for Enclosed Gear Drives	1971	Withdrawn without replacement	--
AGMA 291.01	Reducer Assembly Designations	1962	AGMA 420.04	Figure 3
AGMA 295.04	Specification for Measurement of Sound on High Speed Helical Gear Units	1977	AGMA 297.02	Figure 13
AGMA 297.02	Sound for Enclosed Helical, Herringbone, and Spiral Bevel Gear Drives	1983	ANSI/AGMA 6025-C90	Figure 13
AGMA 298.01	Sound for Gearmotors and In-line Reducers and Increasers	1975	AGMA 297.02	Figure 13
AGMA 299.01	Sound Manual: Part 1 - Fundamentals of Sound as Related to Gears. Part II - Sources, Specifications, and Levels of Gear Sound. Part III - Gear Noise Control	1987	AGMA 914-A04	--

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AGMA 321.05	Design Practice for Helical and Herringbone Gears for Cylindrical Grinding Mills, Kilns, and Dryers	1970	ANSI/AGMA 6004-F88	Figure 12
AGMA 323.01	Standard for Helical and Herringbone Gearing for Rolling Mill Service	1969	ANSI/AGMA 6005-B89	--
AGMA 330.01	Design Manual for Bevel Gears	1965	ANSI/AGMA 2005-C96	Figure 19
AGMA 331.01	Manual for Assembling Bevel and Hypoid Gears	1969	ANSI/AGMA 2008-B90	--
AGMA 341.02	Design of General Industrial Coarse Pitch Cylindrical Wormgearing	1965	ANSI/AGMA 6022-C93	Figure 4
AGMA 342.02	Design of General Industrial Double Enveloping Wormgears	1965	ANSI/AGMA 6030-C87	Figure 15
AGMA 360.02	Manual for Machine Tool Gearing	1971	Withdrawn without replacement	--
AGMA 370.01	Design Manual for Fine Pitch Gearing	1973	AGMA 917-B97	--
AGMA 374.04	Design Manual for Fine Pitch Wormgearing	1973	ANSI/AGMA 6022-C93	Figure 4
AGMA 390.03	Gear Handbook; Volume 1 - Gear Classification, Materials, and Measuring Methods for Unassembled Gears	1980	AGMA 390.03a & ANSI/AGMA 2000-A88	Figure 1
AGMA 390.03a	Gear Handbook; Gear Classification, Materials, and Measuring Methods for Bevel, Hypoid, Fine Pitch Wormgearing, and Racks Only as Unassembled Gears	1980	ANSI/AGMA 2009-A98, ANSI/AGMA 2011-A98 & ANSI/AGMA 2111-A98	Figure 1
AGMA 411.02	Design Procedure for Aircraft Engine and Power Take-off Spur and Helical Gears	1966	AGMA 911-A94	--
AGMA 420.04	Practice for Enclosed Speed Reducers or Increasers using Spur, Helical, Herringbone, and Spiral Bevel Gears	1975	ANSI/AGMA 6010-E88, ANSI/AGMA 6023-A88, & ANSI/AGMA 6123-A88	Figure 3
AGMA 421.06	Practice for High Speed Helical and Herringbone Gear Units	1969	ANSI/AGMA 6011-G92	Figure 11
AGMA 422.03	Standard Practice for Helical and Herringbone Speed Reducers for Oilfield Pumping Units	1984	Withdrawn without replacement	--

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AGMA 423.01	Thermal Capacity of Helical, Herringbone, and Combination Spiral Bevel Speed Reducers	1963	AGMA 420.04	Figure 3
AGMA 424.01	Practice for Helical and Herringbone Gearing for Oilfield Mud Pumps	1963	Withdrawn without replacement	--
AGMA 425.01	Practice for In-line Reducers and Increasers	1965	AGMA 420.04	Figure 3
AGMA 426.01	Specification for Measurement of Lateral Vibration on High Speed Helical and Herringbone Gear Units	1972	ANSI/AGMA 6000-A88	--
AGMA 427.01	Systems Considerations for Critical Service Gear Drives	1976	ANSI/AGMA 6011-H98	Figure 11
AGMA 430.03	Practice for Speed Reducers and Increasers Employing Spiral Bevel Gearing	1963	AGMA 420.04	Figure 3
AGMA 431.01	Design Procedure for Aircraft Engine and Power Take-off Bevel Gear	1964	AGMA 937-A12	--
AGMA 440.04	Practice for Single and Double Reduction Cylindrical Worm and Helical Worm Speed Reducers	1971	ANSI/AGMA 6034-A87	Figure 14
AGMA 441.04	Practice for Single, Double, and Triple Reduction Double Enveloping Worm and Helical Worm Speed Reducers	1978	ANSI/AGMA 6017-E86	Figure 15
AGMA 442.01	Practice for Worm Hollow Output Shaft Speed Reducers	1965	ANSI/AGMA 6034-A87	Figure 14
AGMA 460.05	Practice for Gearmotors using Spur, Helical, Herringbone, and Spiral Bevel Gears	1971	ANSI/AGMA 6019-E89	Figure 3
AGMA 461.01	Practice for Worm Gearmotors	1966	ANSI/AGMA 6034-A87	Figure 14
AGMA 480.06	Practice for Spur, Helical, and Herringbone Gear Shaft Mounted Speed Reducers	1977	ANSI/AGMA 6021-G89	Figure 3
AGMA 481.01	Drive Shafts for Screw Conveyor Drives	1971	Incorporated into 6021-G89	Figure 3
AGMA 490.02	Spiral Bevel, Helical, and Herringbone Gear Units for Water Cooling Tower Fans	1972	Withdrawn without replacement	--

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AGMA 510.03	Nomenclature for Flexible Couplings	1984	ANSI/AGMA 9009-D02	--
AGMA 511.02	Bores and Keyway Sizes for Flexible Couplings	1969	ANSI/AGMA 9002-A86	Figure 16
AGMA 512.03	Keyways for Flexible Couplings	1974	ANSI/AGMA 9002-A86	Figure 16
AGMA 513.01	Taper Bores for Flexible Couplings	1969	ANSI/AGMA 9002-A86	Figure 16
AGMA 514.02	Load Classification and Service Factors for Flexible Couplings	1971	AGMA 922-A96	--
AGMA 515.02	Balance Classification for Flexible Couplings	1977	ANSI/AGMA 9000-C90	--
AGMA 516.01	Metric Dimensions for Gear Coupling Flanges	1978	ANSI/AGMA 9008-B00	--
AGMA 600.01	Standard for Metric Usage	1979	AGMA 904-B89	--
AGMA 904-A94	Metric Usage	1994	Withdrawn without replacement (refer to ISO 80000 series)	--
AGMA 906-A94	Gear Tooth Surface Texture with Functional Considerations	1994	Withdrawn without replacement	--
AGMA 912-A04	Mechanisms of Gear Tooth Failures	2004	ANSI/AGMA 1010-F14	Figure 5
AGMA 915-1-A02	Inspection Practices - Part 1: Cylindrical Gears - Tangential Measurements	2002	AGMA ISO 10064-1-A21	Figure 1
AGMA 921-A97	Recommended Practices for Design and Specification of Gearboxes for Wind Turbine Generator Systems	1997	ANSI/AGMA 6006-A03	--
AGMA 931-A02	Calibration of Gear Measuring Instruments and Their Application to the Inspection of Product Gears	2002	AGMA ISO 10064-5-A06	Figure 20
AGMA 935-A05	Recommendations Relative to the Evaluation of Radial Composite Gear Double Flank Testers	2005	Incorporated into ANSI/AGMA 2116-B24	--
AGMA ISO 18792-A19	Lubrication of Industrial Gear Drives	2019	Similar to AGMA 955-A22; new ISO document under development Q4 2024	--
AGMA 2000-A88	Tolerances and Measuring Methods for Unassembled Spur and Helical Gears (Including Metric Equivalents)	1988	AGMA 915-1-A02, AGMA 915-2-A05, AGMA 915-3-A99, ANSI/AGMA 2015-1-A01, & ANSI/AGMA 2015-2-A06	Figure 1

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Document #	Title	Year Published	Replaced by or Incorporated into	History Tree
ANSI/AGMA 2001-D04	Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth	2004	Replaced by ANSI/AGMA 2101-E25 - metric only	Figure 2
ANSI/AGMA 2005-D03	Design Manual for Bevel Gears	1988	AGMA ISO 22849-A12 & ANSI/AGMA ISO 23509-A08	Figure 19
ANSI/AGMA 2007-C00	Gears - Surface Temper Etch Inspection after Grinding	2000	ANSI/AGMA 14104-A17	Figure 18
ANSI/AGMA 2009-B01	Bevel Gear Classification, Tolerances, and Measuring Methods	2001	AGMA ISO 10064-6-A10 & ANSI/AGMA ISO 17485-A08	Figure 1
ANSI/AGMA 2010-A94	Measuring Instrument Calibration - Part I, Involute Measurement	1994	AGMA ISO 10064-5-A06 & ANSI/AGMA ISO 18653-A06	Figure 20
ANSI/AGMA 2015-1-A01	Accuracy Classification System - Tangential Measurements for Cylindrical Gears	2001	ANSI/AGMA ISO 1328-1-B14	Figure 1
ANSI/AGMA 2015-2-B15	Gear Tooth Flank Tolerance Classification System - Definitions and Allowable Values of Double Flank Radial Composite Deviations	2015	ANSI/AGMA ISO 1328-2-A21	Figure 1
Supplemental Tables for AGMA 2015/915-1-A02	Accuracy Classification System - Tangential Measurement Tolerance Tables for Cylindrical Gears	2002	ANSI/AGMA ISO 1328-1-B14	--
ANSI/AGMA 2110-A94	Measuring Instrument Calibration - Part I, Involute Measurement (Metric)	1994	AGMA ISO 10064-5-A06 & ANSI/AGMA ISO 18653-A06	Figure 20
ANSI/AGMA 2113-A97	Measuring Instrument Calibration, Gear Tooth Alignment Measurement	1997	AGMA ISO 10064-5-A06 & ANSI/AGMA ISO 18653-A06	Figure 20
ANSI/AGMA 2114-A98	Measuring Instrument Calibration, Gear Pitch and Runout Measurements	1998	AGMA ISO 10064-5-A06 & ANSI/AGMA ISO 18653-A06	Figure 20
ANSI/AGMA 6004-F88	Gear Power Rating for Cylindrical Grinding Mills, Kilns, Coolers, and Dryers	1988	ANSI/AGMA 6014-A06	Figure 12
ANSI/AGMA 6005-B89	Power Rating for Helical and Herringbone Gearing for Rolling Mill Service	1989	ANSI/AGMA 6015-A13 & ANSI/AGMA 6115-A13	--

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ANSI/AGMA 6009-A00	Standard for Gearmotor, Shaft Mounted, and Screw Conveyor Drives	2000	ANSI/AGMA 6013-A06	Figure 3
ANSI/AGMA 6010-F97	Standard for Spur, Helical, Herringbone, and Bevel Enclosed Drives	1997	ANSI/AGMA 6013-A06	Figure 3
ANSI/AGMA 6017-E86	Rating and Application of Single and Multiple Reduction Double Enveloping Worm and Helical Worm Speed Reducers	1989	ANSI/AGMA 6035-A02 & ANSI/AGMA 6135-A02	Figure 15
ANSI/AGMA 6019-E89	Standard for Gearmotors using Spur, Helical, Herringbone, Straight Bevel, or Spiral Bevel Gears	1989	ANSI/AGMA 6009-A00 & ANSI/AGMA 6019-A00	Figure 3
ANSI/AGMA 6021-G89	Standard for Shaft Mounted and Screw Conveyor Drives using Spur, Helical, and Herringbone Gears	1989	ANSI/AGMA 6009-A00 & ANSI/AGMA 6019-A00	Figure 3
ANSI/AGMA 6023-A88	Design Manual for Enclosed Epicyclic Gear Drives	1988	ANSI/AGMA 6123-B06	Figure 3
ANSI/AGMA 6030-C87	Design if Industrial Double Enveloping Wormgears	1987	ANSI/AGMA 6035-A02 & ANSI/AGMA 6135-A02	Figure 15
ANSI/AGMA 6109-A00	Standard for Gearmotor, Shaft Mounted, and Screw Conveyor Drives	2000	ANSI/AGMA 6113-A06	Figure 3
ANSI/AGMA 6110-F97	Standard for Spur, Helical, Herringbone, and Bevel Enclosed Drives	1997	ANSI/AGMA 6113-A06	Figure 3
ANSI AGMA ISO 17485-A08 - Supplemental Tables	Bevel Gears - ISO System of Accuracy - Tolerance Tables	2008	Withdrawn without replacement	--

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ANSI/ABMA 1-1990	Terminlogy for Anti-Friction Ball and Roller Bearings and Parts	1990	2000	ISO 5593:1997
ANSI/ABMA 10-1989	Metal Balls	1989	2001	ANSI/ABMA 10A-2001 and ISO 3290:2001
ANSI/ABMA 13-1987	Rolling Bearing Vibration and Noise (Methods of Measuring)	1987	2012	ISO 15242-1:2004, ISO 15242-2:2004, ISO 15242-3:2006, and ISO 15242-4:2007
ANSI/ABMA 16.1-1988	Airframe Ball, Roller and Needle Roller Bearings – Metric Design	1988	1999	ISO Aerospace Airframe standards
ANSI/ABMA 16.2-1990	Airframe Ball, Roller and Needle Roller Bearings – Inch Design	1990	1999	ISO Aerospace Airframe standards
ANSI/ABMA 17-1980	Needle Rollers	1980	2000	ISO 3096:1996
ANSI/ABMA ISO 199-2014	Rolling Bearings – Thrust Bearings – Geometrical Product Specification (GPS) and Tolerance Values	2014	2025	Withdrawn without replacement
ANSI/ABMA ISO 3096-2014	Rolling Bearings – Needle Rollers – Dimensions and Tolerances	2014	2025	Withdrawn without replacement
ANSI/ABMA/ISO 13411:1997	Spherical plain bearings - Part 1: Radial spherical plain bearings	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 13412:1997	Aerospace - Airframe needle roller, needle track roller and cylindrical roller bearings - Technical specification	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 13413:1997	Aerospace - Airframe track roller, yoke type, single row, sealed - Inch series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 13414:1997	Aerospace - Airframe track roller, yoke type, double row, sealed - Inch series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 13415:1997	Aerospace - Airframe needle roller, single row, shielded - Inch series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 13416:1997	Aerospace - Airframe track roller, stud type, single row, sealed - Inch series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 13417:1997	Aerospace - Airframe track roller, yoke type, single row, sealed - Metric series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14190:1998	Aerospace - Airframe track roller, stud type, single row, sealed - Metric series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14191:1998	Aerospace - Airframe Rolling Bearings: Ball and Spherical Roller Bearings Technical Specification	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)

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ANSI/ABMA/ISO 14192:1998	Aerospace - Airframe Spherical Roller Bearings, Single Row, Self-Aligning, Diameter Series 3 and 4 - Metric Series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14193:1998	Aerospace - Airframe spherical roller bearings, single row, self-aligning, shielded, intermediate duty - Metric series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14194:1998	Aerospace - Airframe spherical roller bearings, single row, self-aligning, sealed, extended inner ring, intermediate duty - Inch series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14195:1998	Aerospace - Airframe spherical roller bearings, double row, self-aligning, extended inner ring, sealed, extended inner ring, heavy duty - Inch series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14196:1998	Aerospace - Airframe spherical roller bearings, double row, self-aligning, sealed, torque tube design, light duty - Inch series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14197:1998	Aerospace - Airframe spherical roller bearings, double row, self-aligning, sealed, plain inner ring, heavy duty - Inch series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14201:1998	Aerospace - Airframe spherical roller bearings, single row, self-aligning, sealed, intermediate duty - Inch series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14202:1998	Aerospace - Airframe ball bearings, double row, self-aligning, diameter series 2 - Metric series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14203:1998	Aerospace - Airframe ball bearings, single row, rigid, diameter series 0 and 2 - Metric series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14204:1998	Aerospace - Airframe ball bearings, single row, rigid, diameter series 8 and 9 - Metric series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14206:1998	Aerospace -Airframe ball bearings, double row, rigid, diameter series 0 - Metric series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14207:1998	Aerospace - Airframe Ball Bearings, Single Row, Rigid, Sealed, Light Duty - Inch Series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14208:1998	Aerospace - Airframe ball bearings, single row, rigid, precision, sealed, light duty - Inch series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)

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ANSI/ABMA/ISO 14209:1998	Aerospace - Airframe ball bearings, single row, rigid, sealed, intermediate duty - Inch series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14210:1998	Aerospace - Airframe Ball Bearings, Single Row, Rigid, Precision, Sealed, Intermediate Duty - Inch Series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14211:1998	Aerospace - Airframe ball bearings, single row, rigid, sealed, torque tube design, light duty - Inch series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14212:1998	Aerospace - Airframe Ball Bearings, Single Row, Rigid, Precision, Sealed, Torque Tube Design, Light Duty - Inch Series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14213-1998	Aerospace - Airframe Ball Bearings, Single-Row, Rigid, Sealed, Torque Tube Design, Extra-Light Duty - Inch Series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14214:1998	Aerospace - Airframe Ball Bearings, Single Row, Rigid, Precision, Shielded, Torque Tube Design, Extra-Light Duty - Inch Series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14215:1998	Aerospace - Airframe Ball Bearings, Double Row, Rigid, Sealed, Heavy Duty - Inch Series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14216:1998	Aerospace - Airframe Ball Bearings, Double Row, Rigid, Precision, Sealed, Heavy Duty - Inch Series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14217:1998	Aerospace - Airframe Ball Bearings, Double Row, Self-Aligning, Sealed, Heavy Duty - Inch Series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14218:1998	Aerospace - Airframe Ball Bearings, Double Row, Self-Aligning, Precision, Sealed, Heavy Duty - Inch Series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14219:1998	Aerospace - Airframe Ball Bearings, Single Row, Self-Aligning, Sealed, Heavy Duty - Inch Series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14220:1998	Aerospace - Airframe ball bearings, single row, self-aligning, precision, sealed, heavy duty - Inch series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)
ANSI/ABMA/ISO 14221:1998	Aerospace - Airframe ball bearings, single row, self-aligning, sealed, light duty - Inch series	1999	2016	Withdrawn without replacement (see SAE AS 7949 as a possible replacement)

Notes:

- Red text boxes denote withdrawn documents
- Blue text boxes denote current documents

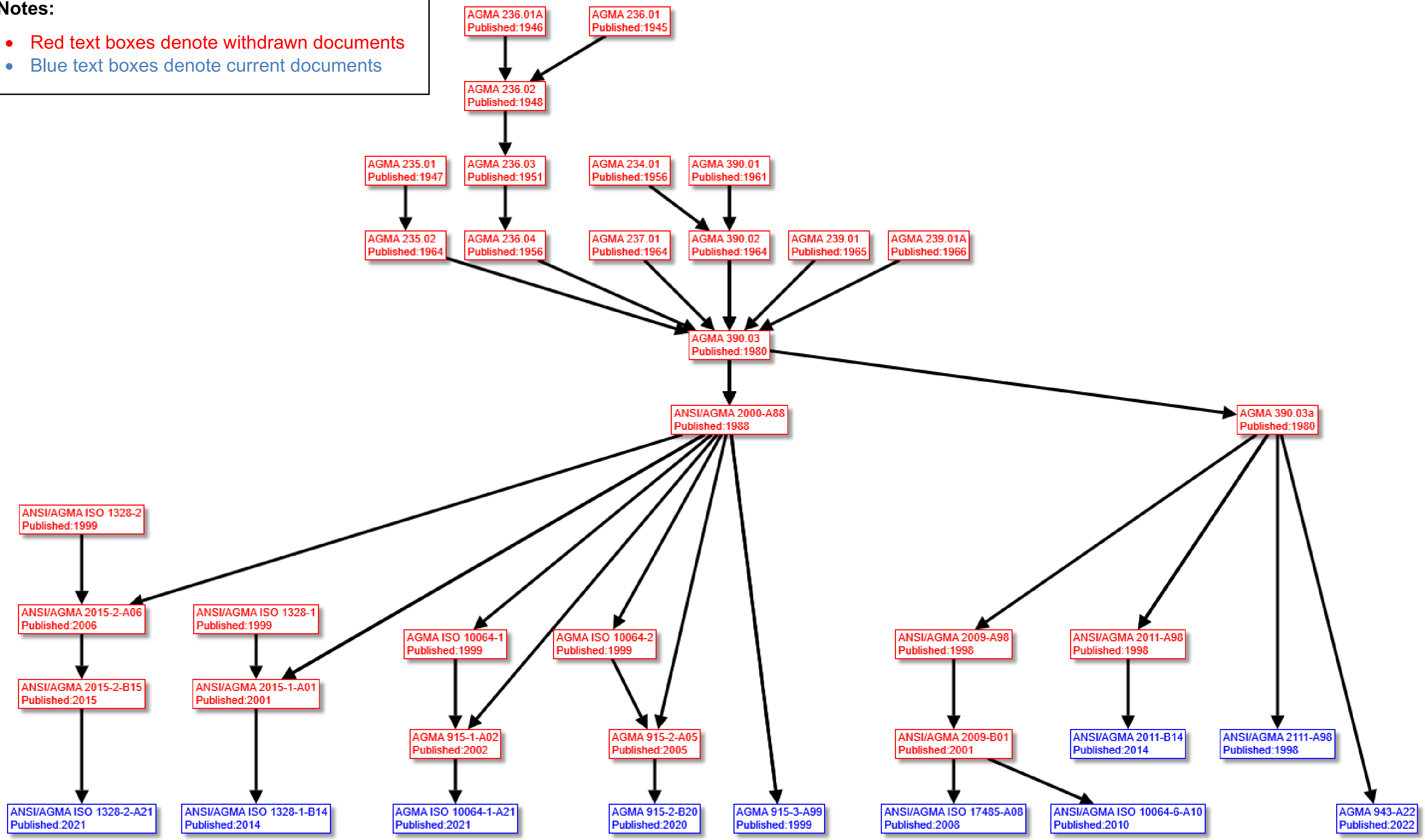

Figure 1 – AGMA Inspection Documents

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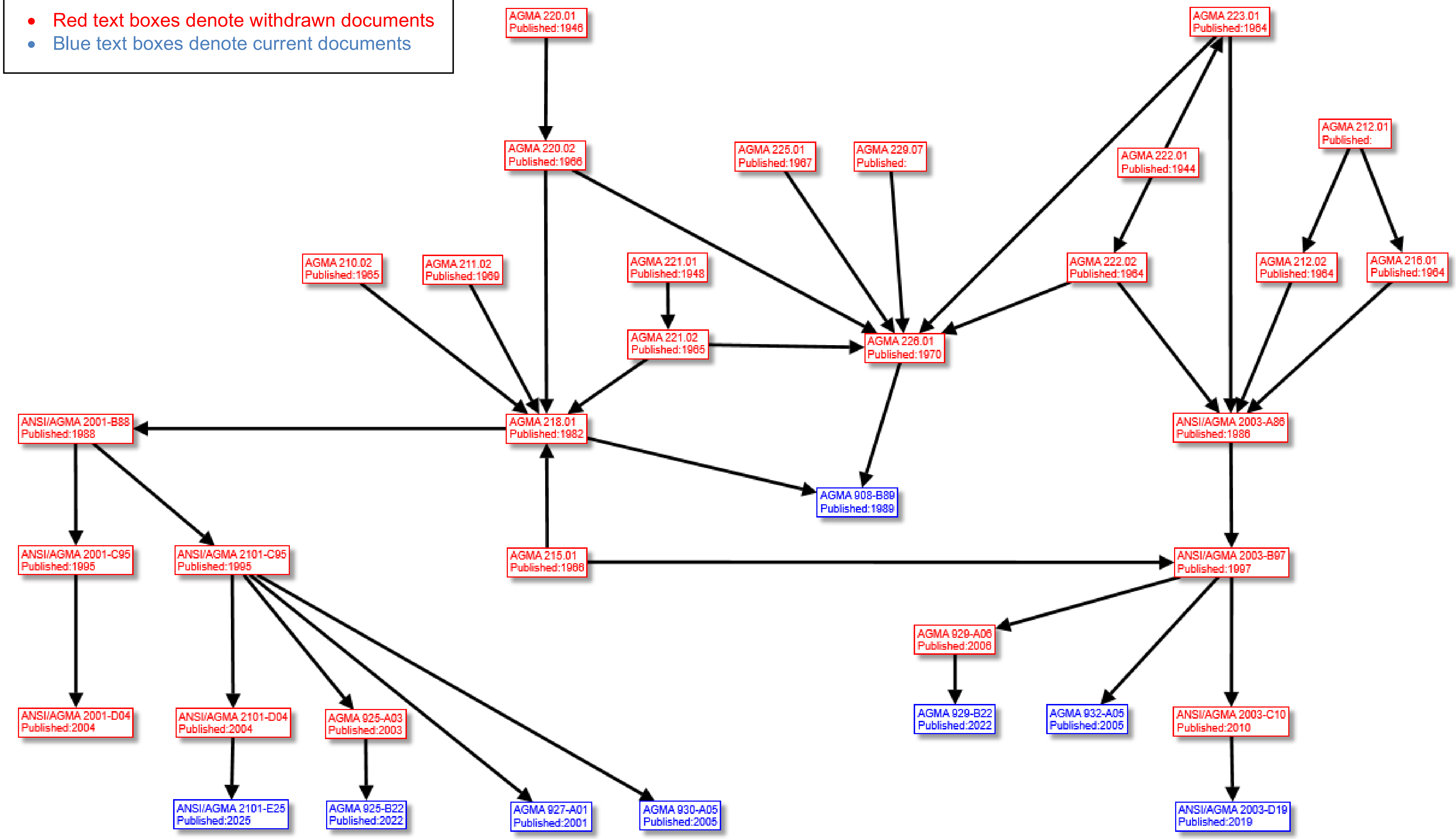

Figure 2 – AGMA Rating Documents

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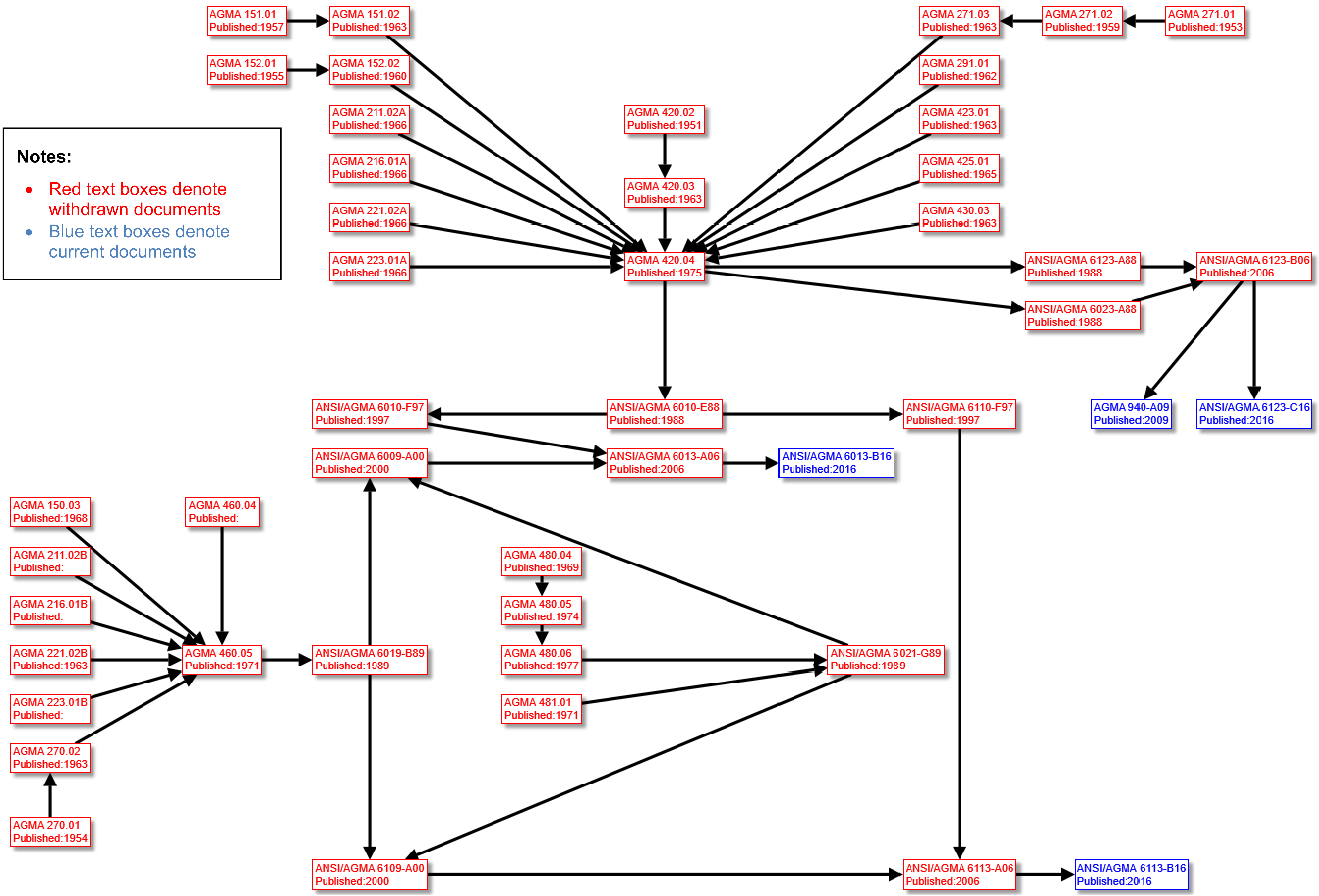

Figure 3 – AGMA Enclosed Gear Drives Design Documents

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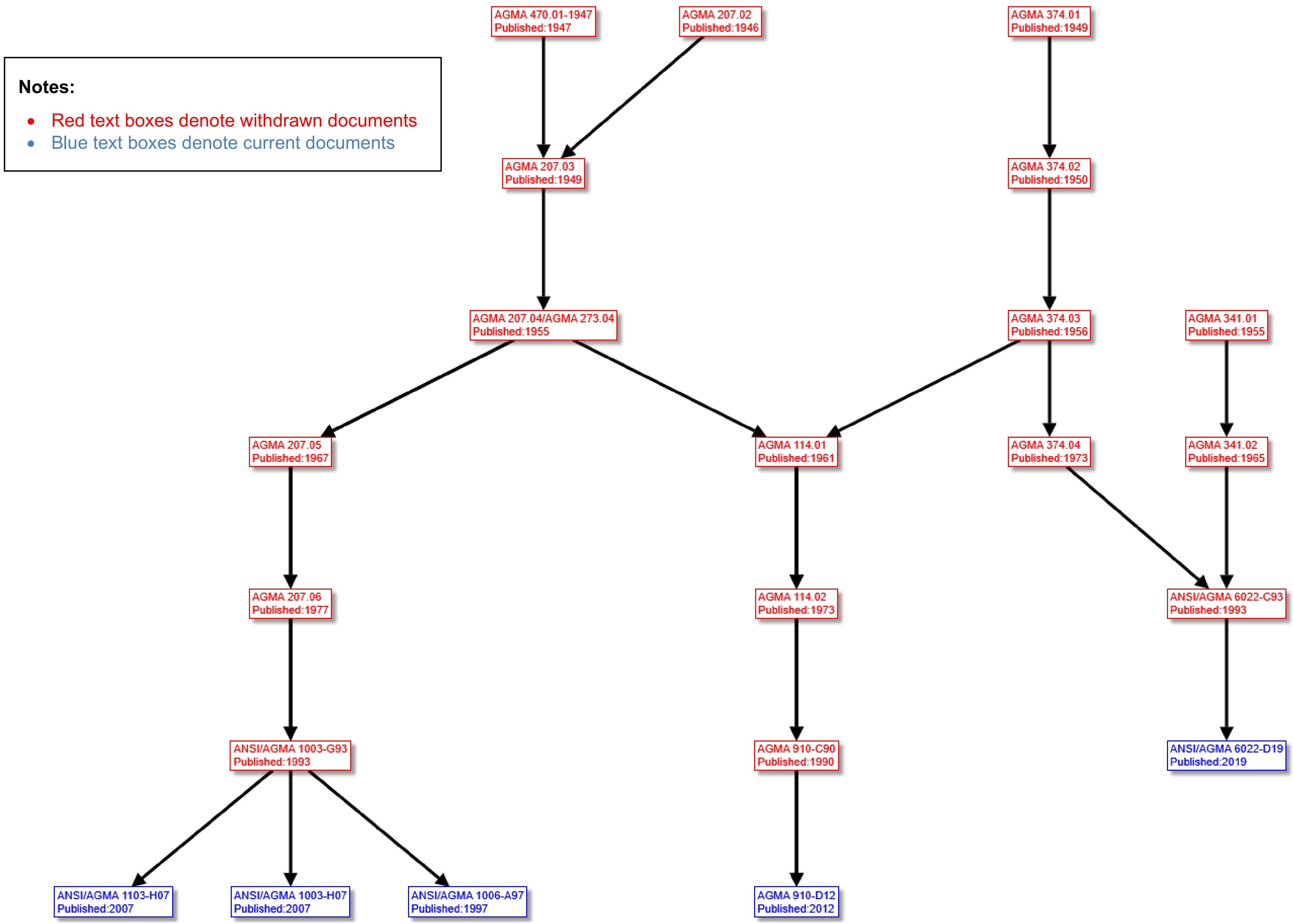

Figure 4 – AGMA Fine Pitch Documents

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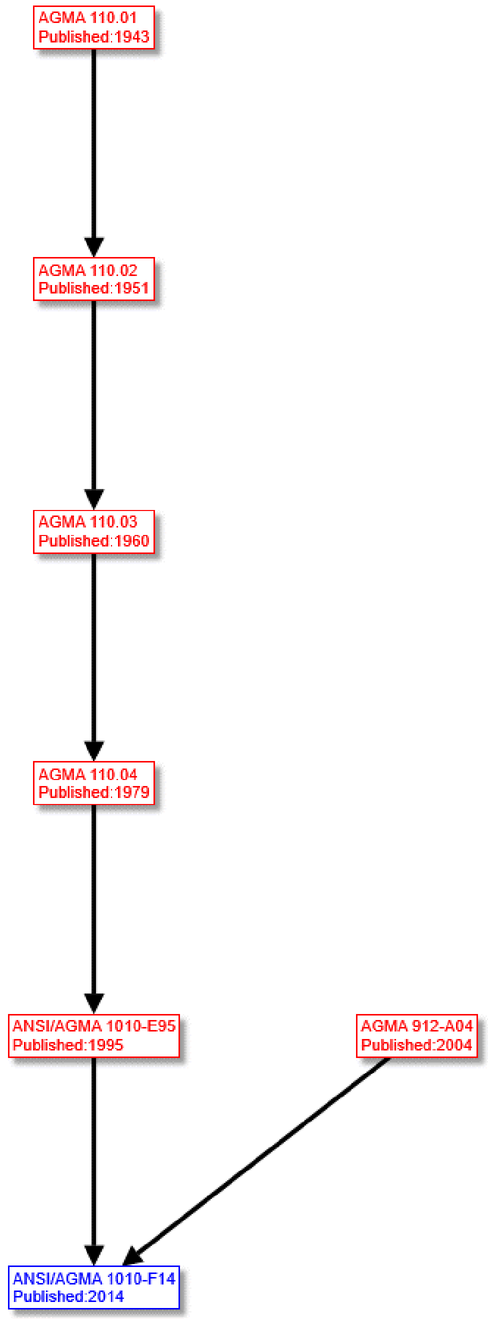

Figure 5 – AGMA Terminology of Wear and Failure Documents

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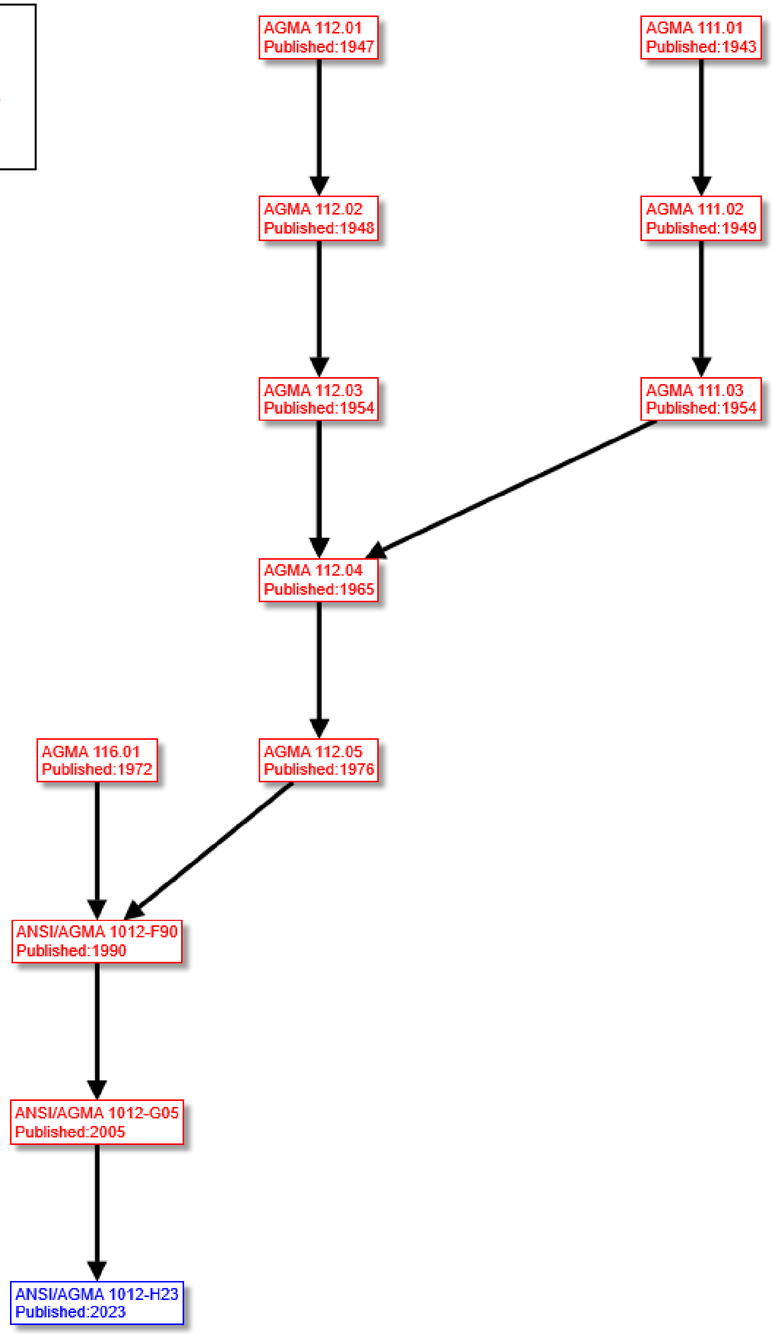

Figure 6 – AGMA Nomenclature Documents

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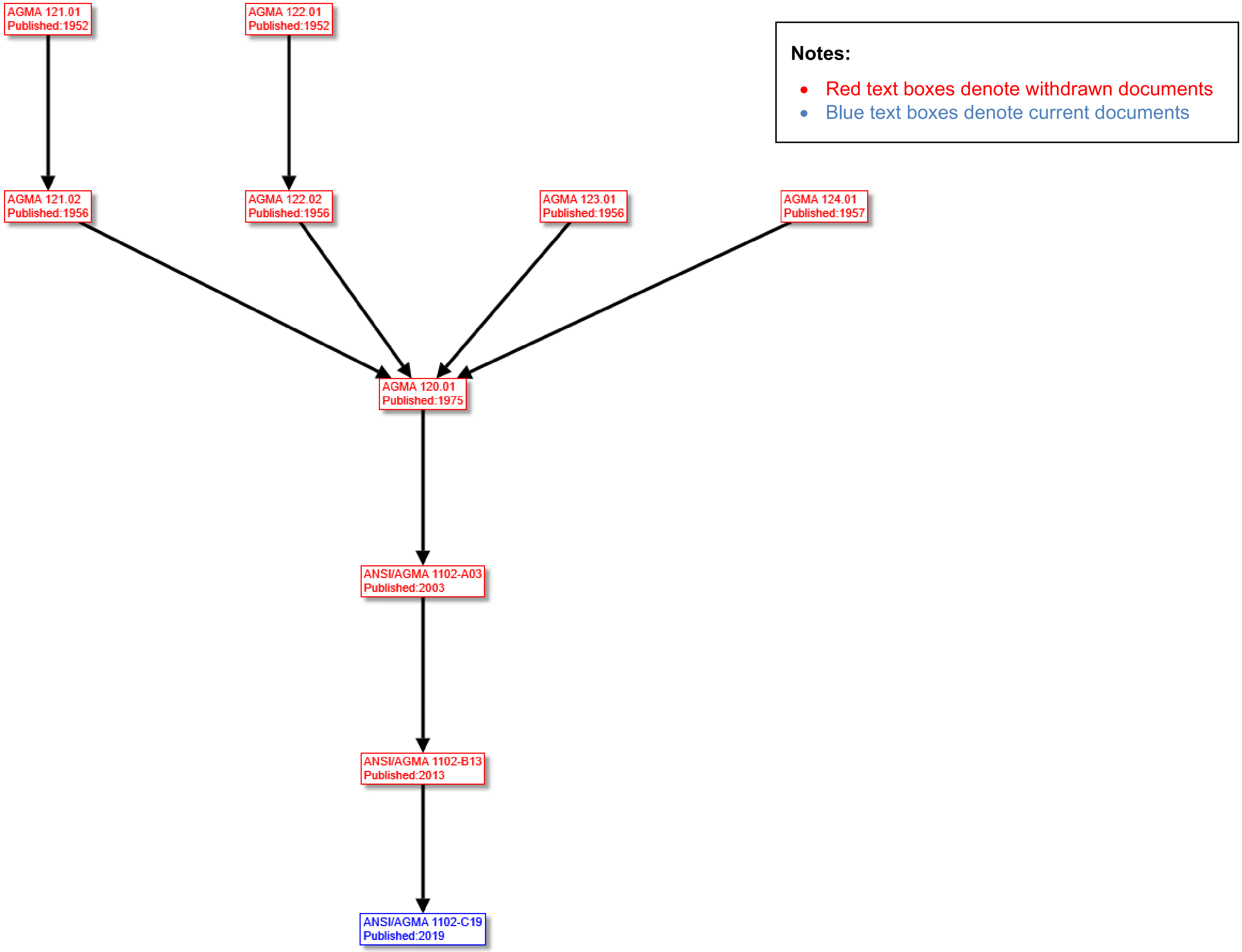

Figure 7 – AGMA Hob Documents

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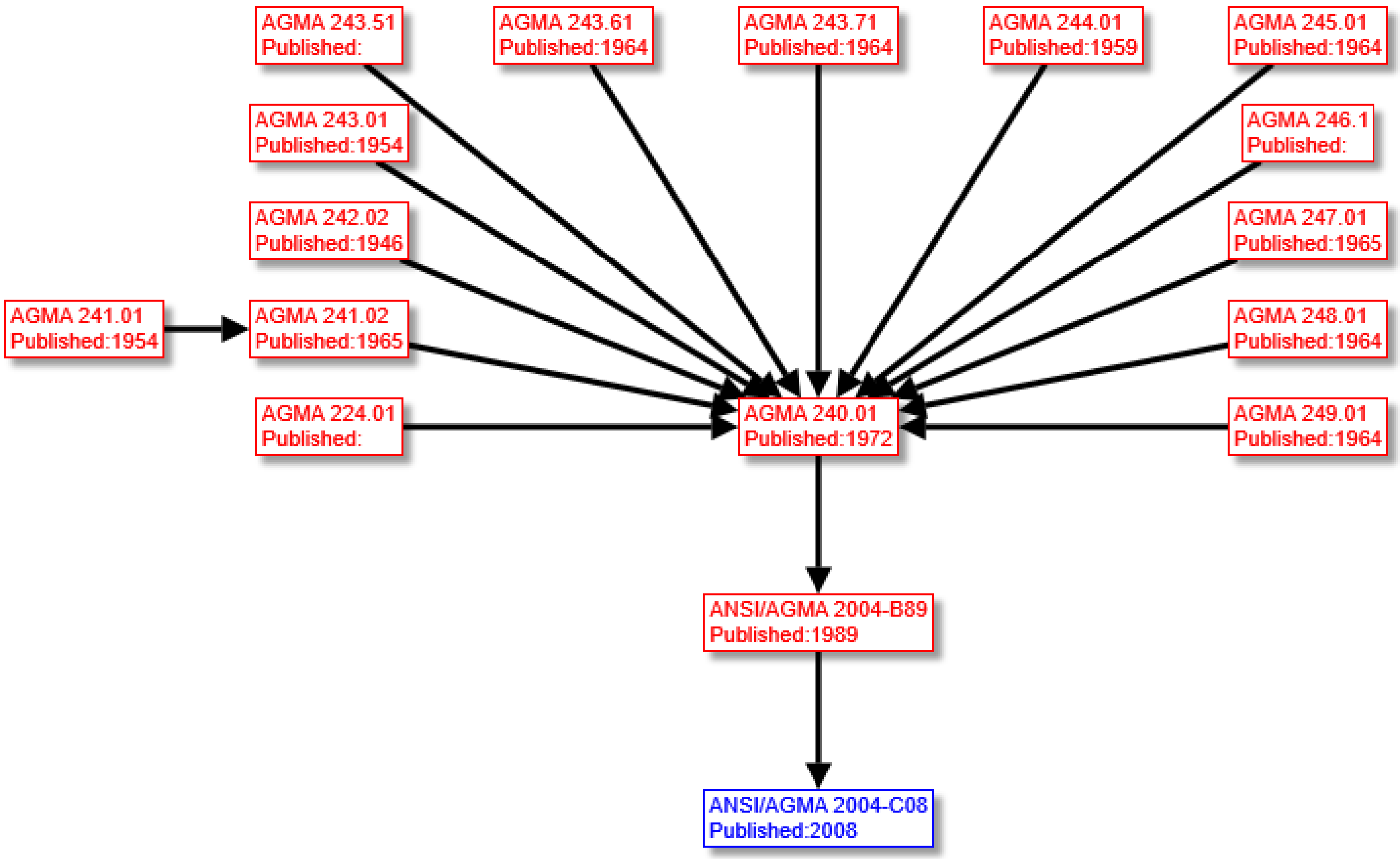

Figure 8 – AGMA Gear Materials and Heat Treatment Processing Manual Documents

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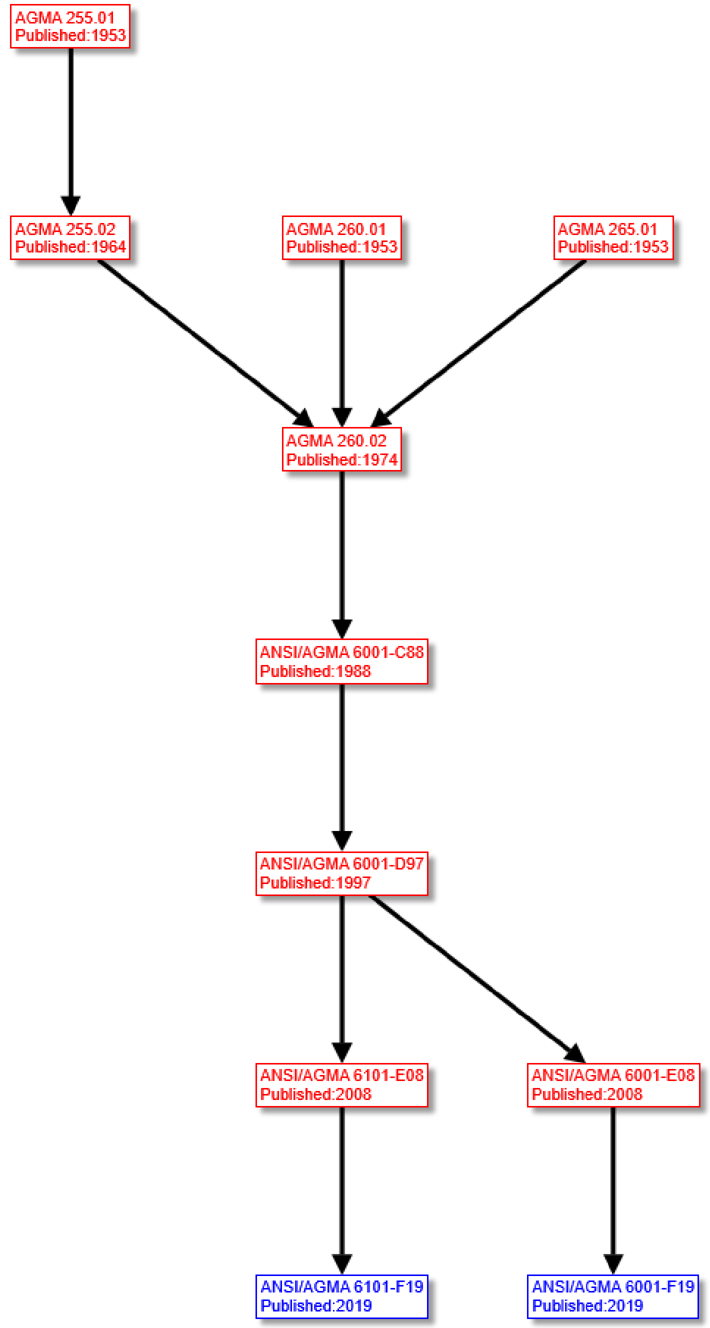

Figure 9 – AGMA Design and Selection of Components for Enclosed Gear Drives Documents

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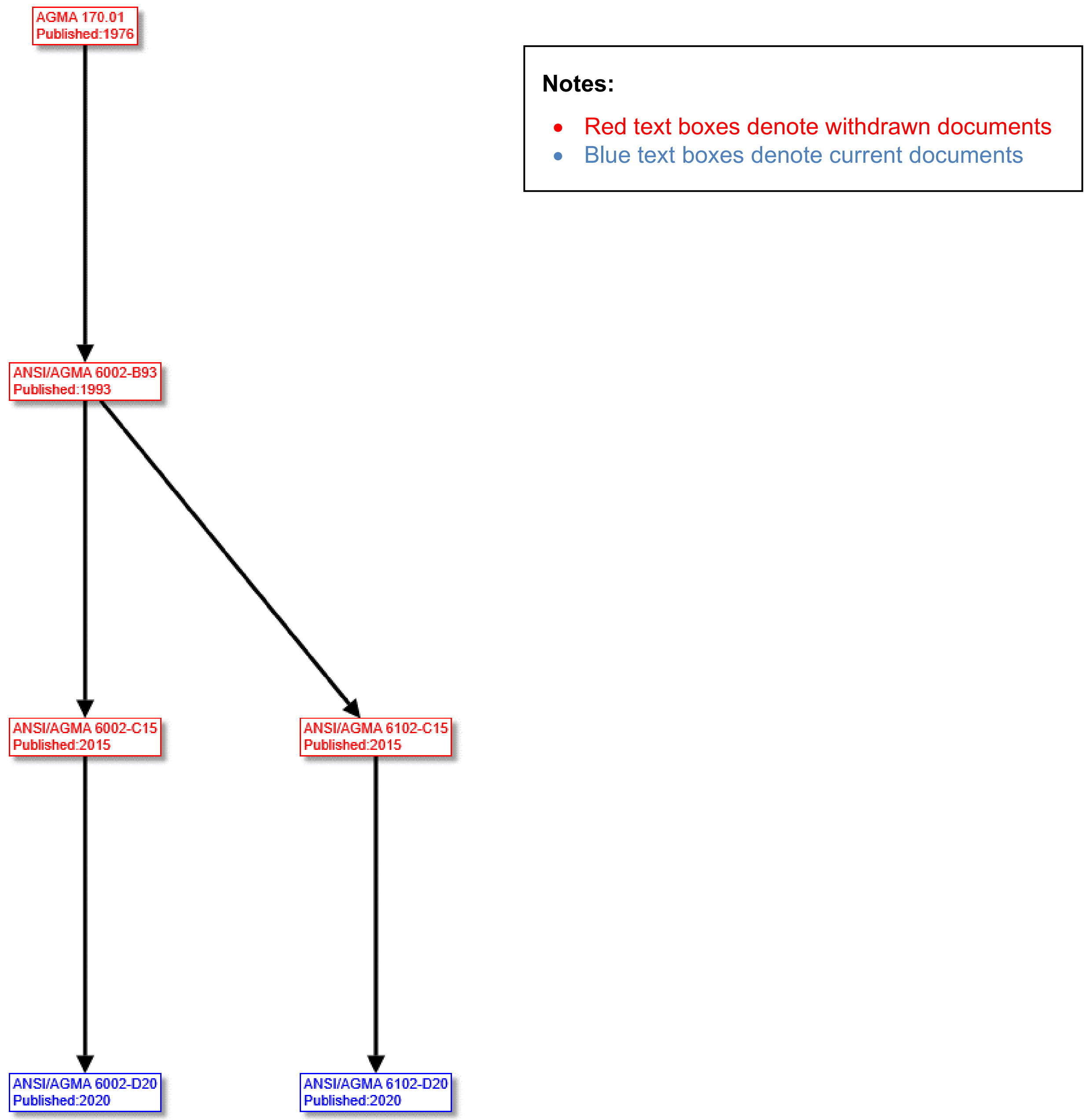

Figure 10 – AGMA Vehicle Gearing Documents

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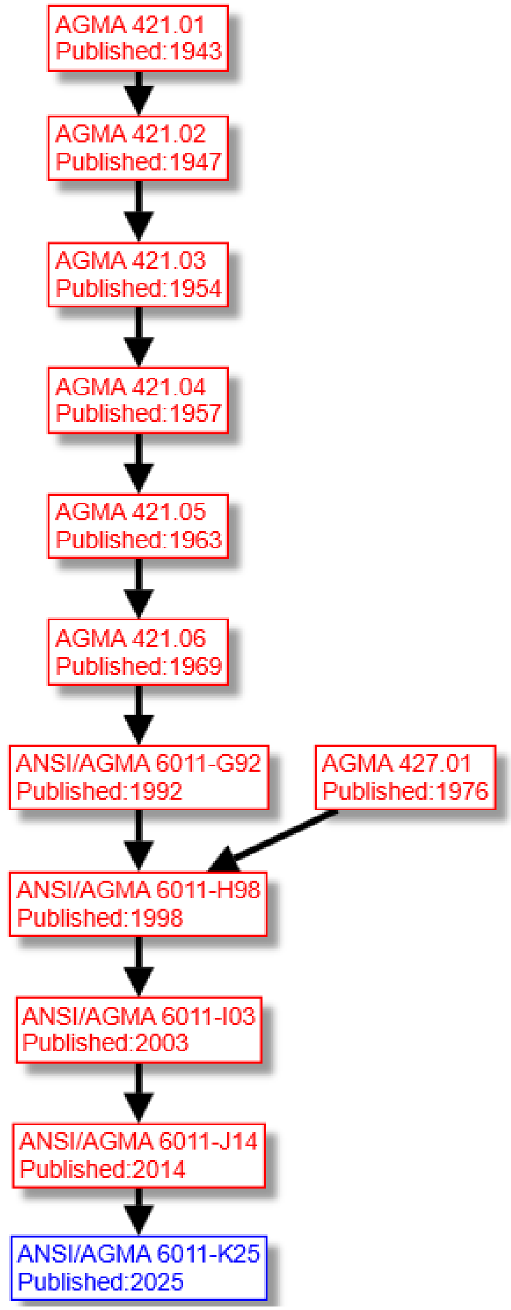

Figure 11 – AGMA Specification for High Speed Gear Units Documents

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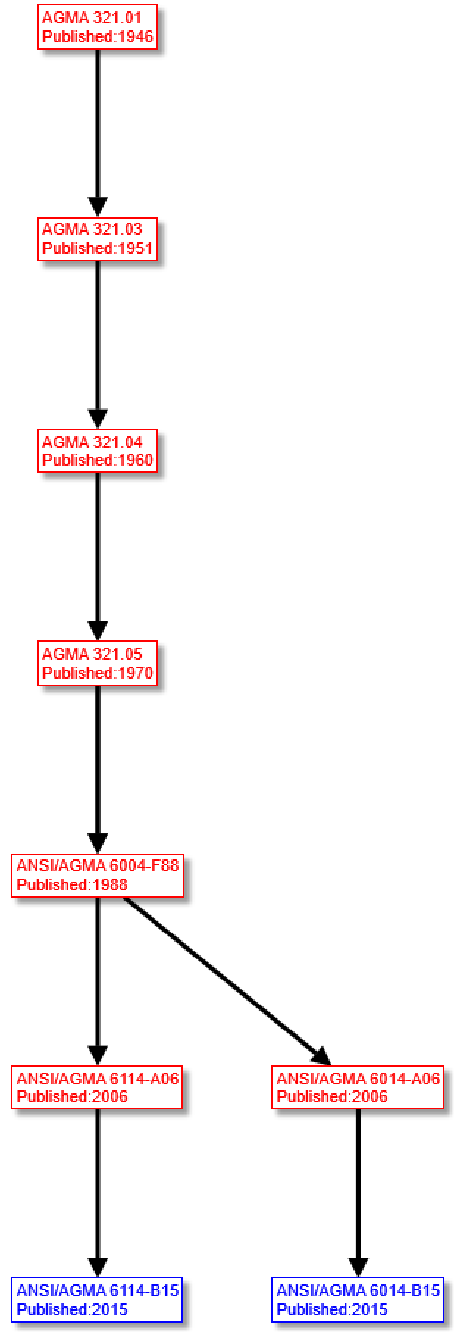

Figure 12 – AGMA Gear Power Rating for Cylindrical Shell and Trunnion Supported Equipment Documents

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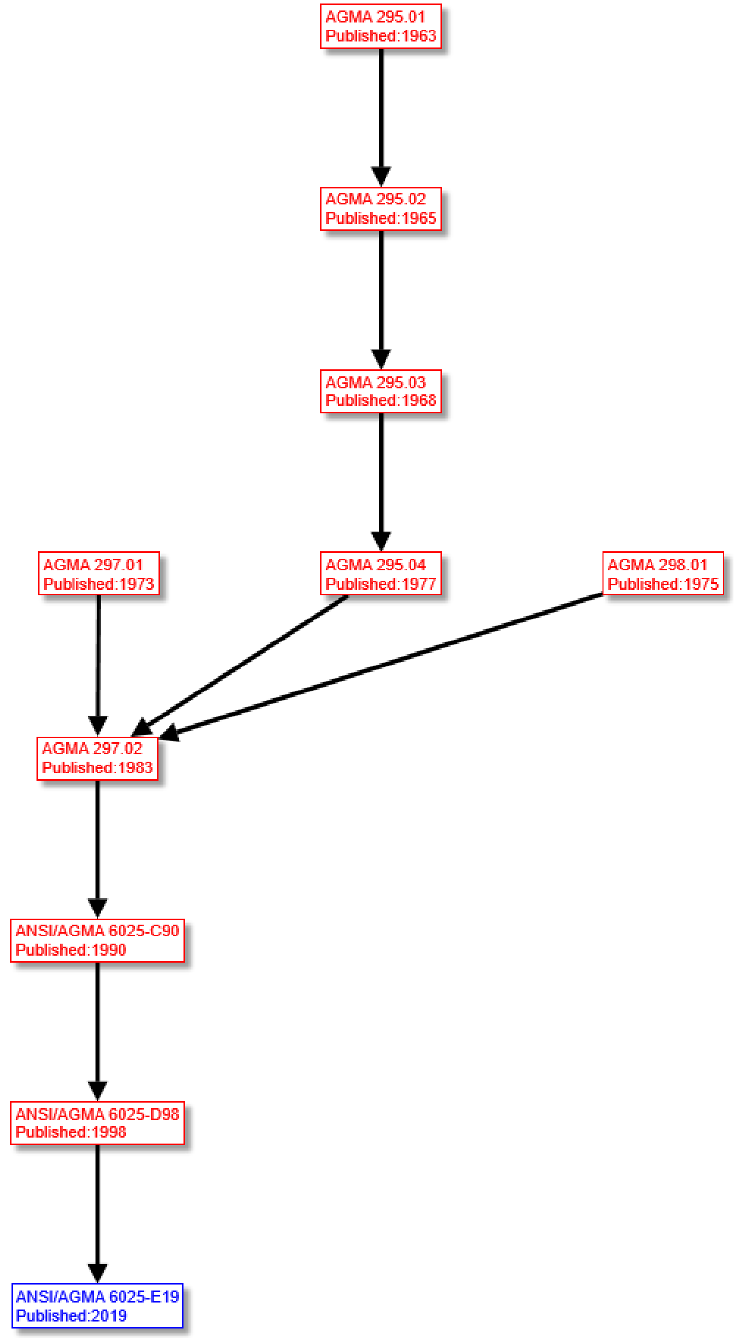

Figure 13 – AGMA Sound for Enclosed Helical Herringbone and Spiral Bevel Gear Drives Documents

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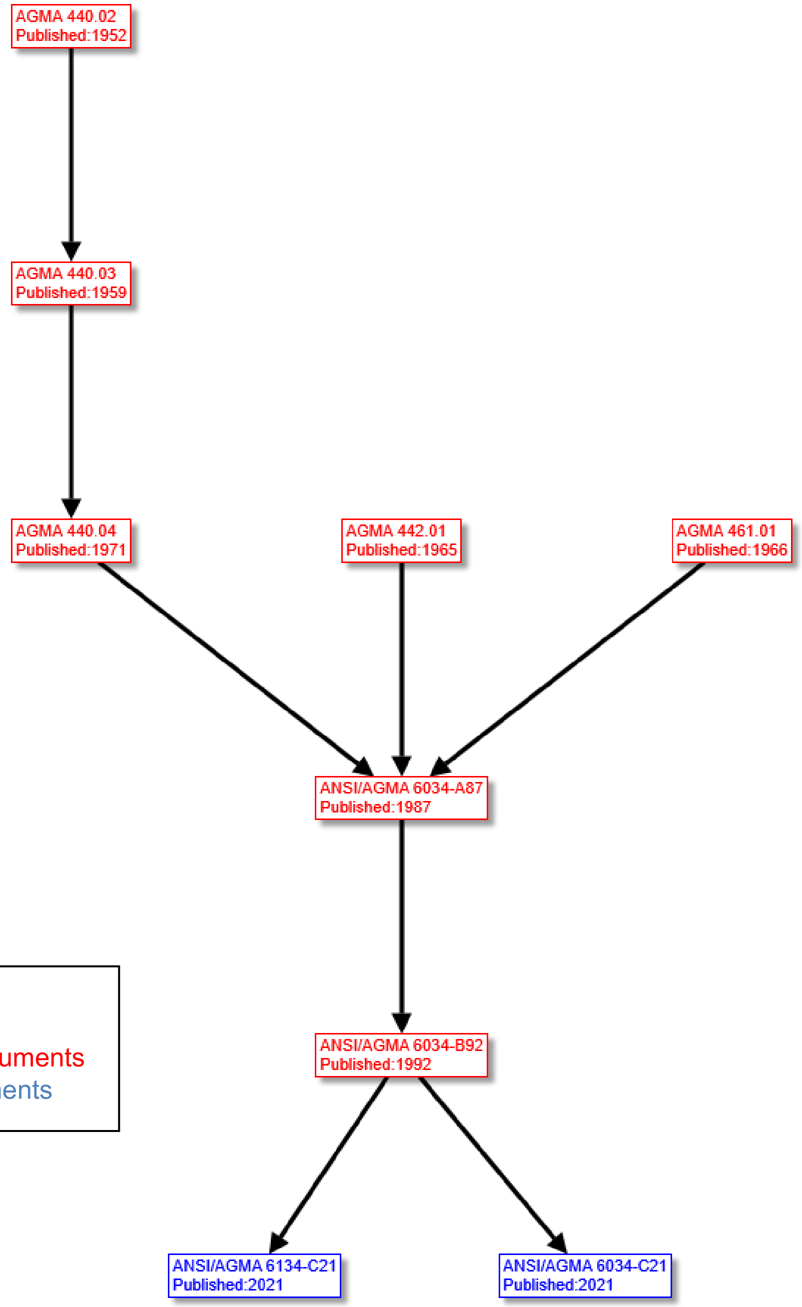

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Figure 14 – AGMA Practice for Enclosed Cylindrical Wormgear Speed Reducers and Gearmotors Documents

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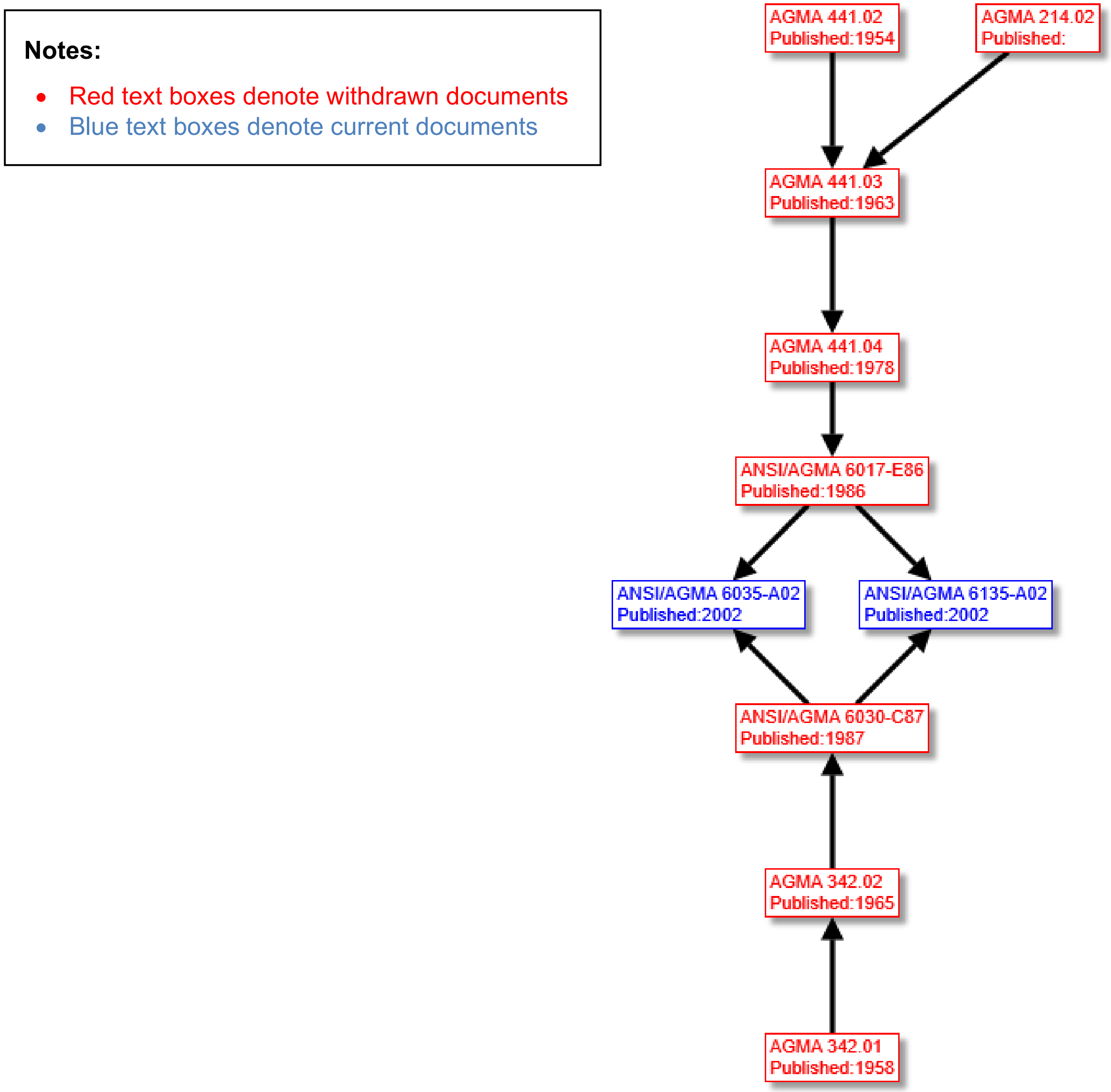

Figure 15 – AGMA Wormgearing Design Documents

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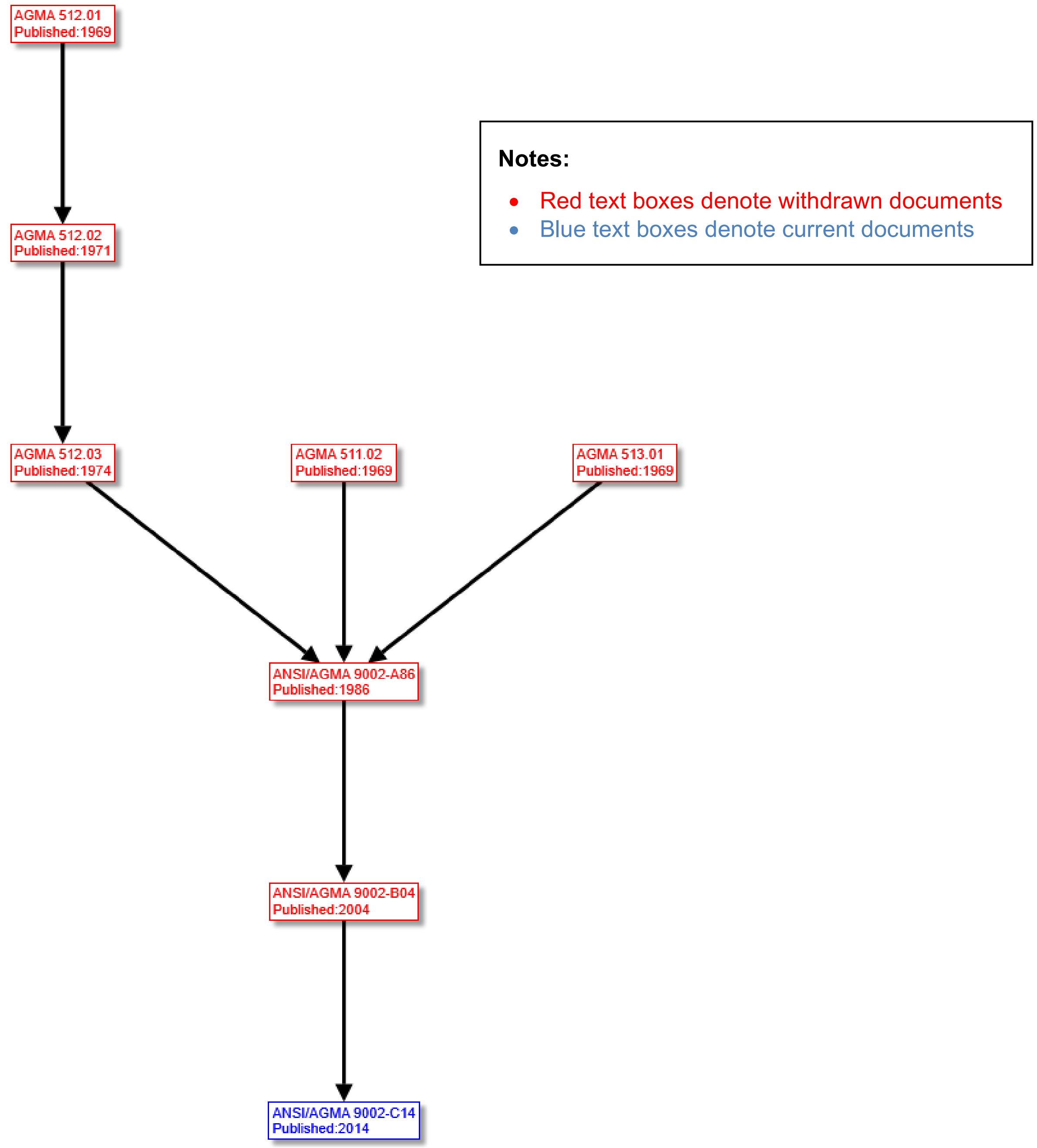

Figure 16 – AGMA Bores and Keyways for Flexible Couplings (Inch Series) Documents

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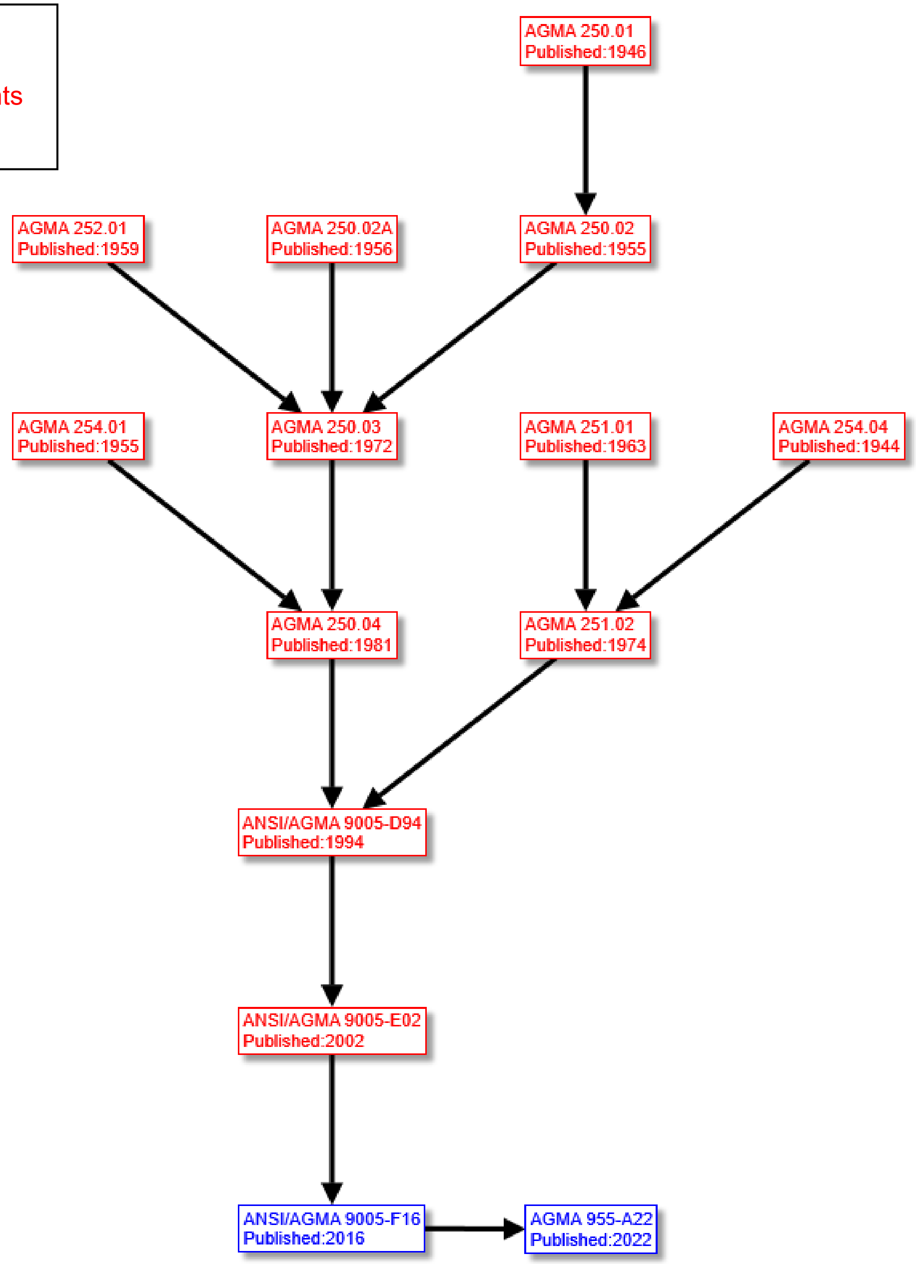

Figure 17 – AGMA Gear Lubrication Documents

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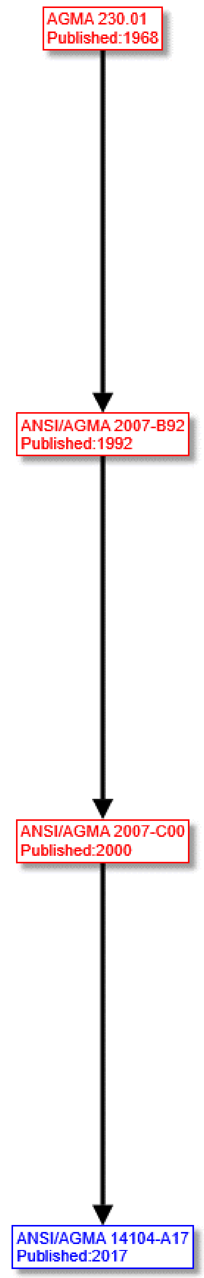

Figure 18 – AGMA Surface Temper Etch Inspection Documents

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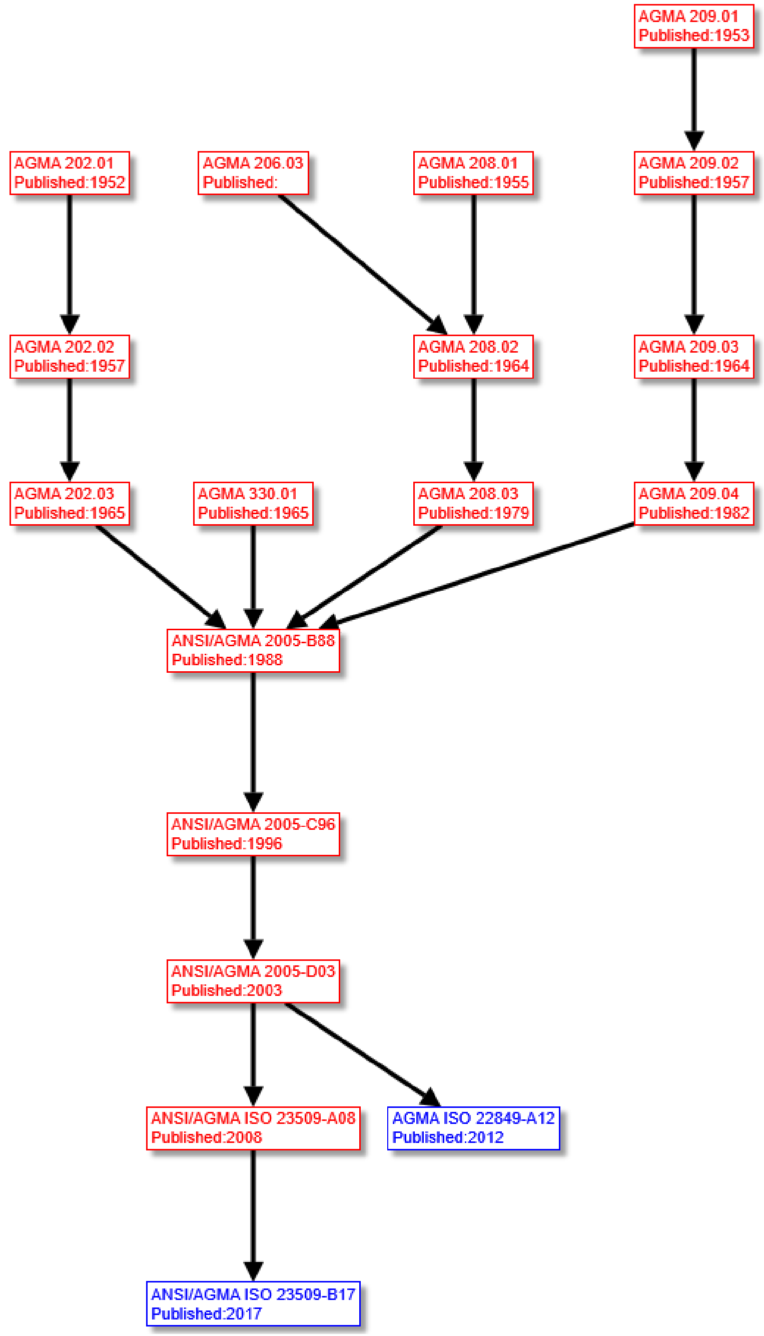

Figure 19 – AGMA Bevel Gear Design Documents

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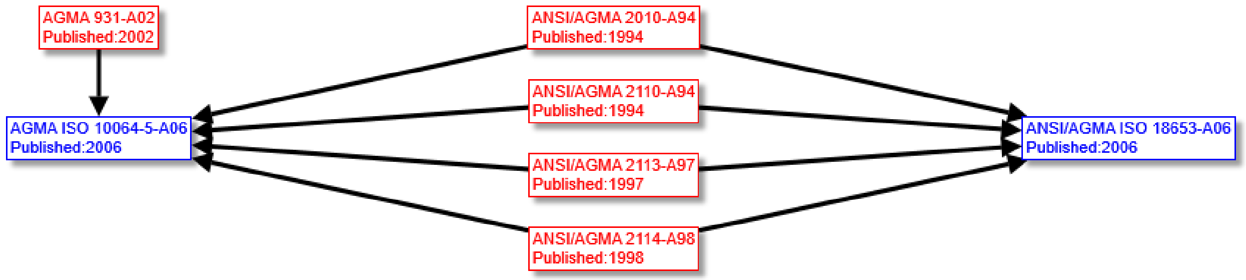

Figure 20 – AGMA Gear Measuring Instruments Documents

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FTM documents

Document	ISBN	Pages
25SP1		23

Activities and Responsibilities of ISO/TC 60/SC 2/WG 6

Prof. Dr.-Ing. K. Stahl

Activities and Responsibilities of ISO/TC 60/SC 2/WG 6

Document	ISBN	Pages
25FTM29	978-1-64353-231-8	9

Water Spray Quenching – A New Intensive Quenching Process for Case Hardening of Gears

Dr. Volker Heuer, Christof Ziegler, Dr. Klaus Loeser

Water Spray Quenching (WSpQ) has been established in industry for many years, e.g., in steel production for the quenching of strips or for semi-finished products. When applying WSpQ, water-mist is formed in nozzles and accelerated with high velocities towards the components to be quenched. WSpQ provides very high cooling rates that are much higher than quenching in liquid medium (e.g., with oil or with polymers). Additionally, by varying air-flow and water-flow, the quench intensity can be varied in a wide range.However, for the heat treatment of complex-shaped, industrially manufactured serial components, such as gear-wheels or gear-shafts, this process has not yet been successfully implemented. So far, this was not possible, since the water spray could not reach into the center of the heat treat loads consisting of multiple layers where the outer parts of the load shield the inner parts from the effect of the water spray.With a new combination of vacuum heat treatment in single layers with subsequent WSpQ, this intensive quenching process can now be applied to serial parts. An industrial-scale test rig has been developed and used to investigate the following topics:– cooling curves,– heat transfer coefficients,– core hardness – values,– case hardening depth – values (CHD)– surface quality after quenching and– the effect of a variation of quench intensity.It was demonstrated that the process offers very high cooling rates with heat transfer coefficients up to 4000 W/(m2K). Even when using low alloyed case hardening steels, high core hardness values were successfully reached.Additionally, it was demonstrated that the cooling rates can be varied in a wide range. This means that the process can be adjusted to the hardenability of the material and the gear-geometry.

Document		ISBN	Pages
25FTM28		978-1-64353-230-1	16

Surface Hardening of Gears: Current State of the Art and Prospects

Noah J. Kantor, Christopher P. Clark, Richard Chen, Ellen K. Troyanosky, Qianchen Zeng, Jianyu Liang, Thomas L. Christiansen, Carola Sekreter, Thomas Wingens

The present paper is an overview of selected relevant surface hardening techniques for gears. In the first part of the paper, the basic mechanisms and concepts are provided for the conventional thermochemical surface engineering methods, gas- and vacuum carburizing, carbonitriding and ferritic nitriding. Additionally, high temperature solution nitriding is showcased as an interesting new alternative for surface hardening of martensitic and ferritic stainless steels in applications where corrosion performance is also relevant. The second part addresses fast quenching as a promising alternative to the traditional thermochemical surface hardening methods. Fast quenching results in enhanced surface hardness, presumably due to a change in the mechanism of martensite formation and leads to high compressive surface stresses that enhance fatigue performance. The technique also offers a more uniform hardened case and reduced and controlled distortion. Moreover, the concept of fast quenching is associated with a significantly lower carbon footprint than conventional hardening methods applied in the gear industry, thus making this a fast and easy-to-implement technology for reducing costs and CO2 emissions. The current contribution is not an in-depth treatise of all surface hardening methods for gears but reflects ongoing research and development activities in the Center for Heat Treating Excellence.

25FTM27		978-1-64353-229-5	19

Twenty Years of Pulsator Tests on Helicopter Gears

Luca Bonaiti, Carlo Gorla, Ugo Mariani, Rosanna Molinaro, Sara Rustici, Sergio Sartori

Due to the high performances in terms of power and torque density, and to the safety requirements of the Main Gearboxes of Helicopters, their gears must be designed on the basis of validated methodologies and reliable data. Even if, generally speaking, bending fatigue is not the most limiting failure mode for helicopter gears, the exact knowledge of the safety margins is fundamental due to the catastrophic consequences of its occurrence. In particular, the fatigue strength data of the material must be fully representative of the specific experience and practices of the manufacturer and must include the effects of several parameters related to geometry, manufacturing, heat and mechanical treatments, and finishing processes.For these reasons, Leonardo Helicopter has been performing a systematic campaign of tests on the bending fatigue strength of gears for almost twenty years. The tests are performed with the Single Tooth Bending Fatigue (STBF) approach, and the results for the first lot of families tested were presented at the 2008 AGMA FTM: they were focused on some variants of case-hardened gears. Since that time, six more lots of gears have been considered, including nitriding and precipitation hardening materials, and additional influences have been investigated, like different manufacturing, heat treatment, shot peening parameters, and superfinishing, both with traditional and REACH compliant processes. Leonardo now owns a comprehensive database of bending fatigue data.Some partial results of the campaign have been presented at gear or helicopter conferences, but many of them are still unveiled and a complete summary of the whole test campaign has never been published: the aim of the present contribution is to summarize the results of the entire campaign and to compare and discuss them, including the approaches used to define the S-N diagrams used for the design of transmission components.

Document	ISBN	Pages
25FTM26	978-1-64353-228-8	12

Optimizing the Surface Integrity of Gears: Combined Effects of Peening and Superfinishing Processes

Gilberto Martins de Oliveira Gomes, Naiane Souza, Ronnie Rego, Andre Santana

Increasing the load capacity of agricultural transmissions presents the challenge of enhancing fatigue resistance while maintaining or reducing the size of rotating components. In this context, processes that define the surface integrity properties have been considered as a possibility for optimizing gear flanks. This study addressed the combined effect of gear flank optimization on the residual stress state and topography. Case hardened gears were submitted to a shot peening process to induce compressive residual stress, followed by an isotropic superfinishing process to homogenize the peaks and valleys of the gear's contact surface. Among the groups evaluated, the shot peening (SP), isotropic superfinishing (IS) processes, and the combined effect of both (SP+IS) were examined. Roughness, profile deviation, residual stress, hardness, and microstructure tests were conducted to assess the surface. These evaluations were used to classify the heterogeneity of the surface integrity achieved by the different manufacturing processes. It was found that the SP+IS samples exhibited more compressive residual stresses and lower roughness, along with a reduction in intergranular surface oxidation. The surface also showed a slight variation in its manufacturing quality class, changing from a status of DIN class 7-8 to a class range of 8-9. By evaluating the residual stress states of different manufacturing routes, it was observed that the IS process preserved the heterogeneity of residual stresses previously established by the SP process.

Document	ISBN	Pages
25FTM25	978-1-64353-227-1	15

Strategy for Accounting Residual Stresses Heterogeneity on the Stress Modelling Oriented to Tooth Root Bending Fatigue

Caio Felipe Siqueira Gomes, João Pedro Vieira, Guilherme Fernandes Guimarães, Ronnie Rodrigo Rego, André Luiz Rocha D'Oliveira

Energy transition has driven the search for torque efficient drivetrains, resulting in the downsizing of components. In this context, residual stress is a key factor for achieving higher power densities, due to its influence on fatigue resistance. Due to its complex nature, however, including heterogeneity along the component surface, this knowledge is not properly incorporated into gear rating standards, hindering it to be widely accepted as a design tool for downsizing. Therefore, the objective of this study is to develop a strategy to account for the residual stress heterogeneity influence on the fatigue life estimation at the gear tooth root. The assessment started with a review of the Dang Van and Fatemi-Socie fatigue models regarding their consideration of the residual stress influence. Further on, the Finite Element Method was used to simulate the shot peening process at the gear's tooth root, oriented to identify the residual stress heterogeneity induced at the surface. The selected fatigue models were then used to combine the simulated residual stress profiles with the bending stresses at the tooth, allowing to estimate the influence in fatigue life. Distinct combinations of residual stress states and actuating stresses were achieved, as a consequence of the variation of the residual stresses in the tooth root, revealing a variation in the failure tendency along the tooth.

Document		ISBN	Pages
25FTM24		978-1-64353-226-4	18

A Comparative Study of the Effect of Damping in the Dynamic Analysis of Drivetrains for NVH Performance Evaluation

Saeed Ebrahimi

This study compares the effect of internal damping of the elements of a drivetrain under various loading conditions and evaluates the damping effect on the NVH characteristics. To achieve this goal, a typical model of a two-stage gearbox is considered. The forced response analysis of the model is carried out in KISSsoft to calculate the dynamic behavior of the gearbox model subjected to dynamic loads from different excitation sources. Such analysis provides a detailed understanding of how the system responds across the spectrum, highlighting areas prone to excessive vibration or noise. As the main step in this study, the effect of damping in bearings, shafts, and gear meshes is separately investigated to provide more insight into to their individual effect on the reduction of the meshing contact forces and the bearing reaction forces. The investigation is carried out for a wide range of running speeds, input torques, and damping values. Then, the analysis is followed by considering the case when the effect of damping in all elements is combined. For intuitive characterization of the emitted noise of the gearbox model, the exciting bearing reaction forces of the forced response are then imported to RecurDyn and applied to the housing. As the result of NVH analysis, the contour plot of the equivalent radiated power (ERP) is shown to demonstrate the noise level. Within this step, the effect of damping in each analysis case on the noise emitted from the housing surface can be further investigated. This can be particularly useful for designers and engineers to observe how different sources of damping can result in the improvement of the NVH characteristics of a drivetrain.

25FTM23		978-1-64353-225-7	16

Holistic and Statistical Approach to the Impact of Manufacturing Deviations on the Transmission Error, Structural Vibrations and the Acoustic Behavior of

Dennis Tazir, Denis Werner

In electric-drive systems, especially in the e-mobility sector, the absence of masking noise from internal combustion engines has heightened the importance of NVH optimization. A critical contributor to NVH in transmissions is the transmission error (TE), which is influenced by manufacturing deviations in gears. Understanding and mitigating these effects early in the development phase is essential for enhancing NVH performance in the context of increasingly shorter development cycles.A comprehensive design process should not be based exclusively on limit value considerations but should also include statistical statements. Limit value considerations can give the impression that extremely rare conditions occur, which often leads to over-dimensioning and to tough tolerances. This results in time-consuming, unnecessarily expensive development processes aimed at eliminating these unlikely extreme cases. A statistically balanced approach enables more efficient and targeted development.This paper presents a comprehensive workflow for investigating the impact of manufacturing deviations on TE, structural vibration, and acoustic behavior. A gear design tool capable of fast and efficient computations is employed to analyze the effect of tolerances on TE. The tolerances of the crownings and slopes in profile and lead direction are modeled as a normal distribution. The study focuses on the first gear stage of an exemplary gearbox in its mounted position, accounting for the influences of other gearbox components. This approach yields a wide range of TE curves as functions of applied torque, from which specific characteristic curves are identified.To evaluate the dynamic behavior of the system, these characteristic points are further analyzed using a multibody dynamics model of the transmission. Due to the increased numerical complexity of multibody dynamics, only key scenarios are considered. The structural response is then calculated for runups and critical rotational speeds, enabling the comparison of the variants. The span of structural vibration is determined, and the most probable variant is assessed using the normal distribution of manufacturing tolerances.Finally, the structural response data is used to identify relevant frequencies, which are analyzed with an acoustic simulation tool to assess their impact on airborne noise. This step highlights the influence of gear manufacturing deviations on the acoustic behavior of transmissions.

Document	ISBN	Pages
25FTM22	978-1-64353-224-0	19

Efficiency of Bevel and Hypoid Gears –Calculation Approach and Comparison with Experimental Test Results

Josef Pellkofer, Lorenz Constien, Michael Geitner, Karsten Stahl

Due to the increasing challenges of climate change and its consequences at the present time, gear engineers are encouraged to design sustainable gears that are both efficient and have a high load-carrying capacity. Currently, for bevel and hypoid gears, only basic calculation methods are available, given in ISO/TS 10300-20:2021 [1] and ISO/TR 14179-1:2001 [2], for load-depending calculating the gear power loss PVZP. Both calculation approaches are of standard level C, which allows a rough estimation of the gear power loss PVZP but also requires little information. This paper presents a newly developed method based on the standard calculation approach of the virtual cylindrical gear given in method B1 of ISO 10300-1:2023 [3] for calculating the gear power loss PVZP. The calculation method is validated by experimentally determined gear power losses for bevel and hypoid gears using the FZG bevel gear efficiency test rig. The validation given in this paper shows that the accuracy and reliability of the calculated results of the gear power losses PVZP using the newly developed calculation method allow the method to be classified in standard level B and, therefore, extend the current state of-the-art. It is recommended in further work to introduce the provided calculation method within the calculation approach of the load-carrying capacity regarding scuffing, given in ISO/TS 10300-20:2021 [1], as a calculation approach of standard level B. Consequently, gear engineers can use a standardized calculation method for the gear power loss PVZP representing a reliable tool for designing efficiency-optimized gears in an early stage of the design process, which only requires basic knowledge of the macro geometry.

Document	ISBN	Pages
25FTM21	978-1-64353-223-3	12

Application of PM Solutions for Optimization of Transmission Gear Noise in Battery Electric Vehicles

Preetham Jonnalagadda, Dr. Philipp Kauffmann, Dr. Patricia de Oliveira Löhrer

With the automotive industry's pivot towards Battery Electric Vehicles (BEVs), the absence of the internal combustion engine (ICE) noise exposes the operational vibrations of transmission gears. These vibrations are perceived as more intrusive than the low-frequency vibrations emitted by ICEs, due to the predominantly high-frequencies generated from the rapid rotation of electric motors. To avoid or reduce the undesired noises created by the transmissions, an optimization of the gear meshing characteristics and micro geometry are usually employed. For powder metallurgy (PM) gears, optimization opportunities for NVH (Noise, Vibration and Harshness) are particularly numerous, due to the unique properties of the powder materials in addition to the design flexibility inherent in the manufacturing process. Among the various potential optimization opportunities for PM gears, identifying an optimal design solution that not only addresses the noise issue but also meets other requirements of the gear can be challenging.This paper discusses an innovative solution proposed by the company [company name], aimed at overcoming this challenge. This solution focuses on noise damping on the transfer path by PM materials and demonstrates the impact of different gear body designs to tune the natural frequency of gears for resonance interruption, ultimately decoupling the excitation and resonance frequencies to reduce noise perception. In the end, different case studies are investigated, demonstrating a significant reduction in operational noise. Moreover, the developed solution leverages state-of-the-art AI technique to optimize the gear body design and predict gear performance, significantly shortening the development cycle and enabling a faster response to market demands for quieter BEV transmissions.

Document		ISBN	Pages
25FTM20		978-1-64353-222-6	16

Investigating the Effects of Wear, Lubrication and Material Pairing on the NVH Performance of Plastic Gears

Damijan Zorko, Rok Kalister, Borut Černe

Rising expectations regarding user experience increasingly necessitate the minimization of noise, vibration, and harshness (NVH) in gearbox systems. Polymer gears exhibit considerable potential for addressing these NVH challenges in modern transmission applications. Replacing traditional steel gear pairs with steel–polymer or polymer-polymer gear combinations offers a straightforward and effective strategy for achieving substantial NVH reduction. Despite these advantages, several critical aspects of polymer gear NVH behavior remain insufficiently explored. Notably, the NVH performance of plastic gears is highly dependent on material pairing, underscoring the importance of selecting an appropriate combination tailored to specific application requirements. While it is generally acknowledged within the engineering community that gear wear contributes to increased NVH, no comprehensive studies have been published to date that systematically investigate the influence of progressive wear on the NVH performance of polymer gears. Similarly, although the beneficial effects of grease lubrication—such as reduced noise and vibration—are widely recognized, these effects have yet to be thoroughly quantified through systematic experimental evaluation. The present study addresses these gaps by analyzing six distinct material combinations of drive and driven gears, including a steel–steel reference configuration, as well as steel–polymer and polymer–polymer pairings. The first phase of the study evaluates the inherent NVH characteristics of each material combination, while the second phase investigates the impact of progressive wear and the application of grease lubrication on NVH behavior. To the authors' knowledge, this is the first study to systematically assess the combined effects of material selection, wear progression, and lubrication on the NVH performance of polymer gears. The findings contribute valuable insights to existing gear design methodologies and support the development of more NVH-optimized polymer gear systems.

25FTM19		978-1-64353-221-9	21

A Novel Prediction of the Transmission Accuracy by Means of the Integrated Position Error Phenomenon for a Gear Pair

Bahadır Karba

Gear integrated position error (IPE) that was revealed the first time in "George W. Michalec Precision Gearing: Theory and Practice Book" to investigate gear accuracy. This phenomenon consists of functional interrelation between integrated backlash (IB) and integrated transmission error (ITE). Then, this approach is transformed into transmission accuracy by the gear engineers considering classified IB and ITE separately. Transmission accuracy in gear systems refers to how precisely the gears mesh and transmit motion or force from one gear to another. This lack of precision is revealed by constant and variable sources inevitable direct and indirect effects on the gear mesh performance. This novel study is based on manufacturing imperfections and assembly variables that inherently occur in gear meshes and analyses their effect on the IPE, which is expressed as a composite function of first time used peak-to-peak integrated backlash and generally used peak-to-peak integrated transmission error, the main source of precision and accuracy. The novel prediction method based on IPE phenomena for gear pairs has the potential to enhance the accuracy and performance of gear systems. The IPE analysis helps identify specific manufacturing tolerances and installation variations that have the most significant impact on transmission accuracy. By considering the collective effects of various position errors and developing predictive models, it could lead to more efficient, durable, reliable, and high precision gear systems across industries such as space, robotics, medical, medical, medical, automotive, aerospace, defense industry, military, and radar systems. In addition to that, peak-to-peak IPE can be implemented to gear engineering literature to use as a composite measurement phenomenon to understand performance in terms of tribology, endurance, noise-vibration-harshness, mesh quality and transmission accuracy on gear pairs.

Document		ISBN	Pages
25FTM18		978-1-64353-220-2	19

Hard Gear Skiving with High-Performance Tools – An Innovative Technology for Future Drivetrains

Andreas Hilligardt, Christoph Leonhardt, Maximilian Zimm

Due to the increasing demand for drivetrains with even higher power densities, high efficiency and low noise emissions, new gearbox concepts with planetary gear sets are increasingly being developed. Internal gears with a high load capacity and geometric accuracy in a thin-walled design are required for these concepts. These requirements can be met in particular by hard fine machined, case- or induction-hardened gears. However, the high hardening distortions of thin-walled components create major challenges for hard fine machining, meaning that there is currently no economical hard fine machining process available for internal gears.In the last 15 years, gear skiving has established itself as one of the most important processes for the production of internal gears in green machining. However, attempts to use the process in hard fine machining have failed due to the limited tool life that can be achieved with tungsten carbide tools and the resulting quickly insufficient workpiece quality.This paper introduces a novel PCBN tool system for the high-quality, economical hard finishing of internal gears. The tool system is complemented by a highly specialized hard skiving machine. Application examples demonstrate how this technology machines internal gears to a quality of ISO class 5 or better, achieving tool lives exceeding 2000 workpieces per resharpening.

25FTM17		978-1-64353-219-6	13

Vibration Analysis for Fault Diagnosis of Cycloidal Gearbox Using Wavelet Transform

Sandeep V. Thube

Vibration analysis plays an important role in analyzing the performance of rotary machineries. Some traditional digital methods including time waveform and frequency (Fast Fourier Transform, or FFT) spectrum have shown to be useful in analyzing 'stationary signal' generated by components like bearings and involute gears. These methods, however, often fall short to identify faults when it comes to the cycloidal gearing, which is used in a variety of applications. The frequency spectrum may not be able to clearly distinguish a faulty cycloidal gearbox from one that operates normally.The paper discusses Wavelet Transform method to process non-stationary vibration signal and diagnose the health of the cycloidal gearbox components including Cycloidal discs. This information is critical for design, fault diagnosis, noise reduction and predictive maintenance purposes. The vibration data was collected from normal and faulty gearbox setups under identical load conditions. This data was evaluated to find wavelet leaders using Discrete Wavelet Transform, and also to plot FFT graphs. The wavelet leaders were then used to perform multifractal analysis, during which the signal was analyzed for mono and multifractality. When plotted, the multifractal spectra clearly distinguished the signals from two different gearbox setups.

Document		ISBN	Pages
25FTM16		978-1-64353-218-9	13

Residual Stress Evolution and Stability: Assessing Heterogeneity and Relaxation in Gear Operation

Bruno Lima, Matheus Rubik, Ronnie Rego

This study addresses the sensitive aspects of the residual stress heterogeneity and its impact on the relaxation phenomena during the gear's operation. The primary objective is to evaluate how the operational loads can change the residual stress state due to the initial heterogeneity, specifically aiming to correlate the impact of these changes within the gear lifetime. Fatigue tests were performed, in which samples with different conditions of number of cycles were evaluated to observe the residual stress relaxation. This approach enabled the evaluation of the residual stress stability of the samples based on the evolution of the residual stress state. Aspects such as contact pressure, cyclic deformations, and retained austenite transformation were considered to evaluate the shakedown. Preliminary results of the surface residual stress relaxation have already provided relevant information related to the tendency for relaxation during gear operation due to a higher heterogeneity level. The comprehensive analysis of the residual stress state highlights the potential to optimize the gear manufacturing chain. With that, this approach can make it possible to understand and achieve more stable residual stress profiles in gears, ensuring their benefits are maintained for a long period throughout the gear's lifetime.

25FTM15		978-1-64353-217-2	19

Extraction of Imaged Tooth Contact Patterns by Iterative Least Squares Approach

Tom Abraham, Dr. Alfonso Fuentes-Aznar

Crowned gears exhibit localized contact forming a defined area on the tooth surface, known as the tooth contact pattern, where the teeth of two mating gears come into contact during meshing. The contact pattern is indicative of the misalignment insensitivity and excited noise throughout the corresponding function of transmission errors. This makes it a critical design factor for many types of gears, especially some applications of bevel and hypoid gears. It is in constant consideration while designing the geometry, and thus it is a measure that is often inspected.Traditionally, the contact pattern is inspected by painting the teeth of a pinion and gear with a marking compound, assembling the pair into mesh, and then rotating the pinion with a slight braking torque applied to gear. This process is time and labor intensive. Many attempts have been made towards automating the process over the last several decades for this reason. Despite significant incentives, innovative methods, and advancements in technology, a universally reliable approach for automating the determination of tooth contact patterns has yet to be provided.In this paper, a method of extracting tooth contact patterns is established using only the virtual model of the gear teeth, an image of the gear, and a known calibration fiducial. A reproducible mathematical approach is presented and utilized to identify contact patterns and extract them back to the 3D model. Once there, it can be mapped into the commonly known radial projection and used for manufacturing and assembly corrections.

Document		ISBN	Pages
25FTM14		978-1-64353-216-5	16

Acceleration Data-Based Analysis of Tool Wear in Gear Hobbing

Steffen Hendricks, Mareike Davidovic, Christian Westphal, Thomas Bergs

Gear hobbing is one of the most used processes for soft machining in gear production due to its high productivity. When optimizing the process, the reduction in production costs is offset by the simultaneous maintenance of the required gear quality. Shortening the process time by increasing the process parameters leads to increased tool wear and possibly a reduction in workpiece quality. Therefore, knowledge of tool wear during the process is necessary for the most economical manufacturing process while maintaining the workpiece quality. Tool Condition Monitoring (TCM) provides a methodical approach to detect wear during the manufacturing process. Tool Condition Monitoring is defined as the use of sensor technology to directly or indirectly monitor and predict the tool wear. By analyzing the signal data, taking into account the process characteristics, it is possible to draw conclusions about tool wear. So far, there has been limited scientific research into TCM in gear hobbing. Information on the influence of chip geometries, which vary in the generating positions over the process time during gear hobbing, on TCM and an analysis of different evaluation methods are not yet available.This report presents a TCM method in which the process is analyzed separately along the generation positions during hobbing using acceleration data. For this purpose, the fly-cutting trial is used as an analogy trial for gear hobbing. The individual analysis of certain generating positions enabled more in-depth process knowledge to be obtained and wear monitoring each area of the cutting edge to be performed. In generating positions with multiple engagements of the tool and the workpiece, characteristic values of higher orders were particularly suitable for wear detection. In contrast, lower orders or peak-to-peak values were suitable for generating positions without multiple tool engagements. With this process knowledge, the hobbing process can be optimized and better monitored.

25FTM13		978-1-64353-215-8	16

Areal Surface Characterization of Involute Gears With Microgeometry Corrections and Contact Fatigue Damage for Tooth Contact Analysis

Tom Reavie, Robert Frazer, Robert Lambert, Steve Wilson, Navid Pourmohammadi, Christopher Aylott, Brian Shaw

Characterizing the surface geometry of involute gears is crucial for many high-performance applications and when innovative machining and finishing processes are used. While traditional line (1D) measurements are well-defined by international standards, guidelines for gear surface measurement are currently not available. Despite this, surface measurements have been performed in industry and explored in literature over the past decade.The National Gear Metrology Laboratory (NGML) at Newcastle University have recently developed an involute gear surface characterization capability. The evaluation strategy implements Ni and Goch's proposed areal extension of traditional parameters by fitting Chebyshev polynomials. NGML developed a method to estimate the measurement uncertainty of the characterization parameters using traceable and calibrated 1D helix and profile measurements. The method also quantifies microgeometry corrections such as tip relief, root relief, and end relief.To demonstrate the method's applicability, contact fatigue test gears were analyzed to quantify micropitting and compared to current damage evaluation methods used by the Design Unit at Newcastle University.Measurements were conducted using a tactile probe on a Klingelnberg P65 gear measurement machine. Contact stress and transmission error were simulated in Dontyne Systems 3D FEA based tooth contact analysis model. Surfaces with no or nominal modifications, as-manufactured surfaces, and subsequently damaged surfaces were analyzed and are discussed.Future work and other potential applications will be discussed including quantifying surface run-in effects, coatings, micropitting progression, and other gear performance standards and model validation.

Document	ISBN	Pages
25FTM12	978-1-64353-214-1	21

Interaction of Gear and Bearing Simulation for Planetary Gear Stage Optimization

Michael Otto, Jonas-Frederick Berger, Karsten Stahl

Achieving compact gearbox design requires high-end simulation by local tooth contact analysis. Recent developments show a trend towards more complex planetary gear designs to further increase power density. This can be observed in the field of e-mobility or e-micromobility. For high ratio and small housing dimensions not only classical minus planetary gear stages are designed but also designs with stepped planets are discussed. These designs bear some extra complexity which can be thoroughly analyzed by current algorithms available in specialized gearbox software packages. However, in many cases not only is the optimization of the gear mesh necessary, but the rolling bearing situation under these severe space restrictions proves to be the limiting factor. High radial loads of the smaller gear of the stepped planet may lead to uneven loading of the bearings and even edge loads. Designing a gear microgeometry which ensures even loading of the tooth flank does not solve the issue. One possibility to prevent a steep decrease in bearing lifetime may be an optimization of the gear microgeometry which also includes the influence on the load distribution of the rolling elements within the bearing. Only a local bearing analysis directly linked to the local tooth contact analysis allows a fair evaluation of the situation. The respective algorithms must be formulated with an adapted level of detail to balance the time for modelling and solving between the domains of bearing analysis and gear simulation. In this paper the authors present an approach based on the algorithms implemented in the software package RIKOR. The influence of the level of detail in the simulation of gear mesh on the bearing contact conditions and vice versa is documented in theory and by an example gearbox design.

25FTM11	978-1-64353-213-4	19

High-Damping Lightweight Design for Laser Powder Bed Fusion 20MnCr5 Gears

Matheus Vieira, Guilherme Guimarães, Bruno Lima, Ronnie Rego, Alfredo Faria

The increasing demand for sustainability and e-drive transmissions is reshaping the gear industry, requiring mitigation of Noise, Vibration and Harshness (NVH). In this scenario Laser Powder Bed Fusion (L-PBF) is a promising additive manufacturing technology offering design freedom while maintaining a mechanical behavior suitable for gear application. Despite the capabilities of AM, there remains a gap in systematically applying its design freedom to enhance the vibration behavior of gears. This study proposes a method that takes advantage of the design freedom of L-PBF to enhance the damping behavior of a pinion gear while simultaneously reducing its mass. The proposed method reduces the component's weight by topology optimization, while simultaneously, the topology optimization is calibrated to ensure that stiffness modifications resulting from the structural changes enhance NVH characteristics by improving component's damping. Additionally, the method incorporates transmission error simulations, enabling informed design decisions that help avoid resonance frequencies. Applying this method resulted in approximately 22% reduction in gear weight and a substantial improvement in damping properties. Moreover, the stiffness modifications adjusted the transmission error pattern, effectively avoiding critical frequencies. The method supports the development of advanced and sustainable gear systems tailored to the future demands of electromobility.

Document		ISBN	Pages
25FTM10		978-1-64353-212-7	13

Impact Load Considerations in Automotive Gear Design

Hareesh B. Kurup, Carlos H. Wink

Automotive drivetrains often encounter impact loading due to sudden acceleration, deceleration, and road obstacles. Uneven gear shifting, particularly with manual clutches, is another significant source of transient impact loading. If not accounted for during gear design, transient loads may influence transmission performance under certain operating conditions. Gear rating standards, such as ANSI/AGMA 2101- D04 and ISO 6336 -1, recommend accounting for all potential torsional vibrations and impact loads in the rating calculations. An overload factor or application factor is used to account for all externally applied loads exceeding the nominal tangential load on the gear. These standards allow gear engineers to define the overload factor based on their experience with the application, acknowledging the wide and complex nature of load variations. This paper presents an approach to incorporating the effect of drivetrain shocks in transmission gear rating and includes a case study identifying impact loads from gear shifting events as a significant factor. Measured transient loads from an on-road vehicle drivetrain are studied for their impact on transmission gear life compared to the gear performance under steady state loading. Impact loading considerations are incorporated into the gear analysis performed, and the analytical predictions correlated with investigation findings.

25FTM09		978-1-64353-211-0	24

Investigations on the Wear Behavior of Plastic Crossed Helical Gears

Martin Weber, Lorenz Constien, Michael Geitner, Prof. Dr.-Ing. Karsten Stahl

Compact electric drives are increasingly in demand for various applications, including robotics, medical technology, transportation (e.g. e-bikes and scooters), and auxiliary drives in motor vehicles. Crossed helical gears are particularly well-suited for these applications due to their high transmission ratio in a single stage and their freely selectable axis crossing angle. Using plastic materials for the gearings can improve NVH performance, efficiency, emergency running capabilities, and allow a significant reduction of production costs, enabling the development of cost-effective but also compact and resource-efficient drives.Scientific research on crossed helical gears made of plastic materials is still limited, and the available methods for calculating and testing of the wear behavior are primarily type-specific. Existing approaches are based mainly on studies of steel worm and plastic wheel pairings, making them only partially applicable to plastic/plastic combinations. Furthermore, methods for metal crossed helical gears fail to account for plastics' complex, non-linear, and highly temperature-sensitive material properties. Additionally, weight-based wear measurement methods are not viable in this context due to the chemical and physical interactions between the plastic material, the lubricant, and moisture from ambient air, which can significantly influence the material's properties and, therefore, the measurement results.This paper presents a novel method for in-situ evaluation of the wear behavior of plastic crossed helical gears based on angular difference measurements and compares it to existing wear measurement techniques. The applicability of the method is demonstrated by experimental investigations. An exemplary PEEK/PEEK crossed helical gear pairing is analyzed using a newly developed, flexible test rig. A comparison of the experimental results obtained with the new method to common wear measurement techniques shows a strong correlation while simultaneously significantly reducing the effort required.

Document		ISBN	Pages
25FTM08		978-1-64353-210-3	15

Performance-Driven Design of Multi-Stage Gear Transmissions for E-Drive Systems

Claudio Autore, Luca D'Angelo, Marco Cirelli, Pier Paolo Valentin

Performance-driven design approaches can minimize the weight and volume of modern e-drive systems customized for specific applications while greatly increasing their efficiency and reliability. Position and size restrictions are rarely explicitly included in the optimization process of these multi-stage gear transmissions in the existing literature. Furthermore, despite their importance in gear transmission production, design-specific limitations like tooth interference reserve, tooth clearance, and tooth tip thickness are frequently overlooked. This work directly addresses these issues by presenting an innovative multi-objective optimization approach for the design of multi-stage spur gear transmissions that incorporates these limitations in the optimum definition. Hence, the designs obtained directly satisfy size requirements and manufacturing specifications, eliminating the need for post-optimization verification and ensuring better performance. The optimization process is divided into two stages: a critical characterization of the gear's domain, constituted of several macro-geometry variables, followed by an optimization phase based on an elitist non-dominated sorting genetic algorithm. The KISSsoft power loss calculation, based on the Ohlendorf-Niemann formulation, and the Anderson-Lowenthal model, are employed to estimate both load-dependent and load-independent power losses while satisfying geometric, layout, and size constraints and guaranteeing the safety requirements evaluated with ISO standards' safety factors. The methodology, adaptable to a wide range of gear transmission designs, is then applied to a two-stage transmission system, evaluating and confronting two different setups: a gear train with an idler and a countershaft four-gear arrangement. The results indicate that in both cases, the most efficient solutions typically feature a large number of teeth, a low module, and wide face widths, while designs prioritizing low volume tend to have larger modules but more compact geometries. Moreover, the idler configuration achieves significant volume reduction at the cost of lower efficiency, while the four-gear configuration more uniformly populates the feasible domain.

25FTM07		978-1-64353-209-7	26

Nanocomposite Coatings for Thermoplastic Gears

Peter Schmidt, Borut Černe, Saumya Kotha

Gears formed with thermoplastic materials have made significant strides in strength over the last decade. Gears manufactured with these materials have been tested extensively, showing bending strength and fatigue performance levels that make them potential candidates for mobility applications. Thermoplastic gears are of particular interest to designers in the EV space. Wear of gear tooth surfaces, along with fatigue failure, remains a challenge, however. With the goal of reducing wear and potentially improving fatigue durability, gears manufactured from reinforced Polyetheretherketone (PEEK) meeting ASTM D8033-22 PEEK012CF30 were examined, analyzed, and coated using Plasma Enhanced Chemical Vapor Deposition (PECVD). Due to the nature of the plasma deposition environment, this coating process can be performed below the substrate material's glass transition temperature (Tg). A thin film coating system, developed for aerospace applications and composed of a metallic adhesion layer and a nanocomposite carbon matrix layer, was applied after surface finish improvement to the gears under evaluation. This coating system was initially designed to increase the resistance of steel gears to scuffing and to reduce friction in the mesh. Results of standard tribological testing (ASTM G99) and standard thin film coating testing (ISO 26423, ISO 20502, VDI 3198), documenting performance on the PEEK substrate, are reported. As molded and improved gear surface finish data and photographs are also included, with examples shown prior to coating and after coating. Coated gears were then tested in accordance with VDI 2736-4 in oil-lubricated conditions in a plastic-to-steel pair configuration for comparison with previously obtained results from the same test setup with uncoated gears. The tests were carried out to characterize fatigue S-N curves and evaluate tooth profile wear. The results are supplemented with gear images, showing the test articles before and after testing. Testing showed that the coating applied to the gears improved fatigue and wear durability, prolonged the gear’s service life near the low-cycle fatigue area by up to 8.9x, and allowed up to 33-% higher load-carrying capacity in the same low-cycle area.

Document		ISBN	Pages
25FTM06		978-1-64353-208-0	16

Repair and Fabrication of Gears Using Laser Directed Energy Deposition

Dr. Diego Montoya-Zapata, Maria Azpeleta Ortiz, Dr. Aaron Isaacson, Matthew Wagner

Additive manufacturing has positioned in the manufacturing industry due to its capabilities to fabricate complex parts. Moreover, the use of Laser Directed Energy Deposition (LDED) in repairs and refurbishments considerably reduces the lead times. The gear industry could benefit from these advantages of LDED. However, there is a lack of research and data on the performance of gears manufactured and repaired by LDED, which hinders the adoption of this technology in gear applications. In this work, we focus on the application of LDED for gear repair, addressing the selection of material, gear mechanical performance, and the relation between the LDED parameters and the properties of the final part. The martensitic tool steel Dievar was chosen to perform teeth repairs on actual gears. Firstly, several teeth were removed and reconstructed on a spur gear. Then, the methodology was applied on an actual industrial case, by repairing a gear that broke during the assembly process of a machine for aluminum parts production in the EV automotive industry. Preliminary results are presented on the bending fatigue response and the corresponding S-N curve of gear teeth manufactured with Dievar. The results of the experiments (bending fatigue testing and actual gear teeth repairs) demonstrate that LDED has large potential for being widely adopted in gear repair applications. However, there are still some challenges that comprise material processability (by LDED), productivity and deposition rate, geometrical strategies, and consistency of the mechanical performance of the final parts.

25FTM05		978-1-64353-207-3	

Local Damage Based Micro Geometry Design Method for Planetary Gears Considering Axis Misalignments and Load Deformations

Simon Nohl, Christian Westhal, Prof. Christian Brecher

CAE-based micro geometry design of cylindrical gears enables us to optimize the operational behavior of gearboxes and enhances the lifetime due to the reduction of root stress and flank pressure. A common state of the art approach is to reduce the maximum flank pressure and tooth root stress for each load case of a load collective and optimize the micro geometry according to the most often occurring load cases. Linear damage accumulation hypotheses, however, suggest that gear failures are the result of repeating stresses and occur at the location where the highest accumulated damage relative to the material's local load-carrying capacity arises. In planetary gears, due to complex kinematic and kinetic relationships between the gears and the surrounding elastic system, manufacturing errors and load deformations result in a variation of the contact behavior over the rolling circumference of the planet carrier. Additionally, axis misalignments of all elements impact the load distribution among the planets, which could lead to failure of the highest damaged planet resulting in complete gearbox failure. This paper therefore describes a micro geometry design method for planetary gears focusing on planet carrier deviations. The underlying tooth contact analysis was developed to efficiently consider unequal load-sharing among the planets as well as load- and axial position dependent meshing interferences. The evaluation technique compares local root stress and flank pressure to the local load carrying capacity based on several damage accumulation techniques to perform an iterative process between an adjustment of the micro geometry and tooth contact analysis. The design method optimizes the operational behavior towards a load collective considering the effects of the surrounding elastic structural components. A more robust micro geometry can be achieved, to reduce high damage concentration areas and increase safety margins. The iterative design method is compared to a particle swarm optimization algorithm which can optimize the overall static transmission error additionally but takes significantly more calculation time and brings results dependent on the target function. For the future, it is aimed to validate the method with test rig results or data from industrial applications.

Document	ISBN	Pages
25FTM04	978-1-64353-206-6	17

TIFF Identification and Resolution of Automotive Straight-Toothed Bevel Gears

Caleb Gurd, Benjamin Sheen

This paper presents a comprehensive framework for identifying and mitigating Tooth Interior Fatigue Fracture (TIFF) in straight-toothed, net-forged bevel gears used in automotive differentials. As modern drivetrains demand higher torque in increasingly compact and reliable packages, traditional gear design methodologies are being pushed to their limits. While surface- and near-surface-initiated failures are well understood and routinely addressed through established practices, subsurface failure modes such as TIFF require a more advanced understanding of material behavior and internal stress distributions.Leveraging on real-world case studies, current industry practices, and academic research, this work defines effective strategies for diagnosing and addressing TIFF. Techniques including visual inspection, magnetic particle inspection (MPI), scanning electron microscopy (SEM), microgeometry optimization, and heat treatment modifications are critically evaluated for their diagnostic and preventative effectiveness.By consolidating proven techniques and engineering insights, this paper serves as a practical guide for professionals encountering TIFF for the first time, as well as a technical reference for experienced engineers seeking to enhance their expertise. Advancing the understanding of complex failure modes like TIFF is essential to improving drivetrain reliability and supporting the continued evolution of high-performance gear systems.

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Design and Load Capacity of Crown Gears in Comparison to Bevel Gears

Joachim Thoms, Jürg Fürst

The market is demanding ever more efficient gearboxes. New types of gear sets are becoming increasingly interesting in order to realize such transmissions. The crown gear (also known as face gear) is not actually a new type of gear, but in the past, it has led a rather niche existence due to the complicated production of the crown wheel. New, more productive manufacturing methods and new design and calculation options are bringing the crown gear back into focus. It therefore makes sense to take a closer look at the advantages and disadvantages of crown gears, especially in comparison to bevel gears.Today, crown gears are designed with the help of modern flank generators, as it has long been standard practice for bevel gears. With the help of the complete tooth model, this approach allows the creation of nominal measurement data for 3D gear measuring devices at the same time as the ease-off analysis. This not only enables the exact topological measurement of the crown gears, but also represents the first approach for a subsequent closed loop in production. In addition to load capacity calculations similar to ISO 10300, which are also possible with less data, complex tooth contact analysis under load (LTCA) can also be carried out with the complete gear model. If relative position deviations under load are taken into account, complete load capacity analysis can be carried out accurately using modern calculation methods. The relative position deviations can be calculated with the help of CAE tools.Two examples (an actuator gear and a differential gear set) are used to show the various possible applications of crown gears in comparison with similar bevel gears. The advantages and disadvantages of crown gears compared to bevel gears can be derived from the comparison.

Document		ISBN	Pages
25FTM02		978-1-64353-204-2	12

Gear Scuffing Analysis Comparison Study

Zhiyuan Yu

The rapid advancement of electric vehicles (EVs) has heightened the demand for reliable and efficient transmission systems, making the study of gear scuffing increasingly critical. Gear scuffing, a form of surface damage caused by metal-to-metal contact under high load and speed conditions, poses a significant challenge to the durability of EV gearboxes. To address this, advanced analytical software tools have been studied to predict and mitigate scuffing risks. Two primary software tools are utilized in this paper's gear scuffing analysis: Masta and Windows LDP. Masta, which relies on ISO 6336, uses empirical correlations to account for gear geometry, material properties, lubrication election, and operating conditions. In contrast, Windows LDP models the dynamic behavior of the lubricant film using an elastohydrodynamic lubrication (EHL) model, providing a physics-based approach to scuffing prediction. Recent developments in these simulation techniques have significantly improved the accuracy of scuffing surface temperature predictions. However, comparison studies in this paper found discrepancies between the two software at various surface roughness, torque load, speed, and lubrication properties. The case study in this research shows that the deviation could be up to 40%. To bridge this gap, this research proposed a dual approach, using analytical software Masta and Windows LDP, and correlating their results with physical testing on custom-designed test rigs. These rigs should replicate actual gears and operating conditions, such as lubricant spraying into or out of meshing, nozzle configuration, more accurately than standardized tests, ensuring more reliable predictions. This integrated approach not only enhances the reliability of EV transmission systems but also accelerates the development of more robust and efficient gearboxes.

25FTM01		978-1-64353-203-5	15

Independent Pinion and Gear Profile Shift for Bevel Gears

Hermann Stadtfeld

Bevel and hypoid gears as well as straight bevel gears require a positive profile shift for the pinion in case of low number of teeth. Profile shift for cylindrical gears is defined in AGMA 901-A92, Annex A, which can be used as guideline also for bevel gears. If the number of pinion teeth is below 13 or even lower, the pinion develops a severe undercut which eliminates a large portion of the tooth profile in particular at the toe area. This effect leads to a weakening of the tooth root and also a reduction of the flank contact area. As result, the root bending stress and the surface stress are high, and the bevel gear pair has only a fraction of the load carrying capacity compared to a bevel gearset without undercut.
In bevel and hypoid gears, as well as straight bevel gears, the pinion profile shift coefficient X1 and the gear profile shift coefficient X2 have the same absolute amount but opposite signs (X1 = -X2 or X1 + X2 = 0). In cylindrical gears this prevents a change of the center distance. In bevel gears this is analogous to preventing a shaft angle change. This means that a positive profile shift in both members of a bevel gearset would change the shaft angle Sigma by Delta Sigma = (X1 + X2) * mn / Mean Cone Distance.
The new developed independent profile shift allows a positive profile shift in pinion and gear without a change of the shaft angle, yet having all the advantaged like elimination of undercut, Increased contact ratio and improved NVH as well as stronger tooth profiles especially in case near miter ratios with a low number of teeth.
The paper presents the theory of this new method and includes case studies and test results

Document		ISBN	Pages
24FTM32		978-1-64353-200-4	18

Micropitting Load Carrying Capacity of 5-Axis Milled Gears

Lennart Schierholz, M. Sc., Dr.-Ing. Jaacob Vorgerd, Prof. Dr.-Ing. Manuel Oehler

This article presents the results of tests performed on a backtoback test rig for large module gears (center distance a = 508.33 mm, module mn = 25 mm) and on a FZG gear test rig (a = 91.5 mm, mn = 4.5 mm) in order to investigate the micropitting load carrying capacity using 5axis milled gears. The fine machining using 5axis milling influenced the topography and the macroscopic gear quality. After the load stage test, significant wear in form of a profile form deviation in connection with scrape marks could already be observed, in comparison to identical flank shape modifications of largemodule gears. These can be attributed to a premature meshing impact, which is favored by the large, negative profile angle deviations fHα. In contrast, the average profile form deviation observed in the micropitting area correlates well with the smallmodule gear sets and those with large module but different machining process. In general, the 5axis milled gears exhibit similar wear depths in terms of micropitting, accompanied by a simultaneously larger micropitted damage pattern. The resulting 5axis milled surface caused higher local contact stress, which resulted in an early wear phenomena and larger worn surface. A reduction in the oil injection temperature from 90°C to 60°C results in a smaller micropitting area and wear depth due to improved lubrication conditions, particularly on the microgeometric surface of 5axis milled, largemodule gears. Furthermore, a test was conducted on a stream finished large gear pinion to assess the potential for postmachining. While the surface roughness was reduced, this was insufficient to compensate for the unfavorable surface in terms of micropitting caused by local topography maxima.All the test results show that it is important to ensure good geometric quality in the manufacturing of gears so that gear meshing can take place undisturbed. During the machining process, it is of significant importance to pay close attention to the surface quality of the tooth flanks, in order to prevent the formation of contact pressure peaks on protruding flank areas, which would otherwise lead to accelerated wear caused by micropitting.

24FTM31		978-1-64353-199-1	12

Influence of Material Removal Rate on Residual Stress State in Gear Grinding

Angelo Carvalho, André Oliveira, Naiane Souza, Ronnie Rego

The knowledge of the residual stress state is of interest to the gear industry due to its critical role in avoiding fatigue failure mode. Since fatigue cracks are always nucleated and propagated under tensile actuating stresses, a suitable compressive residual stress state is desirable to decrease the total stress profile, by the superposing principle. Usually applied as the last process of the gear manufacturing chain, grinding provides both thermal and mechanical loads, from which residual stresses are induced. The intensity of such loads is associated with the material removal rate (MRR); however, it is not constant along the tooth profile, due to the complex kinematics of gear grinding process. The objective of this study is then the comprehension of how the variation of material removal rate along the tooth profile influences the grindinginduced residual stresses. Casehardened steel discs were manufactured with different material removal rates, induced by varying grinding parameters. The ground surface integrity of such simplified samples was characterized in terms of residual stress distribution on the surface and indepth profile. ITA Geometry gear samples were manufactured with profile gear grinding. The characterization of the surface integrity state of the ground teeth was similar to the disc assessment and showed a good correlation regarding the material removal rate and the residual stress state along the tooth profile. Such results highlight that a strategic definition of grinding parameters by material removal rate can improve the residual stress state, leading to more reliable gear fatigue prediction.

Document		ISBN	Pages
24FTM30		978-1-64353-198-4	28

Cutting Tool Selection Criteria for Cylindrical Gear Manufacturing

Massimiliano Turci

This paper concludes the trilogy on the relationship between design and production of cylindrical gears.The focus has already been on design using the available tools, which is the first step in answering the designer's question "can this gear be manufactured?".The closedloop relationship between design and production with mutual exchange of information has also been discussed. The closedloop involves the active and synchronous involvement of production in the design process.These two scenarios are typical of companies that have both design and production capabilities.In this third "episode," the typical situation of subcontractors who receive the drawing of a single gear and wonder "how can this gear be manufactured?" is examined instead.Particular attention will be paid to the choice of the pressure angle of the hob.As usual, the paper does not describe an academic research project but shares a good practice, already applied in several companies in Italy.

24FTM29		978-1-64353-197-7	23

Innovative Processes and Strategies for Increasing Machining Efficiency for Worms and Worm Gears

Jörg Lohmann, Dipl.-Ing

(1) Recent increases in digitalization, connection and automation led to a demand for higher degrees of automation and flexibility. Industrial gearboxes, such as fractional horsepower and worm gearboxes, are increasingly important, since they significantly impact production of automation solutions, robots and other handling systems. [1] With increasing quantities, the requirements on the gears' level of accuracy, their efficiency and the corresponding gear machining processes have risen, too.(2) When (soft) gear machining those parts, traditional machining processes – hobbing and single index milling with form cutters – are usually applied. In common manufacturing environments, flexibility of equipment is limited by available machining cycles. Cycle times often are long when workpieces like worm gears with high helix angles are hobbed.Moreover, when worm milling by single indexing, internal tensions within the workpiece material may be released during machining, which can lead to distortion that negatively influences gear accuracy.(3,4)
This report shows how worms can be machined more efficiently by replacing the single index worm milling process with a more efficient hobbing process, using a special hobbing strategy. Cycle times and tool costs are reduced thanks to machine kinematics employing new machining cycles that allow hob shifting.Additionally, this report offers a machining strategy for single index worm milling, avoiding deviations in the gear geometry caused by internal material tensions released during cutting.Moreover, the report explains how to increase efficiency by avoiding return strokes within the machining cycle.

Regarding machining of worm gears, modern hobbing methods, such as the highperformance worm gear hobbing process, ensure high accuracy workpieces and efficient manufacturing processes at the same time. (5) These process improvements cannot be applied to all geometries of gears or worms; however, where applicable, the increase of efficiency in their production process is significant.

Document	ISBN	Pages
24FTM28	978-1-64353-196-0	15

Generating Gear Grinding in EMobility: Challenges and Solutions

Dr. Maximilian Zimmer, Christoph Leonhardt

The topic of this paper is the changing focus in gear design and the resulting challenges in gear production, in particular for continuous generating gear grinding with the rising influence of the Emobility in the automotive industry. Especially the subdomain Noise Vibration Harshness, also known as NVH, has become one of the most important topics in the development of automotive drive trains. Besides the current challenges of Emobility drivetrains and the working mechanisms behind gear noise excitation, the author will show a quick technological overview of the most important characteristics of the continuous generating grinding process, which is the context of this paper. Knowing the characteristics of the generating grinding process, as well as the root causes of gear noise excitation in the gear box, methods for optimizing the NVHbehavior of a gear will be presented. A comprehensive approach has to consider the whole process containing the gear design and all the involved manufacturing processes. Even though all influence factors of the grinding process have been optimized according to best practice, it is still possible that ground gears fail on the endofline test bench due to increased noise level. In this case it is important to know which tools are available to reliably identify the sources of NVH issues and therefore being able to fix them. In particular, the external excitation of components in the grinding machine which typically results in NVH issues will be discussed. In this context the paper will show the fundamental effects of external excitation frequencies in the grinding machine and an approach to solve the problem.

24FTM27	978-1-64353-195-3	20

A Review on Gear Transmission Error

Zhaoyao Shi, Huiming Cheng

This paper traces the nearly centurylong research history of transmission error (TE) of gear, highlighting three stages of understanding TE from geometric error, kinematic error, and dynamic error. The relationship between TE and elemental gear deviations is discussed, and the classification of TE is proposed. Furthermore, the composition of TE is clarified, emphasizing their dynamic nature. The application of TE in various areas, such as gear design, process error analysis, transmission chain accuracy characterization, and gear NVH evaluation, is summarized. Finally, the limitations and deficiencies of TE are outlined, and a resolution to solve these problems is proposed by considering gear pair integrated errors.

Document	ISBN	Pages
24FTM26	978-1-64353-194-6	16

Statistical Analysis of the Position Tolerances of Planet Pins in Planetary Gearboxes

Benjamin Abert, Tim Erlewein

Planetary gearboxes are widely used in transmission systems as they have a higher power density and better efficiency than parallel shaft gearboxes. However, the design of planetary gearboxes requires more components with tighter tolerance ranges. Assuming constant material prices, this leads to higher manufacturing costs compared to spur gears.The simulation of planetary gearboxes often assumes a nominal geometry for the planet carriers. However, it is known that the position of the planet pin has an influence on the load sharing factor $K_γ$, as defined in ISO 6336. Thus, we can assume that the positional tolerances will also have an effect on the load capacity. A static loaded tooth contact analysis (LTCA) is used to determine the load distribution on the planets, and a condensed stiffness matrix is used to consider the influence of the planet carrier. The primary aim of this work is to systematically analyze the positional tolerances of the pin in the planet carrier. A statistical tolerance analysis is used to evaluate the load capacity of a planetary gear stage. This makes it possible to correlate tolerances with the customer's required nominal loads and define a loaddependent tolerance system. As a result, a methodical procedure for analyzing planet carrier tolerances is presented using two different designs, and the use of loaddependent tolerance systems is also discussed.

Document	ISBN	Pages
24FTM25	978-1-64353-193-9	26

Efficient Numerical Assessment of Thermal Effects in a Gearbox Using Smoothed Particle Hydrodynamics

Benjamin Legrady

The oil in industrial gearboxes serves two purposes: It is a lubricant and a coolant. This poses a particular challenge to gearbox engineering, as the oil properties, most importantly its viscosity, change with temperature. One option in the design cycle would be to run extensive experiments. However, especially at an early design stage, this may not be possible. Engineering then may resort to computational fluid dynamics (CFD) to tackle the issue. However, lubricant flow is an intricate subject to model as it interacts with the air and its viscosity may dramatically change with temperature. Moreover, the moving parts of a gearbox render the generation of numerical meshes difficult. In recent years meshless methods such as the smoothed particle hydrodynamics (SPH) have become increasingly popular for tackling the issue. In this paper we illustrate how the SPH method can be used with temperaturedependent oil models, to assess the thermal management concept of an industrial gearbox. We particularly discuss the merits of this method for fastpaced design cycles, where experiments are no option and other computational fluid dynamics (CFD) techniques are too complicated to set up in a short time. Special emphasis is given to how to set thermal boundary conditions pragmatically and how to evaluate the uncertainty at an early design stage.

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24FTM24	978-1-64353-192-2	18

Advanced Lubricant Technology for Open Gear Applications

Dr. Jennifer Clark, Ph.D., Dr. Robert Dura, Ph.D., CLGS, Roberto Saruls

Proper lubrication is critical for all open gear applications. These applications are extremely demanding and range from sugar mills to mining across many different environmental conditions. Traditionally, asphaltic lubricants dominated this product space encompassing both solvent and solvent free variants. Over time, asphaltic stock have been phased out in favor of physically cleaner and more visually appealing polyisobutylenes (PIB), API Group II oils, higher paraffinic base fluids and Polyalphaolefins (PAO).The advantage of PIB compared to traditional black oils is that they are clear, allowing for easier gear inspection, and decreasing equipment downtime. In addition to easier inspections, PIB does not present any performance loss when compared to asphaltic materials. PAO based fluids also provide clear products and have other desirable attributes such as increased efficiency and lower operating temperatures; however, typically present a higher cost for the consumer.Recently, a new family of unique performance polymers (UPPs) were used to develop fluid lubricants for open gear applications. Using these UPP's as a base fluid provided many benefits ranging from a decrease in operating temperature, improved energy efficiency and reduced product consumption compared to traditional lubricant families.The primary focus of this work is to illustrate the development of a new fluid lubricant technology from ideation through performance in real world applications. Our initial work focused on FZG testing, traction studies and other traditional bench tests to validate basic performance before we moved to a sugar mill and on to larger equipment including a ball mill. As expected, we found that this new technology could improve over the incumbent fluids. Where this paper focuses on fluid type products, we have also validated the performance of the UPPs in grease type materials, illustrating additional lubrication opportunities and potential end uses.

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Mitigation of Gear Whine Noise in Agricultural Tractor Application

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This comprehensive study explores an approach to mitigate gear whine noise in tractor applications using simulation and physical validation. The study systematically examined loaddependent noise during field operation, where two distinct gear orders were prominently observed in application, evident in the noise order analysis.Subsequent to drivetrain NVH simulation, the focus of the study was on optimizing the gear macro geometry, particularly the helix angles and face width, accompanied by refinements to the gear micro geometry. Additionally, the study addressed gear manufacturing variations by transitioning from traditional shaving processes to gear teeth grinding methods, thereby effectively controlling and refining the gear manufacturing process. A subsystem (Drivetrain) level bench test was conducted to calibrate the simulation model using gear contact pattern correlation approach.To validate the proposed modifications, proto gears were developed to facilitate physical experimentation, employing multiple Design of Experiments (DOE). The collective interventions culminated in considerable reduction of noise at the vehicle level, demonstrating the effectiveness of the comprehensive and cohesive approach in design, analysis and testing of gear whine noise in realworld tractor applications.This study emphasizes the significance of meticulous geometric modifications in addressing and minimizing gear whine noise, ultimately contributing to enhance the overall tractor performance and user experience.

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How to Replace Oil as a Lubricant in Worm Gearboxes with Grease

Felix Müller, Manuel Oehler, Oliver Koch

Lubricating oils are the most used type of lubricant in many commercially used gearboxes. Due to special requirements and environmental conditions, however, the need for drive systems without oil lubrication is increasing, which can be met in certain applications using lubricating greases. Replacing lubricating oil with grease, and the associated change in the properties of the lubricant, leads to new requirements for the design, calculation and tribological description of the respective gearbox. This work deals with the rheological properties of greases, the tribological description of a greaselubricated contact and the behavior of lubricant distribution within a gearbox. For this purpose, various lubricants are examined using different tribometers and the behavior in a real gearbox is analyzed. In addition to that the results of the experimental analysis are compared to analytical calculation methods to describe the tribological contact. The tribological investigations include film thickness measurements on a modern EHL tribometer as well as viscosity and friction coefficient measurements. For the behavior in real gearboxes, tests are presented for the analysis of grease distribution using fluorescent particles in the lubricant during operation. The results of these investigations are used to demonstrate the potential and take advantage of greases in worm gears by predicting the friction in the greaselubricated application and designing the gearbox for the resulting demands.

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CFD Simulation of Power Losses and Lubricant Flow in Gearboxes

Franco Concli

In the last years, efficiency has become an increasingly crucial factor across various industrial sectors. The automotive industry, for instance, is requested to develop drivetrains that are not only economically efficient, but also environmentally friendly and reliable. Being able to predict the efficiency and the lubricantbehavior in gearboxes remains an imperative engineering challenge. Existing mathematical models available in literature rely on empirical relations and dimensional analysis, providing accurate results only within narrow operating ranges.A comprehensive approach capable of precisely predicting lubricant flows and power losses in geared systems could significantly advance the field. Thanks to recent evolutions in computer science, Computational Fluid Dynamics (CFD) has emerged as a crucial tool for engineers studying gear lubrication and efficiency. Nevertheless, the widespread adoption of CFD has been hindered by the substantial computational resources required for simulations. The implementation of a computationally efficient meshhandling strategy, along with the development of advanced solvers capable of addressing new phenomena like cavitation, aeration, oil suspension or unconventional lubrication (e.g., nonNewtonian fluids), has made this technology ready for an extensive industrial application. Compared to a decade ago, the computational effort has been slashed by 97%, enabling the simulation of complex systems within a few minutes.This paper presents application examples across various gear types, showcasing the versatility of the developed approach. Additionally, it shows some real case studies: an industrial multistage and a planetary gearbox. This effective and computationally efficient approach has enhanced the understanding of the physical phenomena involved in gearbox lubrication, providing theoretical explanations for experimental observations that were previously challenging to interpret.

Document	ISBN	Pages
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Nanocomposite Coatings for Gears

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Plasmadeposited nanocomposite coatings can offer substantial operational performance and durability improvements to interfaces in rolling or sliding contact without significantly adding to overall part volume or affecting heat treatment of the substrate. This coating system is typically implemented by depositing thin layered metallic or organometallic films using Plasma Enhanced Chemical Vapor Deposition (PECVD). These layers work in concert to increase surface resistance to abrasion while lowering the coefficient of friction between the surfaces in contact. Due to the nature of the plasma deposition environment, deposition processes can be performed at lower temperatures that do not affect the physical properties provided by heat treatment of gear materials. This permits coating deposition to be performed as a final production step. This work describes the development and initial testing of a thin film coating system designed for aerospace gear sets. The predecessor coating system was developed for use on racing hypoid gear sets and has been successfully deployed on automotive platforms. Dynamometer testing of vehicles employing this coating showed a nontrivial increase in brake horsepower available. Depositions of the latest version of the coating system on material coupons and scuffing test samples were performed as a part of a US Air Force SBIR program. Based on previous experience, scuffing tests were performed employing unequal flank dimensions on gear test sets. Results of standard tribological testing (ASTM G133), standard thin film coating testing (ISO 26423, ISO 20502, VDI 3198), and ASTM D5182 / ISO 146352 gear scuffing tests documenting performance improvements are reported. Gear surface finish data and photographs are also included, with examples shown prior to testing and after testing.

24FTM19	978-1-64353-187-8	17

Advanced Gearbox Lubrication Analysis: A Virtual Lab for Design Optimization

Benjamin Beckelynck

This paper presents a workflow for analyzing gearbox lubrication, leveraging advanced Computational Fluid Dynamics (CFD) and heat transfer simulations. Developed in collaboration with a company transitioning from combustion engines to electric vehicles, this workflow addresses the complex physics of lubrication, particularly focusing on a bearing overheating issue caused by inadequate lubricant flow. Traditional physical testing methods pose significant challenges, including high costs, long development times, and difficulty in extracting precise engineering data. In the electric mobility market, a swift timetomarket is crucial for maintaining competitiveness and achieving commercial success.Our innovative approach involves creating a virtual model of the gearbox, enabling a virtual lab environment to test multiple conditions and scenarios. This workflow, implemented with the XFlow 2023 solver leveraging GPU cards, significantly reduces computation times from weeks to days, making it an affordable solution in terms of computing power. By simulating the turbulent multiphase flow and heat transfer processes, the workflow provides detailed insights into lubricant behavior, heat transfer, and component interactions that are difficult to capture with physical testing.Gearbox manufacturers can use this workflow to rapidly and costeffectively iterate on their designs, preventing flaws, improving efficiency, and extending the lifespan of their gearboxes. The virtual tests allow for the exploration of "what if" scenarios and the optimization of design variations without the constraints of physical prototyping. Validation of the workflow through visual comparisons, churning loss measurements, and temperature data correlation has demonstrated its accuracy and reliability. This simulationdriven approach not only enhances product performance but also accelerates development timelines and reduces costs, offering a robust tool for solving complex engineering challenges in gearbox design.

Document		ISBN	Pages
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Influence of Nonlinear Cumulative Damage in Gear Lifetime Analysis

Riley Damm, Isaac Hong

In many gearing applications the gearbox or transmission system is subject to complex load spectra and mission cycle loading. This adds complexity to gear lifetime analysis which is traditionally handled through cumulative damage rules. Many classical and contemporary studies have shown that damage accumulation in metals is nonlinear, and the order of the loading should not be ignored. Yet, standard calculation methods for gears such as ISO 63366:2019, ANSI/AGMA 2001D04, and IEC 614004:2012 still employ a linear damage rule. The implications of using linear versus nonlinear damage rules for gear lifetime analysis remain largely unexplored. In this study, various prominent classical and contemporary damage rules are leveraged to perform lifetime analyses of gears subject to variable loading. The published load spectra and gear strength rating available in ISO 63366:2019 is utilized as an example realistic mission cycle for a gear. The influence of load spectra order and mission cycle length on estimated design life using nonlinear damage is explored. Artificial load spectra are generated to examine the influence on life estimates from a wider range of loading conditions.

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Influence of Unbalanced Sliding Conditions on the Pitting Load Carrying Capacity of Internal Gears

Michael Geitner, M.Sc., Dr.-Ing. Thomas Tobie, Prof. Dr.-Ing. Karsten Stahl

Certain gear failure mechanisms are strongly affected by tribological effects on the flank surface. Here, the contact sliding conditions can play a decisive role due to i.e., crack direction and nearsurface TEHL induced stresses. Macropitting and micropitting for example occur predominantly in contact areas of negative specific sliding. Unlike for external gears, a positioning of pitch point C outside of the active profile is possible for internal gear designs. This allows to completely avoid negative sliding either on the planet or the ring gear. Conversely, the corresponding gear is exposed to negative sliding only. It is assumed that the flank load carrying capacity of each meshing partner can be affected by different positions of the pitch point and the resulting differences in the specific sliding, allowing a lifetime optimization of the full gear stage by taking into account e.g. the load capacity reserves for different material pairings.Systematic results on internal gears with pitch point positioned outside of the active profile are not available. Existing standardized load carrying capacity calculation methods are typically based on investigations considering external gears with balanced sliding conditions.Systematic theoretical and experimental investigations on the pitting load capacity of internal gears in the pairing of a throughhardened respectively nitrided ring gear with casehardened planets were performed. Therefore, a reference geometry with balanced sliding conditions was compared to gear designs with pitch point below and above the active profile. The results confirm a distinct influence of unbalanced sliding conditions, showing a significant increase of the pitting load capacity by avoiding contact areas of negative sliding on the ring gear, while an exposure to negative sliding only leads to a reduction of the pitting resistance. This influence was quantified and recommendations for the design of internal gears were derived.

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24FTM16	978-1-64353-184-7	12

Investigation of Gear Involute Deviations Under Press-Fit Conditions

Anusha Anisetti, Carlos Wink, Paul Wilson

Tooth form is critical to gear performance. Intentional design modifications and manufacturing deviations of tooth flanks affect load distribution of the meshing teeth and consequently bending stress, contact stress, and gear noise. The tooth form and tolerances are commonly specified on gear drawings, which are used for gear procurement. Industry standards, such as ISO 1328, provide tooth flank tolerances of unassembled gears. In gearboxes, gears are attached to rotating shafts through different ways, such as splines, keyway, welding, and pressfit, where the latter is a costeffective solution and largely used in many applications. As the gear is pressed onto the shaft under interferencefit condition for assembly, there is a deformation of the gear. The gear body is expanded radially after assembly changing the tooth form, which may impact the gear performance. Therefore, it is important to predict the influence of this deviation and include any required corrections to the gear drawings during the design process. In this paper, the effect of profile slope deviation of pressfit gears is investigated and a process to correct the deviation is presented. The paper focuses on 1) predicting the magnitude of profile slope change due to pressfit 2) correction of the deviation during gear design process 3) validation of the involute deviation correction through measurements of gears before and after assembly 4) presentation of results on how the corrections of gear profile prior to assembly benefit in improving the contact fatigue life of the gear pair.

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Evaluation of Gear Contact Fatigue Surface Integrity Aspects in Fatigue Lifetime Using the Barkhausen Noise Technique

Bruno Lima, Ronnie Rego

This study addresses the Magnetic Barkhausen Noise (MBN) technique as a nondestructive testing method for detecting contact fatigue in gears within an industrial context. The primary objective is to evaluate the MBN signal evolution during the lifetime of gears, specifically aiming to detect contact fatigue failures in their early stages, before any visible damage appears at the flank surface. Fatigue testing was conducted on five gear samples, inducing a natural evolution of gear contact fatigue. Monitoring MBN signals at regular intervals during testing cycles allowed for correlation with surface integrity degradation. Furthermore, the study delves into microstructural aspects related to contact fatigue, exploring various stages in the MBN evolution curve. The MBN technique was employed to characterize magnetic response variations during the initiation of contact fatigue mechanisms. Indepth analyses of residual stresses, microstructure, and microhardness provided a comprehensive understanding of surface degradation. A substantial increase in the MBN signal was identified before fatigue failure, indicating microstructural alterations affecting magnetic properties. Early contact fatigue stages were characterized by surface softening in the nearsurface region, up to approximately 40 μm depth, accompanied by a less compressive residual stress region at 20 μm depth. The study also observed a lower influence of microstrains on the diffractogram, suggesting higher dislocation annihilation during the initial stages of contact fatigue. Results revealed a significant variation in MBN signals influenced by operational loads during tests, with a noteworthy increase observed just before gear failure. Using a scale from 0% (manufactured condition) to 100% (failure), the study successfully detected failures at 17% of the gear's lifespan, providing valuable insights for early failure detection in industrial applications. The findings conclude by proposing a comprehensive approach to understanding early gear contact fatigue mechanisms and highlighting the MBN signal's utility in detecting fatigue damage

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Categorization of Gear Stiffness Calculation Methodologies, Workflows and Software

Adam D. Foltz, Hazim El-Mounayri

The desire for more compact, efficient and quieter powertrains in the Electrification Age has once again brought gears into the spotlight. In the field of modern gear design and analysis, loaded tooth contact analysis is one of the most important simulations performed. Gear stiffness plays a fundamental role in this simulation and is calculated slightly differently in about every software on the market. The need to accurately resolve gear stiffness to capture pitting, bending, scuffing, efficiency and noise characteristics of a gear pair makes the topic very relevant to the entire gear industry. Due to the gear stiffness being calculated in the background of most software and the fact that the calculation is nontrivial in nature, not all gear engineers are familiar with the gear mesh stiffness methods being utilized in their software of choice and what limitations come along with them. The goal of this work is to categorize all the key gear mesh stiffness methodologies and workflows used in both industry and academia and provide the key references where the methodologies originated from. The advantages and disadvantages of each gear mesh stiffness methodology are covered in detail, along with what methodologies are used in the most common gear software on the market. Finally, recommendations for what gear stiffness methodologies to use in different scenarios are provided.

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Influence of Reverse Loading on the Tooth Flank Fracture Load Capacity

Johannes Rolzhäuser, Dieter Mevissen, Christian Brecher

This report deals with the investigation of the influence of reverse loading on the tooth flank fracture load capacity. Due to the power density increase of gearboxes, gears are becoming more and more subject to interior fatigue, since the tribological system as well as the material in the surface zone have been optimized continuously in the past. Due to the optimization in the last years, tooth flank fractures and tooth interior fatigue fractures are increasingly occurring. This results from high stresses in combination with low strength in the tooth volume, where tooth flank fractures have their crack origin. The influence of reverse loading on the tooth flank fracture load capacity is currently only known to a limited extent in research work. Hence, the aim of this report is the investigation of the influence of the reverse loading on the tooth flank fracture load capacity. For this purpose, an FEbased tooth flank fracture load capacity calculation is extended in a way that a reverse load can be taken into account. Subsequently, a simulation study is carried out with the extended method, in which the load capacity as well as the location of the crack initiation for unidirectional and bidirectional loading are examined and compared. The simulation results predict a tooth flank fracture load capacity reduction for gears under bidirectional loading. Finally, the first experimental tests are carried out on a reverse bending test rig. The tests indicate that the calculated reduction in loadcarrying capacity under reverse loading can be validated.

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Calculation of the Scuffing Load Capacity of Spur Gears Using a Local Thermophysical Approach

Mathis Steinrötter, M.Sc., Dr.-Ing. Jaacob Vorgerd, Alexander Thomas, M. Sc., Prof. Dr.-Ing. Manuel Oehler

Current political efforts to realize global climate targets require efficient drive trains. Aspirations to maximize power density include increasing the drive speed and the use of lowviscosity lubricants. However, both parameters decrease the relative scuffing load capacity. Thus, scuffing represents a limiting factor in the design of highspeed gearboxes. The primary influence on the scuffing load capacity of cylindrical gears depends on tribological loads, lubricants and materials used. The flash temperature method is the stateoftheart calculation method for verifying scuffing load capacity.The calculation of the scuffing load capacity is based on speedindependent parameters, which are determined using the test methods in accordance with DIN ISO 146351 and DIN ISO 146352 at moderate pitch line velocities. The calculation method is only valid up to $v_t<50$ m/s, whereby current gearbox development trends exceed this limitation. Furthermore, the influence of the material and heat treatment on the allowable flash temperature is only empirically modelled in the standard calculation using a material factor X_W. The model transfer for estimating the potential of future material developments is therefore only possible to a limited extent due to the lack of physical references and limits technological progress.In this article, an alternative calculation method for the scuffing load capacity of highspeed cylindrical gears, considering the influence of the material which is based on its thermophysical properties is presented. Contrary to the temperature limits according to ISO 633620 and AGMA 925B22, a lubricantspecific curve is used. The permissible flash temperature depends on the diffusive properties of the local thermomechanical contact problem in the form of the PECLET number, which references the conductive material properties in relation to the convective heat input into the slidetoroll contact. This method can be used to evaluate the scuffing load carrying capacity especially for gears in highspeed applications.

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Design Method of System Tolerances in Cylindrical Gearboxes for Cost Efficient Optimization of the Excitation Behavior

Laurenz Roth M.Sc., Christian Westphal M.Sc., Prof. Dr.-Ing. Christian Brecher

The design of cylindrical gears is currently often carried out separately from the development of surrounding gearbox components. This applies in particular to the procedure for defining the tolerances. Mostly, experience is used when the tolerance limits of surrounding housing components, shaft shoulders, rolling bearing operating clearances or bores are defined. The definition of restrictive tolerance limits determines the appropriate manufacturing processes, that are suitable for achieving the tolerance requirements. That influences the total manufacturing costs. Due to the accumulating effect of the system tolerance chain, various types of deviations of surrounding gear components affect the tooth contact conditions in different ways. The aim of the report is to develop a method that enables a tolerance design for various types of deviations within a gearbox with cylindrical gears. It takes into account the tolerance’s relevance for the noise excitation of the gears and the manufacturing costs resulting from the individual manufacturing requirement.A geometric substitute model is used to project deviations of surrounding gear components in the tooth contact. This is followed by a variant calculation in a finite elementbased tooth contact analysis, taking into account tooth flank and profile deviations. The transmission error is calculated as output value. The deviation parameters as input values are used together with the output values to train a metamodel for reduction of calculation time. A closedloop optimization process is implemented, which uses the metamodel and modifies the tolerances based on cost deviation functions for manufacturing processes and the sensitivity towards the transmission error. The output of the method are tolerance limits for the analyzed geometry characteristics, which are determined based on their relevance for the gear excitation and based on minimized manufacturing costs. Thereby, the costeffectiveness of the entire gearbox can be optimized early in the design stage and unnecessary manufacturing accuracy is avoided.

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24FTM10	978-1-64353-178-6	24

Gearbox NVH Analysis – An Engineering Approach for Practical Gearbox NVH Investigations

Dipl.- Ing. Timo Giese, M.Eng. Simon Schneider, Dr. Davide Marano

In the landscape of gearbox engineering, the enhancement of acoustic comfort has become a critical design aspect and has made computational models and simulations increasingly important. These tools are critical for accurately predicting and improving noise, vibration and harshness (NVH) performance. However, a thorough acoustic evaluation of gearboxes requires an approach, that extensively includes experimental data to validate the structural, the dynamic and the acoustic characteristics of the adopted computational model. This paper presents an engineeringbased approach for the numerical investigation of gearbox NVH performance. Initially, a Numerical and Experimental Modal Analysis (NMA/EMA) are performed to validate the natural frequencies of the structural components. Experimental modal data are evaluated against numerical data adopting the Modal Assurance Criterion (MAC), to ensure all the relevant system modes of the computational model are compared with the measurements of multiple accelerometers across the gearbox surface. Modeling guidelines for a simplified representation of housing bolted connections are then derived, based on the NMA/EMA analysis.

Subsequently, a flexible multibody model of the gearbox is developed, adopting modal reduction techniques (CraigBampton) and an advanced mathematical formulation of gear and bearing contacts. To validate the dynamic component characteristics, dynamic simulations are conducted and compared with measurement data. Finally, a time domain boundary element method (TDBEM) approach is adopted for the numerical acoustic analysis of dynamic operating conditions.

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Electric vs. Combustion: A Comparative Analysis of Gear Design for Commercial Vehicle Applications

Soniya Lahoti, Sahil Chawla, Hareesh Kurup, Carlos H. Wink

The automotive industry has seen a significant shift from Internal Combustion Engines (ICE) to Electric Vehicles (EV) over the past decade, primarily in passenger cars. Compared to that the commercial vehicle sector is now beginning to explore EVs. Unlike passenger cars, commercial vehicles demand high torque and low speeds. Trying to achieve this through a direct motor drive calls for the use of a very heavy motor with high torque and low speed specifications which is not good for overall vehicle efficiency and not cost effective as well. System analysis shows that a gear reduction unit between the motor and rear axle can reduce motor weight and improve overall efficiency. However, this requires a different gear design approach from conventional ICE gearboxes. These gears run at higher speeds and are prone to issues like severe pitting, micropitting, scuffing, power loss, and gear whine. This paper explores the design of gears for commercial EV applications, compares it with conventional ICE gear design, and identifies critical parameters for risk mitigation and improved Noise, Vibration and Harshness performance.

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Analytical Calculation of the Gear Body Stiffness of Face Gears

Jonas-Frederick Berger (b. Hochrein), Michael Otto, Karsten Stahl

Due to the constantly increasing requirements, more and more transmissions are being adapted and developed for their specific application. It is of paramount importance to optimally exploit the potential of the gears to meet the design objectives. Target criteria can be the NVH behavior and/or the maximum carrying capacity. To evaluate these objectives, it is crucial to know the load distribution in the meshing.The load distribution can be determined using numerical or analytical models. Despite the constant development of finite element contact simulation, analytical methods are still a subject of research and an important cornerstone in gear calculation, as they enable fast calculations. They are easy to use and allow different variants to be compared quickly. The basis of analytical tooth contact simulation (LTCA) is the accurate representation of tooth and gear body stiffness. The calculation of these has been sufficiently researched and validated for cylindrical gears. The approaches for calculating tooth stiffness can be used for angular gears as well. However, the wheel in this case does not have a cylindrical gear body. Instead, the gear body is like a flat circular disk. Available analytical methods for LTCA do not cover this special geometry. This poses a serious drawback in their applicability to angular gearboxes.This paper presents and discusses a novel approach to determine the wheel body stiffness for disklike gears based on an analytical calculation method. The partial deformation components are calculated using plate/disk formulations and the work integral is determined. Balancing with the external work results in the deformation in force direction, with which the gear body stiffness is finally derived slice by slice over the tooth width. The face gear drive serves as a demonstrator, whereby the approach can be transferred to other angular gears (e.g. bevel gears) without any difficulty.

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Design Alternative for a Helicopter Final Stage Planetary Gearbox, Introducing the Innovative Orbicular Gear Mechanism (OGM)

Mert Vardar, Gustavo Gattinoni, Uğur Çavga, Omer Mehmed, Fatih Erdoğan, Sammy Bouskour, Dr. Rhys Jones

Traditional planetary gear systems, featuring a central external sun gear encircled by planet gears and an internal ring gear, have size, weight, and load distribution limitations. A new orbicular gear mechanism (OGM) has been introduced and designed to replace the epicyclic planetary systems. The OGM includes at least two face gears, one as a sun gear and one as a ring gear, rotating around a central axis, with an external spur or helical planetary gear group connected to a carrier. The concept and the arrangements of the OGM are explained, and a case study of a Btype OGM for a finalstage helicopter gearbox has been designed and studied.

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Experimental Study on the Performance of Plastic Worm Gears

Borut Černe, Rok Kalister, Damijan Zorko

Worm gears are a common type of plastic gears, employed in several actuators, ranging through different industries, e.g., automotive, house appliances, medical. The motion transmission principle of worm gears enables very high transmission ratios in one single stage, which offers high power transmission density. Due to favorable tribological properties of plastic materials they can run in dry conditions for a short duration and under low load, while for transmitting higher powers and for longer operation they usually run in greaselubricated conditions. Despite the fact that plastic worm gears are very commonly used, there has been comparatively limited research done on their performance characteristics. Data on how different plastic materials perform in a worm gear transmission is almost nonexistent. The majority of applications are designed based on an empirical knowhow and by employing conservative methods leading to overdimensioning. This offers a great opportunity for further improvements of the design methods, enabling a much higher material utilization. The study provides a comprehensive overview of the stateofthe art models available for conducting design rating procedures of plastic worm gears. Corresponding to the design models, experimental methods are proposed, which can be used to characterize materials performance under specific load conditions which arise in worm gear pairs. Failure types are identified and conditions which lead to a certain failure mode are investigated. Material data generated by the proposed methodology can be employed in design calculation of newly designed worm gear pairs or during an optimization procedure of an existing one.

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Analysis of Tooth Bending Fatigue of AISI 9310 Gears Through Strain-Based Criteria

Lorenzo Pagliari, Lorenzo Fraccaroli, Lorenzo Maccioni, Franco Concli

When designing gears, the American Gear Manufacturers Association standards prescribe to carefully evaluate tooth bending fatigue, which represents one of the most common causes of gear failure. However, when cyclic loadings induce multiaxial states of stress, the analysis of the fatigue behavior of gears becomes particularly challenging and requires the employment of advanced multiaxial fatigue criteria. The goal of this paper is to evaluate the accuracy of several multiaxial fatigue criteria based on strains, when employed to predict the highcycle fatigue life of gears. This is not how strainbased criteria are typically used. They are mainly employed to predict lowcycle fatigue lives, since they can take plasticity into account, while the highcycle fatigue analysis is usually left to stressbased criteria. However, strainbased criteria are theoretically applicable also for highcycle fatigue conditions. This paper aims to assess their applicability in this field. Specifically, four different criteria based on the theory of critical plane were investigated. Such type of models was chosen because not only they can estimate the level of damage, but they can also predict the direction of crack propagation right after initiation. Data of previous experimental work on AISI 9310 spur gears using the single tooth bending method to achieve crack initiation was considered. Stress and strain tensors developed during the tests were calculated through a finite element model. Subsequently, they were numerically processed employing the selected strainbased criteria. Multiple fatigue life predictions and multiple crack initiation orientations were obtained. By comparing the experimental and the numerical outcomes, it is observed that the accuracy of the tested strainbased criteria varies depending on the principle at their basis. Results show that they represent an alternative prediction tool of theoretical general applicability, which encompasses all fatigue ranges.

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Bending Fatigue Strength of Gear Steels for Automotive Electric Drive Units

Christopher Aylott, Moorthy Vaidhianathasamy, Brian Shaw

Bending fatigue tests were conducted on spur gears manufactured from three commercially available carburizing steels; 20MnCr5, Ovako 236Q and Ovako 158Q (20NiMo97F). The purpose of the testing was to support the development of gearing for future automotive electric drive units which requires increased power density, efficiency and reliability. 20MnCr5 is currently used in such applications and was therefore selected as the baseline steel. Ovako 236Q is an ultraclean variant of the baseline steel that was selected to investigate the effect of inclusion content and Ovako 158Q is an ultraclean steel specifically designed to inhibit the formation of intergranular oxidation during gas carburizing that was selected to determine if increased bending fatigue performance could be achieved without the need for root grinding and/or shot peening. The uplifts in bending fatigue strength that could potentially be achieved using root grinding and/or duplex shot peening were also investigated for each grade of steel.This paper presents the bending fatigue SN curves established for each steel and surface condition tested along with the results of the accompanying metallography, microhardness measurements, residual stress measurements and fractographic analysis. The 2 candidate steels gave a 20 to 29% uplift in mean strength and superior finite life fatigue performance to 20MnCr5 in the carburized condition thus demonstrating that gains could potentially be made without the need for subsequent root grinding or shot peening. Both candidate steels gave improved finite life performance and/or increased mean strength relative to 20MnCr5 in the duplex shot peened and root ground conditions indicating that notable gains could also be made through alternative steel selection. The test work outlined in this paper has therefore shown the ability for alternative steel selection to either achieve increased power density or decrease cost through reduction of manufacturing stages.

Document		ISBN	Pages
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A Preliminary Study on a Novel Procedure for the Assessment of Fatigue Performance of PA6 Polymer Gears

Riccardo Longato, Matteo Autiero, Marco Cirelli, Pier Paolo Valentini

In recent times, plastic gears have gained increased attraction in many fields of application, varying from automotive to medical devices. Their low cost, ease of production, and lightweight are some of the qualities that make this solution viable for such applications. But, along with these merits, the polymer gears hide tackling engineering challenges like strength assessment, tolerances and dimension control and the effect of operating temperature on the performance. Among these, the forecast of bending fatigue life is one of the more troublesome to deal with. Regarding this aspect, VDI standard 2736 Part IV provides extremely valid suggestions and procedures for the statistical evaluation of fatigue. In the present study, experimental tests are conducted in accordance with the standard for both procedures and equipment, but a new procedure is conceptualised for the evaluation of plastic gears. For the test setup, the gears are installed in a climate chamber to achieve the correct temperature test control. With an infrared camera and temperature feedback software, the temperature is set at 30°C. From the triplet σFlimNi (fatigue strength) Ni (number of cycles) θi (temperature) data for each performed test, it is possible to determine a point on the temperaturedependent Wöhler curve. From this curve, the novel approach consists in the forecast of time to failure assuming a Weibull fault distribution. The results obtained are compared with the standard VDI 2736 approach.

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Durability and Performance Rating Procedures for Plastic Spur Gears

Damijan Zorko, Rok Kalister, Borut Černe

High performance plastic gears are increasingly replacing metal gears in several applications due to many advantages. The main ones being lower weight, no need for lubrication, cheaper mass production, significantly better noise, vibration and harshness (NVH) behavior and chemical/corrosion resistance. Naturally, they exhibit also some drawbacks against metal gears, e.g. lower load bearing capacity, thermal sensitivity and inferior manufacturing tolerances. Plastic gears are mainly produced by injection molding, which enables great design flexibility, e.g. joining several machine elements into one molded part. Thermal overload, fatigue and wear are the most common failure modes for plastic spur gears. To ensure a reliable operation of the gearbox each gear needs to be appropriately designed in order to avoid failure within the required lifespan and operating conditions. There is currently no international standard available for the mechanical design of plastic gears. The most uptodate and comprehensive tools are the German guideline VDI 2736 and Japanese standard JIS B 1759, which provide the design procedures and control models for all common failure modes. While the proposed procedures are feasible, the problem arises as each control model requires some gearspecific and experimentally determined material data, to which the calculated values are compared. Fatigue rating is conducted by comparing the calculated stress to a material's fatigue limit, for wear prediction the wear factors are required and for calculating the operating temperature a good assessment on the coefficient of friction is required. A significant lack of required material data is the major drawback which is preventing a larger adoption of plastic gears. The study provides a comprehensive overview of the stateofthe art models employed for rating the thermal, fatigue and wear failure modes, outlining their shortcomings and proposing several improvements to the models. Furthermore experimental methods are presented, which can be employed to characterize the gearspecific material data required during the rating procedures on individual failure modes

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The Role of In-Situ Techniques in Microstructure Optimization of Interstitially Alloyed Steels

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Microstructure optimization of steel for improved performance requires detailed knowledge of the thermal response of the materials. When designing heat treatments of new materials insitu information about, for example, phase transformation, is pivotal. In this work, the use of two complimentary techniques for insitu monitoring of thermal behavior of carbon and nitrogen containing steels, i.e., dilatometry and combined calorimetry and thermogravimetry is presented. To illustrate the importance of insitu techniques for understanding materials behavior, 3 different examples are presented. The examples presented are 1) high carbon martensitic (stainless) steel overspray powders for additive manufacturing; 2) high temperature solution nitriding and the role of nitrogen on microstructure in conventional martensitic stainless steel; and 3) additively manufactured 174PH martensitic stainless steel and the role of nitrogen. It shows how insitu techniques can be applied to record the heat treatment response of these generically different special materials. It is also emphasized how nitrogen can be actively used in steels, which can pave the way for more widespread use of nitrogen containing steels. In addition to insitu techniques, light optical microscopy and Xray diffraction analysis are used for characterization.

Document	ISBN	Pages
23FTM21	978-1-64353-166-3	9

Numerical Approach to Account for Actual Tooth Root Geometry

Burkhard Pinnekamp, Michael Heider, Andreas Beinstingel, Maximilian Fromberger, Michael Keller

Various numerical methods have been suggested for validation of tooth root bending strength. In these approaches, it has always been a challenge to consider local strength – as determined by hardness and residual stresses – in numerical calculations. Therefore, the analytical approaches as described in standards such as ISO 6336-3 prevail in gear rating. This standard, however, does not consider typical or even less typical deviations or variants in the actual tooth root geometry.Geometrical deviations in the form of grinding notches occur due to lack of or insufficient protuberance. In this case, the individual result may have little, moderate or even a significant negative impact on the bending strength. Tooth root geometry may also be different from the shape as described in ISO 6336-3 as generated by form grinding or 5-axes-milling.If carried out with caution, these variants obviously do not cause a significant loss in load carrying capacity but are not fully covered by the analytic calculation methods. The presented approach for external cylindrical gears combines the well-established ISO 6336-3 method with a numerical add-on to identify and consider the additional influence of the actual tooth root geometry. The additional stress concentration in the area of the 30-degree tangent is described as a reduction of safety against tooth root breakage.

Document	ISBN	Pages
23FTM20	978-1-64353-165-6	16

Flexible Planet Pins for High Torque Epicyclic Gears: Experience with Design, Manufacturing and Application

Hanspeter Dinner

For a wind turbine main gearbox (MGB) of the 3MW class, the planetary type low-speed stage (LSS) was designed with five planets and the planet carrier was designed as a single sided carrier. To avoid planet tilting, the planets were supported on flexible planet pins (Flexpin). The Flexpin was optimized, analyzed and tested beyond the prior known state of the art. Objective of the optimization was lowest stiffness at acceptable stress level resulting in the best possible load distribution in the LSS.For this, different shapes for a Flexpin pin were compared and an optimized geometry was found by parameter variation. The resulting pin geometry combines a low stiffness with acceptable stress levels. The deformation behavior and resulting stress state were determined first using a simple beam model and compared to 3D FEM analysis results. The latter was required to consider the influence of the press fit between Flexpin and planetary carrier and between the pin and sleeve of the Flexpin.A spring-based model was established representing the planetary stage with the five. Manufacturing and position tolerances as well as the Flexpin, bearing and gear mesh stiffness are considered. 20 different, random tolerance distributions were created and the load distribution among the five planets was calculated. Due to the low stiffness of the Flexpin, low values for Kγ at Kγ = 1.10 to 1.15 resulted. On prototypes, fatigue tests were performed for a single Flexpin under full load for 1*10^6 load cycles, confirming the pin strength and displacement predictions. The assembled gearbox containing a set of five Flexpins, integrated into the drive train of Ming Yang SCD turbine, China designed by aerodyn GmbH, Germany was tested at the CWD of the RWTH Aachen, Germany. After temperature stability was achieved, full load test and bending load tests were run and the gearbox was inspected by DNV-GL and the author. The resulting tooth contact patterns (and other parameters) yielded the desired results, and the inspection could be successfully closed. Flexpin displacement was measured in situ, and load distribution factors were computed at Kγ = 1.12 (only torque applied to the drive train) and Kγ = 1.23 (torque and bending moment applied to the drive train). The measured values confirmed the assumptions and models used in the design process. In the meantime, several sizes (3MW and higher) and a considerable number of MGB are in operation without any known issues. Higher ratings are in the design phase.

Document	ISBN	Pages
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Determination of the AGMA J-factor for Internal Spur Gears

Alfonso Fuentes-Aznar, José I. Pedrero

The Geometry Factor for Bending Strength, J, also known as AGMA J-factor, is used to assess the tooth-root stress of spur and helical gear teeth. The Information Sheet AGMA 908-B89 presents a calculation method for the AGMA J-factor based on the Lewis' parabola and computes the stress concentration factor from the minimum curvature radius of the fillet trochoid. Although the presented basic gear geometry is valid for external and internal gears, it was stated that the method for the analytical determination of the AGMA J-factor was not appropriate for internal gears and it was beyond the scope of the Standard. By using the Lewis' method, the tooth section with maximum bending stress is calculated and the tooth-root stress determined. However, the modern definition of tooth-root stress considers other influences than pure bending, and therefore the Information Sheet AGMA 911-B21 suggests considering the highest total stress, including the compressive stress and the stress concentration at the considered section. In addition, the root-fillet trochoid is approximated to a circumference arc and the influence of the number of teeth and shift coefficient of the shaper is neglected.In this paper, the AGMA J-factor is calculated in four different ways by considering: (i) the maximum total stress and minimum curvature radius of the trochoid fillet, (ii) the maximum total stress and curvature radius at the corresponding tooth section, (iii) the maximum total stress and circular fillet, and (iv) the maximum total stress obtained from FEM analyses. Based on the comparison of the results of the mentioned four approaches, guidelines for the preparation of a proposal for the calculation of the AGMA J-factor for internal gears are provided. It has been demonstrated that for internal gears generated by a shaper, the number of teeth and the profile shift coefficient of the shaper influences the values of the J factor.

Document	ISBN	Pages
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Local Load Capacity Analysis for the Design of a Balanced Flank Modification for Cylindrical Gears According to Bevel Gear Procedures

Dennis Tazir, Frederik Mieth

In order to be able to carry out an optimal gear design with the aim of cost reduction and the careful handling of resources, load capacity is an important criterion for the evaluation of a gear. Standardized procedures, such as ISO 6336 for cylindrical gears and ISO 10300 for bevel gears, are widely used and established in the design and evaluation of gears. In such procedures, the gear meshing is simplified to a single reference point and a comparative stress is derived. This simplification is based on experience and validation, but the influence of flank modifications is only approximated via factors.Detailed flank modification design with consideration of all possible types of damage for bevel gears is only possible with the aid of local load capacity analyses. Depending on the load, the location of the maximum stress or damage can occur at different points on the tooth. When calculating load spectra, the minimum safety and the accumulated damage can be determined more precisely with local consideration of stresses, lubrication coefficients such as friction and film thickness, and geometry coefficients like sliding speeds. In addition, the local load distribution includes the interaction of the overall system with all of its components and their associated loads. For example, bearing stiffness and clearances, shaft bending and torsion, housing deformation, load-dependent center distance or gravity may be considered. This provides a more accurate picture of the stresses and quickly gives an overview of the possible resulting relevant damage forms.In this paper, the currently available local methods for bevel gears are applied to cylindrical gears. This will demonstrate the benefits of local methods and how they can assist in the design of flank modifications. To validate the accuracy of the calculation methods, a well-documented series of tests from the literature is recalculated and evaluated.

Document		ISBN	Pages
23FTM17		978-1-64353-162-5	19

Holistic Assessment of Drive Systems with Gears, Shafts and Bearings Using Measured Torque-Speed Data

Ulrich Kissling

Careful rating of drive systems is a critical task to prevent premature failure. Any failure is a very adverse event. Priority elements in a drive system are gears, but – for example in wind turbines – often bearings or shafts may be more critical. Calculation methods for lifetime evaluation given in ISO, AGMA, FKM use the S-N characteristics of the material (Woehler line), therefore with damage accumulation and a proper load spectrum the service life can be evaluated. On the other hand, for many drives measured torque-speed data exists - from test drives, from the field or from simulations. To be able to perform a rating, measured data must be converted into a load spectrum. The appropriate method to generate a load spectrum from a measurement varies between gears, bearings, and shafts. For gears the load on a single tooth must be extracted, then converted into a load spectrum with respect to the alternating stress obtained from torque-variation (21FTM07, Use of duty cycles or measured torque-time data with AGMA ratings). For bearings the speed-torque distribution over time is the determining effect for a correct lifetime evaluation. And for rotating shafts alternate bending and shearing stresses are combined with rarely varying torsional and axial stresses.In this paper the method discussed is how torque-speed data given at the input or output coupling of a drive system can be converted in a specific load spectrum for the rating of every gear mesh, bearing and shaft of the system. The procedure for a gear stage was presented in an earlier paper (21FTM07). So, the focus is on the adaptation to bearing calculations (ISO 281 and ISO 16281) and to shafts (FKM Guideline). In the final section, practical applications of the above method with a 3-stage-bevel/helical-gearbox and with a wind turbine is discussed.

23FTM16		978-1-64353-161-8	16

Virtual End of Line Test – Prediction of the Acoustic Behavior of Gearboxes Based on Topographic Deviations Using Neural Networks

Marius Willecke, Jens Brimmers, Christian Brecher

In the series production of gearboxes, most gearboxes are usually tested in an end-of-line test after assembly. Among other things, the noise of the gearbox is checked during such tests. A reason for an acoustical failure can be an unlucky combination of the manufacturing deviation of two meshing gears. If a gearbox appears faulty, it has to be disassembled again, which is labor and cost intensive. To reduce the number of gearboxes sorted out for acoustics reasons, the gearbox acoustic behavior can be simulated prior to its assembly. The simulation considers the specific deviated gears of the unit. This allows the detection of the combination of unfavorable manufacturing deviations. A simulation model domain, generally used to calculate the acoustic behavior of the whole gearbox, is an elastic multi body system model. This model type calculates the acoustic behavior in time domain to consider the nonlinear meshing behavior of gears and other components. The major challenge using this model type is the tremendous amount of calculation time needed to produce suitable results. That is why a method to predict the acoustic behavior of the gears faster than with the currently used simulation models is needed. Otherwise, the simulation cannot be performed in parallel to gearbox manufacturing. To achieve calculation speedup, the size of the mathematical problem is reduced by introducing the sum deviation surface as a generalization of gear topographies. It allows reducing the number of necessary input parameters for the new model. Using the sum deviation surface, variants within a given deviation space are calculated as training dataset. This dataset is utilized to develop a deep neural network model of the gearbox. The network then predicts the acoustic behavior of a whole gearbox based on the topography deviations faster than real-time. Prediction is verified by an independent test data set.

Document		ISBN	Pages
23FTM15		978-1-64353-160-1	28

Power Skiving Tool Offsets and the Feasibility of Using a Calculator for Manipulating the Resulting Geometry

Bethany Cousins, David Curtis, Michael Farmery, Ben Cook

Within this paper, the power skiving process of gear tooth machining was evaluated and developed with respect to cutting tool orientation. The impact of minor variations to the orientation of three factors related to the cutting tool were explored to determine the effect of cutting tool orientation on the output metrics of finished gear geometrical characteristics within the design space.The aim of the study was to use the knowledge gained to develop a statistical based model with the ability to predict how adjustments to the chosen three factors would affect the quality of the gear features produced. This would theoretically allow for tooling errors (or indeed other repeatable errors) to be counteracted through positional changes within the power skiving process based on the design space of the trials.The initial phase of the work utilized a Design of Experiments (DoE) methodology. This was used to assess the gear quality implications of alterations made to the three chosen factors related to the tool position when power skiving with tooling made to drawing specifications. The statistical-based model fit was formed of quadratic, interaction and independent coefficients analyzed to map responses in the gear. Following the experimental trial, the statistical model was reviewed and refined. Ahead of a validation trial, predictions were made to estimate the results of a final block within the DoE which proved the statistical model fit to possess a high level of predictive power.In most cases responses were within 10% of the predicted tolerance and all results were within 50%. This was extremely encouraging, and the work confirmed that a statistical based approach could be adopted to support future predictability of the process.

23FTM14		978-1-64353-159-5	16

Influence of Tooth Root Contour Deviations on the Tooth Bending Strength

Christian Eggert, Dieter Mevissen, Jens Brimmers, Christian Brecher

In order to meet the increasing demand for high-performance applications in the area of power density, new material alloys and heat treatment processes for gears are continuously developed and investigated. The investigation of various combinations of materials and heat treatments are usually carried out by the evaluation of S-N curves. However, when generating S N curves for the tooth bending strength, the influence of deviations in the area of the tooth root contour is often not considered and an identical tooth root contour is assumed for all investigated variants. An evaluation of the tooth quality of the test gears is usually only carried out for the area of the tooth flank by means of ISO 1328-1:2013 due to the lack of a uniform evaluation standard for the area of the tooth root. Accordingly, stress-increasing effects, such as changes in the tooth root radius due to deformations from heat treatments, are often not considered. Especially when investigating gears with an unground tooth root area, shape deviations from the heat treatment have a direct effect on the test results.Therefore, in this study, the influence of tooth contour deviations on the tooth bending strength is investigated using different combinations of heat treatments and material alloys. With the aid of a tactile precision measuring system, the tooth root contours of different combinations are measured. The tooth bending strength of the measured tooth root contours are evaluated using both FE-based and standard-based (ISO 6336-3:2019) stress calculations. Finally, the effect of considering the measured tooth root contours on the determination of the tooth bending strength is demonstrated by an experimental investigation of the measured test gears.

Document		ISBN	Pages
23FTM13		978-1-64353-158-8	13

Laser Material Processing for the Production of Bronze Coatings for Tribological Applications

Hannes Freisse, Timo Schudeleit, Dominik Keller

Bronze has proven itself as a highly functional material in tribological systems for numerous applications. The different bronze alloys offer an adaptation of the material properties to a wide range of loads. Bronze can be used as a solid material in the component or applied locally only as a functional layer in bi-metal components. The bi-metal components offer the combination of the advantages of the good mechanical properties of the steel base body with the very good tribological properties of the bronze alloy. In this paper, the production of coatings used in bi-metal bearings is presented by using laser deposition brazing. The details of the laser coating technology are presented, and the material properties of the bi-metal parts are analyzed.

23FTM12		978-1-64353-157-1	19

Experimental and Analytical Study of the Effect of Shot Peening on Gear Micropitting and Contact Fatigue Failure

Dalia Jbily, Luc Amar, André Simonneau

Gear Micropitting is a contact fatigue failure which mainly appears on teeth flanks of case-hardened gears. This initial failure can lead to larger cracks and eventually to macropitting or spalling which in turn can result in destructive failure. Tooth flank shot peening treatment has been used to increase the fatigue strength of components including gears but to our knowledge, its effect on micropitting has not yet been studied.A previous CETIM study based on a twin disc machine tests has demonstrated that an appropriate shot peening treatment after grinding could reduce the micropitting phenomenon.The aim of this paper is on one side to investigate the effect of shot peening on the gear micropitting and its development to macropitting and on the other side to compare the standardized calculation methods for the prediction of micropitting (ISO/TR 6336-22 :2018) and for pitting (ISO 6336-2:2019 & AGMA 2101 D04). The experimental study is carried out using a back-to-back gear test rig. The micropitting initiation and its propagation on the tooth flank was monitored via an interrupted test method. The fatigue tests are run until the appearance of macropitting. A comparison between experimental results obtained on tested gears and theoretical predictions of micropitting and pitting based on ISO and AGMA standards is presented.

Document		ISBN	Pages
23FTM11		978-1-64353-156-4	17

Tooth Flank Fracture – Investigations on the Influence of Overloads on the Fatigue Strength of Case-Hardened Gears

Sascha Rommel, Jochen Witzig, Thomas Tobie, Karsten Stahl

Tooth flank fracture (TFF) is a gear fatigue failure mode with a crack initiation in larger material depths. It has recently been observed more frequently, especially with larger gear dimensions, such as can be found e.g., in wind turbines and heavy industry applications. In the past, experimental investigations were performed by single load testing to determine the fatigue strength on the level of the endurance limit. However, for example in geared wind turbines, overloads occur due to wind gusts or emergency stops. Overloads can also occur in industrial gear units due to unforeseen impacts. This raises the question whether overloads do have an influence on the fatigue behavior of TFF. In this paper, the first test results with casehardened gears are shown in order to investigate the influence of overloads on TFF. For the experimental investigations, TFF critical test gears with a center distance of 200 mm made of two different casehardening steels (20MnCr5 and 18CrNiMo76) were considered. To investigate the influence of overloads, two stage tests were performed. The first stage represents the overload stage, which the level of the overload and the amount of load cycles was varied for. In the second stage, load levels in the range of the endurance limit were considered, which was determined beforehand. In addition to the experimental investigations, further investigations regarding microstructure, degree of cleanliness, hardness and residual stresses are presented. With these tests an initial assessment is given whether for TFF a damage line exists in SNcurves in comparison to other gear failure modes such as tooth root breakage or pitting. Based on the results that overloads have in fact an influence on TFF, further outlook is given on possible research on a systematic investigation.

23FTM10		978-1-64353-155-7	21

Wear Behavior of Polymeric Compound Measured on a New Test Rig for Plastic Gears

Riccardo Longato, Christine Hamon, Stefano Montani

The objective of this work was to validate a methodology to assess the performance of a polymer compound in gear application with a particular focus on the characterization of the wear behavior of the polymer compound during the gear test.This paper describes how the wear variation of gears made of Ixef® PARA material was determined and demonstrates how the test bench is necessary to characterize the plastic gears.A case study proposed by the Solvay company for a specific test is described and how the testing activity was carried out to validate the product.

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23FTM09	978-1-64353-154-0	17

Use of Gear Reliability Data in a Cloud-Based Gearbox Digital Twin Using Telematics Data

Barry James, Louis Long, Alberto Satine Gioiosa

Technological trends tend to attract convenient phrases whose usage ‘goes viral’, picking up more and more references across the world. In particular, the ‘Digital Twin’ is something that has been spoken about widely yet has rarely (if ever) been seen, for gearboxes at least.For sure, the ‘Design Twin’ exists – a simulation model of the gearbox used during the design process. However, this is simply Computer Aided Engineering (CAE) as practiced by engineers since the late 1980s. The real Digital Twin should exist alongside the physical asset in monitoring and informing about the health of the gearbox in service. In this respect, much has been said and promised about Digital Twins, but very little has actually been delivered. This paper describes one of the projects that Hexagon has completed on behalf of a handful of clients for the implementation of gearbox Digital Twins. These clients are all longstanding users of Hexagon’s software for gearbox simulation, Romax, and are globally recognized brands and cover a wide range of different ground vehicles. Telematic data is uploaded from the vehicles to the Cloud, where it is automatically processed by a simulation model of the gearbox which gives the same results as the model used to design the gearbox by the design engineers. Fatigue data is converted into predicted reliability data, which can be presented to drivers/operators/owners via apps on common mobile devices, along with recommendations to ‘maintain’ or ‘replace’. More detailed data analysis allows unparalleled insight into how the vehicles are being driven, especially regarding the variability of operation. The whole process runs without human intervention or interaction. However, the transition from fatigue damage to reliability is not without its complications. This paper studies the data sources from standards and published technical papers and identifies an enormous variation in implied performance of the gears. Practical difficulties in using such data are also identified. The likely source of this variation is discussed, and practical solutions proposed. In the round, this paper outlines the potential for Digital Twins in vehicle transmissions and shows that, despite the hype and broken promises of the past, practical implementations are working today and the future looks enormously promising.

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Non-Linear Analysis of Gear-Fatigue-Damage Under Variable Load

Daniel Vietze, Josef Pellkofer, Karsten Stahl

During operation, gears usually face variable loads and load sequences. For instance, the load of transmission gearing mainly depends on the input torque, which in many cases is inconstant. These variable loads have to be considered in the design process of gears to achieve an optimal dimensioning of their load carrying capacity.Standardized methods, like those presented within ISO 6336 or ANSI/AGMA 2101D04, factor in variable loads when calculating the service life. These methods all trace back to the linear approach published by Miner and Palmgren in the first half of the 20th century. While this approach considers variable loads, it does not take the load sequence into account. Even though this approach delivers good and useful results, research has shown that neglecting the load sequence is a potential issue. In reality, different load sequences can result in an immensely different service life, even though the same service life is to be expected according to the linear approach. Because of this fact, many socalled nonlinear approaches have been published. All these nonlinear methods take the load sequence into account but come with the tradeoff of a higher complexity. Today, the use of nonlinear methods is uncommon for geardesign and there is no validation for their suitability.In this paper, an extensive set of experimental data investigating the influence of different load sequences on the service life of gears is presented. The data derives from tooth root breakage tests conducted at the FZG. To evaluate the usefulness of nonlinear methods for the service life calculation of gears, the data is first analyzed with the linear approach to set a benchmark. In the next step, a nonlinear method is applied. Finally, the results of both approaches are compared to analyze if the use of the more complex nonlinear method for the servicelifecalculation of gears yields potential benefits.

Document		ISBN	Pages
23FTM07		978-1-64353-152-6	16

Advanced Distortion Control for Case Hardening of Transmission Components

Volker Heuer, David Bolton, Jochen Friedel, Orlando Garcia

In many applications, the high demands regarding fatigue properties of transmission components can be reached only by the application of a customized case hardening. This case hardening process results in a wear resistant surfacelayer in combination with a tough core.However, as a sideeffect the components get distorted during heat treatment. This distortion has a significant costimpact because distorted components need to be hardmachined after heat treatment. Therefore, the proper control of distortion and the variation of distortion is an important measure to minimize production costs. By applying the technology of Low Pressure Carburizing (LPC) and High Pressure Gas Quenching (HPGQ) heat treat distortion can be significantly reduced. Especially for Edrive components significant costsavings can be achieved compared to other processcombinations such as Atmospheric Carburizing with Oil Quenching.HPGQ provides a very uniform heat transfer coefficient. The predictability of movement during quenching is more certain and uniform throughout the load. Further improvements can be achieved by optimizing the gas quenching parameters. Proper fixturing is another factor for distortion control. Modern CFCmaterials (carbon reinforced carbon) are well suited as fixturematerial for gas quenching. When compared to traditional alloy CFC demonstrates no deflection or distortion after many subsequent years of use. This paper provides insight into distortion values of transmission components for various applications after optimizing process parameters and the design of heat treatment fixtures.

23FTM06		978-1-64353-151-9	24

Methodology to Evaluate the Bending and Contact Allowable Stress Numbers of Gear from Rotating Bending Database

Luc Amar, Michel Octrue, Guillaume Thoquenne, Simon Jolivet

Gears must verify a fatigue load capacity concerning tooth bending failure mode at the tooth root and contact pressure or hertzian fatigue failure mode on tooth flanks (called macropitting). Thus, current standards to evaluate load capacity of gears, such as ISO 6336, AGMA 2101 or DIN 3990, allow to compare the effective applied stress to the permissible stress provided by the tooth material and its associated heat and surface treatment.On the one hand, ISO 63365, AGMA 2101 or DIN 3990 standards give a database of bending and pitting allowable stress for several metallic materials (steels and cast irons) and associated heat treatment for a given number of cycles, evaluated with 1% of failure probability. The given fatigue limits are usually evaluated using gear specimens on a backtoback test bench (type FZG) for pitting and single tooth bending test (STBF) with a pulsator for bending. Alternatively, they can be also based on industrial experience from the field of application. Gear testing evaluation represents significant cost and duration, mainly for pitting since the flank loading frequency corresponds to the frequency of rotation of the gear which is lower than the frequency range that can be found on a pulsator (with hydraulic jack or resonance feature). On the other hand, fatigue limit characteristics of materials can be evaluated on generic standardized test (for example plane or rotating bending) with standardized testing devices and process where simpler and cheaper specimens than gears are used on simpler and cheaper to use means. Outside of the field of gear applications, numerous (standardized) databases for most structural mechanical requirements already exist. On this basis, several fatigue data are already accessible with a larger range of material than those covered in ISO 63365, AGMA 2101 or DIN 3990. By this way, it would be easier and cheaper to evaluate fatigue requirement on a new material. This paper presents a methodology which consists of the transposition of standardized generic fatigue characteristics in order to define allowable stress fatigue limit (σHlim and σFlim) of gears. After the development of the method, examples are given first in comparison by using it on ISO 63365 material fatigue limit database and then with fatigue test data developed at Cetim and NRIM. Limits and the recommendation for the application of this methodology are also presented. For now, this method is only validated with steels and cast iron.

Document	ISBN	Pages
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Influence of Precipitation Conditions on the Tooth Root and Pitting Load Carrying Capacity of Carbonitrided and Low Pressure Carburized Gears

Niklas Blech, Thomas Tobie, Karsten Stahl, Holger Surm, Matthias Steinbacher

Today, case hardening represents the standard heat treatment process for highly stressed gears. The microstructure in the surface layer of the gears generally consists primarily of martensite with a certain amount of retained austenite. In national and international standards, retained austenite contents of up to 25 to 30 vol. % are allowed with regard to optimum tooth root and tooth flank load carrying capacity. In addition, precipitations are tolerated only up to certain limits.In a research project between IWT Bremen and FZG, Technical University of Munich, the application and recommended ranges of the standards were deliberately exceeded in order to determine results on the gear load carrying capacity of material structures characterized by comparatively high contents of retained austenite on the one hand and with different carbide respectively carbonitride precipitations on the other. Different heat treatment processes were used. A selection of the experimental results is presented in this paper, with the focus on the results for the material 20MnCr5. In addition to varying the heat treatment, different blasting conditions were investigated.The variants with alternative surface layer structures show in some cases significantly increased load carrying capacity numbers compared to the gas carburized reference variant, although the surface hardness is significantly below typical values for case hardened surface layers. The paper evaluates the experimentally determined strength values in the context of the current state of knowledge and shows possible explanations for the increased lifetime of the alternative surface layer structures.

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Modeling Lubricant Flow and Thermal Response for Gears

Weixue Tian, Pinzhi Liu, Michael Blumenfeld, Ganta Naveen

Interactions between gear and lubricant are very important for understanding and predicting the efficiency and durability of a gearbox. This study investigates two aspects of lubrication related to gearboxes – lubricant flow due to rotating gears, as well as the hardware thermal response due to contact friction. The first part of the paper uses computational fluid dynamics (CFD) to investigate windage and churning loss of a simple gearbox. The results of this modeling provide visualization of lubricant flow and distribution inside the gearbox, as well as quantitative prediction of churning loss inside the gearbox. Lubricant properties affecting the churning loss are also discussed. The second part of the paper presents thermal modeling results of a MiniTraction Machine (MTM) test rig. We chose modeling MTM test rig as the foundational technology demonstration because it is wide availability for lubricant developer and ease of experimental validation for modeling.

Document		ISBN	Pages
23FTM03		978-1-64353-148-9	26

Particle-Based CFD Study of Lubrication in Power Transmission Systems Using Local Refinement Techniques

Benjamin Legrady

Lubrication in power transmission systems directly affects their longevity, efficiency, and overall proper functionality. Thus, constant developments are made in the industry to improve lubrication. To predict it for a gearbox, nowadays comprehensive CFD solutions are used. However, conventional meshbased CFD approaches, like the finite volume method (FVM), introduce limitations. They (i) require timeconsuming and computationally expensive meshing procedures and (ii) introduce large numerical errors for highly fractional lubricant flow simulations.The Smoothed Particle Hydrodynamics (SPH) approach overcomes these impediments due to its meshfree particlebased nature. Nevertheless, utilizing a single particle size introduces limitations when studying small geometric features e.g., gaps, channels, gear contact regions, and bearings, since they all affect the resulting lubrication efficiency. This drives the demand for locally refined particle sizes, which allow a more intricate study of the aforementioned areas of interest.This paper demonstrates how the application of local refinement on power transmission systems improves the prediction of lubrication at critical locations. First, a short review of the state of the art of SPHbased lubrication modelling in gearing applications and local refinement techniques is given. Moreover, a locally refined simulation of a power transmission system is conducted and loadindependent quantities like e.g., churning losses, general oil distribution and component wetting are analyzed. Eventually, the results are compared to experimental data.The abovepresented study lays out an alternative solution that aids the simplification of routinary and laborious tasks in gearbox design cycles.

23FTM02		978-1-64353-147-2	12

Cross-Correlation of Design Variables for Epicyclic Systems

Claudio Autore, Massimiliano Turci

The analysis of mechanical efficiency is becoming an increasingly important topic in the design analysis of gear drives. Automotive industry is looking for mechanical systems that are able to transmit maximum power with minimum weight and marked life; nevertheless the efficiency is a constantly growing topic: design must work together with efficiency study from the beginning. Taking into account weight and efficiency topic, the epicyclic gear train systems permit to achieve very high density power. In epicyclic systems, there are lot of variables that could be chosen by designers, even though it is awkward to have a clear picture from each effect in this global system. The method proposed in this study illustrates, studying a large number of variables, how to find optimal restraint system that meets different resistance requirements and geometrical limitations, studying all possible combinations. The general algorithm’s development and the process of selection of the epicyclic gears are at the heart of this investigation. Modern computers allow us to have multiobjective optimization with more realistic constraints; they can easily handle big data. This paper illustrates a practical case study of gear design optimization, in turn the design is constrained by geometric limitations; each proposal design is considered in term of resistance. The choices must all be integrated in a single loop to detect the best design compromise.The novelty of the article lies in the way of presenting the results: the results are listed in a matrix plot which is very helpful to notice cross correlations between design variables.

Document		ISBN	Pages
23FTM01		978-1-64353-146-5	13

How Many Speed Ratios for Electric Cars? One Example

Bernd-Robert Höhn, Yingying Zhang

The speed (min1) for electric motors are normally much higher than the speed of the wheels because high torque requires high weight. For a lightweight system and the required power, you need highspeed electric motors. Typically, transmissions with four gears are installed, and these without shifting.
For cars with smaller motor power (P < 200 kW) twospeedtransmission are proposed. Using these twospeed transmissions significantly improves both the efficiency and the driving range of batterypowered cars. The layout of such transmission will be introduced. For instance, we will explain a planetary transmission that uses an electromechanical shifting system, which eliminates the need for hydraulic pumps or valves and minimizes torque interruption.
The inertia of the motor will be used for the torque at outputshaft during the shifting process.

22SP1		978-1-64353-144-1	12

Noise Analysis for e-Drive Gears and In-Process Gear Inspection

Antoine Türich, Klaus Deininger

A new inspection concept developed by Gleason features a combination of double flank roll testing and laser scanning. With this new approach gear inspection now can be performed as fast as a typical hard finishing operation takes. As a result, 100% in-process inspection has become a reality, eliminating the need for statistical process evaluation. In addition, the measured data can be further evaluated concerning waviness in profile and/or lead allowing the evaluation of the noise behaviour. Hence, this new system allows an up to 100% in-process noise analysis prediction of the finished gear.
This new inspection concept has been integrated with a modern grinding machine and a fast and flexible automation system to create the Hard Finishing Cell including a Closed Loop correction system.

22FTM23		978-1-64353-143-4	21

Results of ISO/TS 6336-22 Evaluating Full Contact Zone

Robin Olson, David Talbot, Mark Michaud, Jonathan Keller, John Amendola, Sr.

ISO/TS 6336-22 (Calculation of micropitting load capacity) is the ISO technical specification containing a proposal for calculations of the risk of micropitting in gear sets. It assesses micropitting risk through a safety factor calculated as the minimum specific film thickness divided by a permissible specific film thickness. In a previous paper, the calculations were performed using the simplified method (Method B) that evaluates points on the path of contact. This was done for three gear sets that experienced micropitting in operation. A more accurate calculation for these cases (Method A) calculates the specific film thickness across the entire contact zone. This paper applies this Method to the case study from the previous paper. The results are compared to micropitting observed in operation.

Document	ISBN	Pages
22FTM22	978-1-64353-142-7	12

Test Rig for Crowned Spline-Joints with Optimized Surface Treatments Under Misaligned Conditions

Gerrit Hellenbrand, Dieter Mevissen, Jens Brimmers, Christian Brecher

Increasing the load capacity of spline-joints in shaft-gear connections, such as UHBR-aero-engines, leads to a lean and efficient design of the power train components. An approach for this is to apply optimized surface treatments, such as coatings and laser structuring, which can reduce the risk of upcoming wear and fatigue phenomena. To assess the potential of these surface treatments for spline-joints, tests under real working conditions need to be carried out. As the application is an UHBR-aero-engine gas turbine, component tests are not applicable in the application for economic reasons. Hence, a design for a test spline connection, as well as a test rig for investigations of the wear and fatigue behaviour of surface treated spline-joints are presented.

Document	ISBN	Pages
22FTM21	978-1-64353-141-0	11

Experimental Evaluation of Wind Turbine Gearbox Structural Models Using Fiber Optic Strain Sensors

Unai Gutierrez Santiago, Xabier López Fuentes, Alfredo Fernández Sisón, Henk Polinder, Jan-Willem van Wingerden

The rated power and size of wind turbines have grown considerably to reduce the cost of energy from wind. This has pushed gearbox manufacturers to introduce multiple technological innovations to boost the torque density of current designs. One of the critical challenges of next-generation gearbox designs is to optimize structural components and gears. Complex models are needed to predict the gearbox components' load-carrying capacity and fatigue life. These tools need to be verified through experimental evaluation. This study evaluates the structural calculation models used for a modern 6MW wind turbine gearbox through physical testing. The measurement system is composed of fifty-four fiber Bragg gratings. A good correlation between the structural models and the test results in a full-scale back-to-back test bench has been achieved.

Document	ISBN	Pages
22FTM20	978-1-64353-140-3	24

Enhanced Calculation Method for Tooth Flank Fracture Risk with Consideration of Tensile Residual Stresses in Larger Material Depths

Daniel Müller, Thomas Tobie, Karsten Stahl

Tooth flank fracture (TFF) is a gear fatigue failure mode, which is initiated in larger material depths beneath the active flank. Therefore, the residual stresses in larger material depths are decisive for TFF. In these larger material depths, the residual stress conditions are almost unknown up to now. This paper presents a calculation method to assess the residual stresses in gears. The calculated residual stress profiles also consider the existent tensile residual stresses in larger material depths. Based on these predicted residual stress profiles, calculation methods for TFF, including the standard calculation of ISO/TS 6336-4, were extended to consider not only compressive but also tensile residual stresses, which was not possible so far.

Document	ISBN	Pages
22FTM19	978-1-64353-139-7	20

Implementation of a Gear Health Monitoring System on a Power Recirculating Test Rig Using the Average Log Ratio (ALR) Algorithm

Matthew Wagner, William D. Mark, Aaron Isaacson

The ability to detect the onset of a gear system failure via accelerometer measurements is of interest in a research environment as well as in gear systems deployed in the field. An accelerometer based gear health monitoring system is described which was developed for use in a laboratory setting for monitoring power recirculating gear tests. Even angle resampling, time synchronous averaging (TSA), and average log ratio (ALR) algorithms are utilized to detect the onset of gear damage. A summary of these signal processing concepts is given, along with an overview of system hardware, signal processing workflow, and sample data.

Document	ISBN	Pages
22FTM18	978-1-64353-138-0	14

Unconventional Gear Profiles in Planetary Gearboxes

Anand Varadharajan, Pablo Lopez Garcia, Dirk Lefeber, Stein Crispel, Tom Verstraten, Bram Vanderborght

The efficiency of high ratio planetary gear trains (PGTs) is mainly constrained by the meshing efficiency of acting gears in each stage. Such gear wheels, predominantly with involute teeth profiles, work with a meshing efficiency of around 99%. Yet, the overall efficiency of the gearbox drops to even below 70% when gear ratios of a few hundred are exceeded. Unconventional gear profiles are capable of solving the efficiency issue in high ratio planetary gearboxes. A review of existing PGTs with unconventional profiles is discussed along with other possible gear profiles to increase efficiency. The existing unconventional gear profiles are found to have high transmission errors and are intolerant to manufacturing inaccuracies thereby requiring further research to improve them.

Document	ISBN	Pages
22FTM17	978-1-64353-137-3	17

A Decomposition of the Torsional Stiffness of a Worm Gearbox into Individual Components

Kevin Daubach, Manuel Oehler, Oliver Koch

In worm drive applications with precise transmission, the torsional stiffness of the worm gearbox is an important parameter for the positioning accuracy. The torsional stiffness is a result of elasticities from all gearbox components along the load path, which leads to various options for an optimization of the torsional stiffness within the design process of worm gearboxes. However, a targeted optimization with high effectiveness requires information about the distribution of displacements across the gearbox components. A modeling approach is presented to decompose the total angular displacement of worm gearbox shafts under load into individual components, by which sources with high displacement proportions can be identified as targets for the optimization. The distribution of displacement proportions is investigated for specific worm gearboxes.

Document	ISBN	Pages
22FTM16	978-1-64353-136-6	18

A Model for Considering Wheel Body Deformation in Tooth Contact Load Distribution

Benjamin Abert, Georg Hammerl

Gearbox wheel bodies are often designed and manufactured to maximize power density. Strategic use of recesses and bores can achieve significant weight savings in gears. However, wheel bodies are known to have an influence on the gear system. Many CAE tools use the Weber-Banaschek approach to determine the gear stiffness. This is a proven method that has been deemed sufficiently for the simulation of tooth contact. However, this approach uses a simplified consideration of the wheel body as an elastic half-space and cannot represent complex wheel bodies. This paper describes a calculation method which efficiently determines the stiffness of any wheel body geometry using statically reduced stiffness matrices from an FE model and links them to an analytical model of the tooth contact.

Document	ISBN	Pages
22FTM15	978-1-64353-135-9	18

On the Potential of High-Ratio Planetary Gearboxes for Next-Generation Robotics

Pablo Lopez Garcia, Anand Varadharajan, Stein Crispel, Dirk Lefeber, Tom Verstraten, Marcin Wikło, Georgios Vasileiou

On the eve of modern robotic devices leaving their protective safety fences to enter our homes and interact with us, the gearboxes used in the actuators that power these devices still face significant challenges. Modern collaborative robots, including cobots, exoskeletons, prostheses, or AGVs, place more demanding weight, efficiency, and affordability requirements on their gearboxes, which Cycloidal and Harmonic Drive technologies have difficulties fulfilling.This situation provides a highly dynamic field for engineering research. In this paper, we assess the potential of high-ratio planetary gearboxes for modern robotic applications, using an assessment framework to identify their main advantages and limitations, which we then analyze in further detail. The resulting insights indicate that compact planetary gearboxes may see a significant come-back in the next generation of robots.

Document	ISBN	Pages
22FTM14	978-1-64353-134-2	18

Investigations on the Tooth Root Bending Strength of Larger-Sized Induction Hardened Gears

Holger Cermak, Thomas Tobie, Karsten Stahl

Especially for larger-sized gears surface hardening is an economical and technological alternative to case hardening. Due to the necessary high case hardening depths required for larger case hardened gears and due to technological boundaries (e.g., heat treatment furnace size and heat treatment duration) typical surface hardening processes such as flame or induction hardening can exhibit their benefits for these parts. In the framework of this paper, the influence of induction hardening on the tooth root bending strength of larger-sized gears is investigated. Therefore, different variants of larger gears which were induction hardened gap-by-gap are compared. In order to gain a deep understanding, a systematical variation of the surface hardening depth, gear size (mn = 14 mm and 20 mm), and surface condition was carried out.

Document	ISBN	Pages
22FTM13	978-1-64353-133-5	21

Effect of Tooth Root Fillet Design on Tooth Root Stress in Short Fiber Reinforced Plastic Gears

Wassiem Kassem, Manuel Oehler, Oliver Koch

The geometry of plastic gears is usually based on conventional steel gears, which are bound to the restrictions of the machining production of gears. The injection molding process provides more design freedom here. In this work, simulative results in terms of tooth root stress in plastic gears with various tooth root fillet designs are shown. The simulation method is based on finite element analysis and takes into account the different fiber orientation as well as the complex material behavior of short fiber reinforced plastics.The analysis includes fully rounded, elliptical and bionic tooth root fillets. In addition to the tooth root stress in the initial state, results are also presented for the geometry changed by wear during operation.

Document	ISBN	Pages
22FTM12	978-1-64353-132-8	18

Modern Green and Hard Machining of Double Helical Gears

Andreas Mehr, Oliver Winkel, Scott L. Yoders

Green machining of double helical gears can be realized by multi-axis milling, form milling, hobbing and gear shaping. The advantages and the limits of each single gear cutting method is presented in this article. Especially the multi-axis milling and the gear shaping allow the manufacturing of herringbone gears (no gap between the two helical gears), too. For the hard machining, the focus is on the multi-axis milling and generating grinding with small diameter grinding worms. The latest developments on the grinding abrasives and the machine tool enable the continuous generating grinding to become a real alternative to the established profile grinding of double helical gears.

Document	ISBN	Pages
22FTM11	978-1-64353-131-1	16

Closed Loop for Gears: Some Case Studies

Massimiliano Turci, Vincenzo Solimine

The steps to realize good gears are design, manufacturing, measurement, and test. Each step has effect on the next one, and the last one turns back on the first one, and so on. This workflow is valid in several application, from gearboxes with zero-backlash, to automotive transmissions and industrial gearboxes for lifting in offshore application. This workflow is called “closed loop”The paper will present some cases for bevel, cylindrical and worm gears:-exchange of information between design dept. and quality control to compare designed, estimated and realized microgeometry and LTCA-generation of K-Charts for the drawings that can be modified by the designer in case of exceptions for not respected but acceptable requirements, -estimation of the twist due to manufacturing process.

Document		ISBN	Pages
22FTM10		978-1-64353-130-4	17

Mathematical Model of a Straight Bevel Gear on the Straight Bevel Coniflex Generator and Gear Flank Correction

Yi-Pei Shih, Yu-Cheng Hung, Bor-Tyng Sheen, Szu-Hung Chen, Kuan-Heng Lin

Coniflex cutting, a popular mass production method for straight bevel gears, employs two giant interlocked circular cutters to generate tooth surfaces. By controlling the tool pressure angle, Coniflex cutting enables profile and lengthwise crownings that result in advantageously low assembly sensibility. This paper proposes a mathematical model of a Coniflex bevel gear produced on a dedicated machine, whose coordinate systems between cutters and work gear are empirically well-defined. Once the tooth surface is derived from coordinate transformation and gear enveloping theory, ease off and tooth contact analysis can be conducted numerically; after which flank correction is achieved using sensitivity analysis and optimization methods. Both the proposed model and the flank correction are validated using cutting experiments on a straight bevel Coniflex generator No. 104.

22FTM09		978-1-64353-129-8	20

A New Low Pressure Carburizing Solution in a Pit vs. Traditional Pit Carburizing Methods

Thomas Hart

Pit LPC is a new and revolutionary furnace system that is a drop in replacement for traditional atmosphere pit carburizing solutions. This approach can handle the same large and/or long loads with deep ECD while reducing the process time and utility costs. These benefits drastically increase a ROI when converting from atmosphere carburizing to LPC while eliminating carbon emissions associated with gas carburizing.

22FTM07		978-1-64353-127-4	13

Finding the Right Task for Optical Gear Metrology

Markus Finkeldey, Christof Gorgels

Optical metrology is an established technology in the coordinate measurement community, with a growing impact on the specialized field of gear metrology. The idea of a contactless and thus fast technology for quality control is promising. Nevertheless, every new technology raises questions: How to use this technology and what are meaningful use cases? Looking deeply into the field of optics evokes even more questions: What kind of optical technologies do exist, what is the adequate technology for your application and do I need a special sample preparation? This paper provides a quick overview about optical metrology for gear analysis and provides some field results of optical gear measurements. The results are focused on gears for automotive applications, especially for the expanding area of electric drivelines.

Document	ISBN	Pages
22FTM06	978-1-64353-126-7	12

Methods for Checking the Profile of the Path of Contact of Involute Gears

Zhaoyao Shi, Yanqiang Sun, Haobin Li

The profile of path of contact (PPC) is another significant characteristic curve beside involute and helix. During the gear generating machining, this line is consistent with machining curve. During the gear transmission, this line is also consistent with working curve. Therefore, the quality of gear machining and transmission can be reflected by the PPC. However, the existing gear measuring instruments cannot measure it. The theoretical model is given combining the forming principle of PPC. Based on the existing GMC, two methods for measuring the deviation of PPC are proposed, including the four-axis method and the three-axis method. In measurement methods, the measurement of PPC and involute profile is unified. The measurement practice shows that the measurement and evaluation of PPC can be conveniently realized.

Document	ISBN	Pages
22FTM05	978-1-64353-125-0	16

In Process Measurement and Compensation for Manufacturing Skiving Cutters

Stephen Williams, Xiaoyu Wang

Carbide skiving cutters present new challenges for manufacturing. We have developed two complementary methods to address this. Firstly: we have developed a grinding path compensation, allowing flank errors to be corrected, without altering the wheel profile. Secondly: we developed an in-process flank profile measurement procedure, using an analogue probe, which calculates the reference geometry for the flank profile, and graphs the measured deviations. For an involute reference curve, the measurement result will be directly comparable to a traditional gear measuring machine report. However, for complex geometries we can assess whether the ground flanks match the intended design directly, without referring to complex geometric design details. One can then see what compensation should be applied for the desired outcome, without removing the cutter from the machine.

Document	ISBN	Pages
22FTM04	978-1-64353-124-3	14

Optimizing the Operational Behavior of Double Helical Gears by Means of an FE-Based Tooth Contact Analysis

Alexander Mann, Jens Brimmers, Christian Brecher

Double helical gears are becoming increasingly relevant, especially in the fields of drive technology. Interaction effects between the two halves of the gear are becoming increasingly important to ensure low-noise operation. In the current state of the art design processes the interactions between the individual gear meshes of the left and right half are neglected.This paper, therefore, presents a method for considering the quasi-static stiffness behavior of double helical gears for gear design by using an FE-based approach. The developed method is validated by means of experimental studies. The validated method allows to derive design and tolerance recommendations for double helical gears in order to optimize the excitation behavior.

Document		ISBN	Pages
22FTM03		978-1-64353-123-6	10

Aspects of Gear Noise, Quality, and Manufacturing Technologies for Electro Mobility

Hartmuth Müller, Christof Gorgels

This paper explains the formation of transmission noise and the basic cause being the tooth mesh excitation of gears. For detecting the excitation, metrological and functional methods are presented. The paper shows mathematical principles describing the tooth mesh. Beside physical properties, psychoacoustic metrics rating the hearing experience are introduced. Methods for influencing the tooth mesh and the derived rating are presented in the field of macro geometric design and flank form modifications as well as flank surface modulation.

22FTM02		978-1-64353-122-9	14

Mechanical Power Loss of Spur Gears Subject to Various Surface Finish Pairings

Isaac Hong, Emily Aneshansley, David Talbot

Heat generation due to friction at the gear contact interface is a parasitic energy loss and may require designers to include active cooling systems further decreasing the net usable energy. It is known that changing the surface roughness of the mating gear flanks influences friction in the contact. Presenting different surface finishes to the contact directly influences the amount of asperity interaction. Gear designers and manufacturers must carefully balance costs associated with surface finishing processes while achieving target goals for transmission design. This study utilizes a closed form model to predict friction in mixed lubrication contact conditions as well as gear mechanical power loss under a wide variety of surface finish pairings for several operating conditions consistent with automotive applications.

22FTM01		978-1-64353-121-2	16

Development of a New Test Method to Investigate the Scuffing Load Carrying Capacity of Hypoid Gear Oils

Alexander Drechsel, Josef Pellkofer, Karsten Stahl

Highly loaded hypoid gears exhibit an unfavorable combination of high sliding velocities and high contact stresses in tooth contact with regard to the failure mode scuffing. Beyond the loads and speeds that occur during gear operation, the lubricant used and its additives have a significant influence on scuffing load capacity. Since it is generally impossible to determine the influence of the lubricant on the load carrying capacity of gears on the basis of physical or chemical oil data alone, experimental test methods are necessary. An experimental test method was developed based on theoretical investigations. In order to achieve a reproducible test procedure, a running-in procedure was specified based on the results of experimental investigations on a hypoid back-to-back test rig.

Document	ISBN	Pages
21FTM20	978-1-64353-114-4	12

4D Quench – Taking Aerospace to New Heights

Thomas Hart

When providing heat treatment for aerospace gears and bearing components, manufacturers are traditionally left with three choices for thermal processing: continuous flow atmospheric furnaces with press quenching in oil, or batch heat treatment in both vacuum and atmospheric furnaces with quenching in oil (or high-pressure gas, as in vacuum). All three techniques differ in benefits and disadvantages associated with geometric distortion, environmental impact and safety concerns.A single-piece flow (SPF) vacuum heat treatment furnace with the capability to provide high pressure contour gas quenching to a single piece or “4D Quench” (4DQ) provides continuous flow heat treatment with low geometric distortion, environmental impact and personal safety concerns. This system has the flexibility of operating in a batch style work cell or it can be sized up and inserted in a continuous work cell, operating without human interference. 4DQ technology equals the speed of an oil quench and the cooling gas nozzle profile can be optimized based on actual part geometry. By controlling the direction of the cooling gas spray with part rotation, manufacturers now have the ability to control how fast or slow a part section cools providing a better quench. With this improved uniformity, larger and previously pressed quenched parts can now be processed in a 4DQ system.SPF vacuum heat treating system will thermally process and quench every part the same way, in the same position, with the same timing, one by one. All components undergo the same process parameters, producing consistent and high-quality results for an entire part series. With SPF vacuum heat treatment, aerospace gear and bearing manufacturers can safely and environmentally friendly output identically processed and uniform components while reducing geometric distortion of their heat-treated components. This paper will also summarize a half decade’s worth of research associated to SPF with 4DQ Vacuum Heat Treatment.

Document	ISBN	Pages
21FTM19	978-1-64353-113-7	22

Tooth Root Bending Strength of Shot-Peened Gears Made of High-Purity Steels up to the VHCF Range

Daniel Fuchs, Thomas Tobie, and Karsten Stahl

The load capacity calculations for gears according to standardized methods, like AGMA 2001-D04 or ISO 6336, are intentionally conservative to ensure broad applicability in industrial practice. However, due to new applications and higher requirements, more detailed design calculations are nowadays often necessary in order to use possible strength potentials. For example, in wind power gearboxes long operating lives are necessary and in e-mobility applications, due to fewer gear stages and higher speeds at the electric motor, there are higher load cycles per tooth. Hence, higher tooth flank and root load carrying capacities up to the very high cycle fatigue (VHCF) range are desired for gears. To achieve a higher bending strength in the tooth root area of gears, one approach is to induce increased compressive residual stresses into the stressed area, e.g. by a shot-peening process. The drawback is that often there is a change in the crack mechanism. Crack initiation can now occur at non-metallic inclusions in the steel matrix.For that reason, the working hypothesis of this publication is: the higher the cleanliness the fewer the non-metallic inclusions in the material and therefore the higher the tooth root capacity of case-hardened, shot-peened gears. This working hypothesis is verified with tests on FZG back-to-back test rigs up to the very high cycle fatigue (VHCF) range. The test gear variants were manufactured from steels with different degrees of cleanliness. The gears were also examined metallographically, with a special focus on the residual stress state in the tooth root area. As a result, it could be shown that with a higher degree of cleanliness, higher tooth root load carrying capacities up to a higher number of load cycles are possible even taking the different crack mechanism into account.

Document	ISBN	Pages
21FTM18	978-1-64353-112-0	18

Enhanced Distortion Control – ISO Class 8 Gears After Case Hardening

Volker Heuer, David Bolton, Jochen Friedel

Controlling distortion during the case-hardening process is of key importance when manufacturing gears. By effective control of distortion and the variation of distortion, significant costs in post heat treatment machining processes can be avoided. Especially for E-drive gears such as Internal Ring gears or Final Drive Ring gears significant cost-savings can be achieved.If distortion is controlled in such manner that ISO class 8 is guaranteed after case hardening, the grinding operation gets obsolete, and parts may be honed only.The combination of Low-Pressure Carburizing (LPC) and High-Pressure Gas Quenching (HPGQ) offers the potential to provide better control of distortion compared to other process-combinations such as Atmospheric Carburizing with Oil Quenching.This paper analyses distortion values of gear components from a planetary set of a six-speed automatic transmission over a long period of time. The gears were analyzed in terms of circularity, helix average and helix variation. It is demonstrated that distortion data stays stable and predictable even over a long period of time when applying optimized heat treatment process parameters and if the process-steps in the manufacturing chain before heat treatment are frozen and robust.When combining this heat treatment technology with appropriate geometrical inspection, this will result in guaranteed ISO class 8 geometry after heat treatment.The paper gives directions how this goal can be achieved by combining an advanced heat treatment process with advanced gear inspection technology.

Document	ISBN	Pages
21FTM17	978-1-64353-111-3	21

Holistic Evaluation of Involute Gears

Anita Przyklenk, Martin Stein, Tom Reavie, Robert Frazer

The geometry measurement of involute gears is a key step within modelling, manufacturing, and performance evaluation to assure the delivery of high performance and cost-effective gears and gearboxes. Current challenges in manufacturing metrology can be summarized in five keywords: fast, accurate, reliable, flexible, and holistic. Moreover, modern non-generative production methods such as five-axis milling may need different inspection strategies for reliable quality assurance.Standardized strategies refer to the most relevant 2D-sections, single helix, and profile line inspection, which has been state of the art for many decades. These methods are still relevant and continue to deliver high performance gears, but other options are becoming available. Modern coordinate metrology systems such as CMMs or GMMs gather holistic information about dimension and surface form of gears with high point density and accuracy in a short time. Currently, however, we do not know how to use this holistic information.This paper introduces a 3D evaluation strategy for cylindrical involute gears used at Physikalisch-Technische Bundesanstalt. The focus is on describing the holistic evaluation of synthetic and measured data. Considering the complete gear surface in one common model allows us to a) determine deviations along the whole flank, b) obtain more relevant and stable geometrical fitting parameters, c) find correlations between gear fitting parameters and d) properly understand possible manufacturing errors.The paper also shows how Newcastle University’s Design Unit used holistic evaluated data to investigate gear surface harmonic analysis methods. Harmonic analysis of 2D profile and helix measurement data is routinely used by some industries to control gear noise and characterize machine tool performance, but the evaluation of 3D surface measurement data has not been investigated. A review of some candidate methods using synthetic and measured data is presented and some of the challenges interpreting the results is discussed.

Document	ISBN	Pages
21FTM16	978-1-64353-110-6	11

An Accurate Method of Generating Tool Paths for Helical Gears with Crowning Modifications Using a 5-axis CNC Machine

Fei Shen, Luis Vega, Mohammadrafi Marandi, Christoph Kossack, Joshua Tarbutton, Gert Goch

To manufacture gears, special machine tools and corresponding processes, such as hobbing, shaping, planing, profile milling, and broaching, are usually needed. However, the huge investment in such gear machining is prohibitive for manufacturers, which only produce the gears in small batches on an annual basis. To overcome this economic problem in the manufacturing of gears, standard 5-axis CNC machines were proposed as an alternative tool for machining them, and a few approaches were presented to implement this gear manufacturing method. However, machining helical gears with crowning or other modifications has been little studied. This paper proposes an accurate method to manufacture helical gears with crowning modifications using a standard 5-axis CNC machine tool. As gear roughing process, milling using an end mill was selected, where the tool movement follows the generation principle. By incorporating crowning modifications into the tool's movement, an accurate tool path generation method was developed. A CAM software written in C++ was developed to generate, visualize, and simulate the tool path for machining the gear according to user-defined parameters. The tool path was subsequently post-processed into NC code to run on a CNC machine. To validate the generated NC code, an internal helical gear with crowning modification was machined on a conventional 5-axis CNC machine. The machining results confirmed that the proposed method is feasible. The machined helical gears will be measured using optical and tactile CMMs to determine their deviation parameters.

Document	ISBN	Pages
21FTM15	978-1-64353-109-0	28

Power Skiving – A Step Changing Manufacturing Process Applicable to Multifunctional 5-Axis Machine Tools

Bethany Cousins, Chao Sun, David Curtis, Michael Farmery, Steven Staley, Ben Cook

developing gear machining methods using multifunctional 5-axis machine tools with the expertise from collaboration with multiple partner companies. One machining method applicable to multifunctional machine tools is power skiving. This modern gear cutting process is gradually being adopted by industry, but its application is considered a secretive black art. The focus is to develop and quantify the capabilities and publicize this for the benefit of industry. The initial test geometry was a spur gear of 4.75-inch diameter and DP 6.5, which had teeth roughed and finished in 6 minutes 20 seconds, achieving a quality of AGMA 2015-A01 class A5 (AGMA 2000-A88 class Q12).Further test geometries have been trialed, including helical gears, ring gears, and internal splines, to ascertain how process performance transfers to alternate geometries and what the key process variables affecting productivity and gear quality are. Software models have been developed to predict cutting forces and establish cutting parameters for new geometries in order to expedite the process development. A range of cutting parameter strategies has been employed to establish an optimal approach for enhanced quality and reduced vibration. Cutting tool life has also been established for a range of geometries and parameter sets with a view to quantifying the commercial viability of the process.Power skiving offers great opportunities for production with step-changing productivity, particularly for internal gears, whilst offering high quality finishing capabilities and being applicable on a 5-axis machine tool with its inherent flexibility and multi-functionality.

Document	ISBN	Pages
21FTM14	978-1-64353-108-3	11

Investigation of Gear Surface Topography and Deviations in Gear Power Skiving Through Advanced CAD Modeling Based Simulation

Nikolaos Tapoglou

Power skiving is an emerging gear cutting process that has been identified as a process that can provide a step change in the production rate of high precision internal and external involute gear forms. The continuous generating principle is the basis of the cutting process that ensures the increased throughput of the process that is significant for internal gears. The understanding of the loads applied in the cutting tool and the gear as well as the final characteristics of the gear machined through power skiving is of key importance in the optimization of the cutting process. The present research focuses on two strands, first the development of a novel CAD based simulation platform that is able to simulate the power skiving process and calculate the cutting forces and the resulting gear topography. The second strand includes the validation of the model with analytical and experimental data from literature. In depth, investigation in the quality of gears produced is presented as part of this study with a focus in the influence of key process parameters in the resulting gear quality. Through this study a series of process maps can be drawn that assist in the selection of the most productive parameters for machining involute gears.

Document	ISBN	Pages
21FTM13	978-1-64353-107-6	25

Integrated Optimization of Gear Design and Manufacturing

Massimiliano Turci

The word “optimization” is becoming fashionable, also with regard to gear design. It is applied to both macro-geometry and micro-geometry. The approach can be of various types: analytical pre-optimization with different objectives, bulk generation of variants, multi-objective and multi-disciplinary commercial optimizers, generative optimization, and even artificial intelligence. Sometimes the best solution is presented directly, other times the choice is left to the user according to multiple criteria. However, these are all scenarios that assume that the manufacturer will accept any geometry indicated by the designer. This is not certainly the case with the industrial gearboxes on catalog, for which standard cutting tools are used to reduce cost and keep available the interchange of suppliers; nor with special gearboxes, “goods to order,” in which the producers try to use cutting tools already in the tool room. Even in the automotive industry, however, manufacturers try to use existing cutting tools as much as possible, at least during prototyping and for small batches.After presenting some design optimization techniques adopted in different companies, the focus of the paper shifts to some business scenarios where manufacturing has been equipped with a software for a semi-automatic selection of hobbing and pinion type tools, starting from the macro-geometry of the gear. In particular, it will look at the case where a paper database of more than ten thousand hobs, with different dimensioning modes, has requested to be harmonized into a single computer database. The software allows the search for hob even with “modified rolling,” a method very widespread in the automotive industry, practically “unknown” for industrial gearboxes.Finally, for companies that have both design and manufacturing departments, a design optimization with a list of cutting tools as main boundary will be presented.

Document	ISBN	Pages
21FTM12	978-1-64353-106-9	19

NVH Analysis of an Axle Drive with Bevel Gearset

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The geometry of bevel gears, together with the applied ease-off and the misalignment are introduced, and the excitation orders related to the gears and bearings are calculated. The EAxle is modeled as a flexible multi-body system, and the theoretical aspects related to the penalty contact formulation and modal reduction (Craig-Bampton method) are discussed. The NVH performance of the EAxle is evaluated as a function of the mounting distance (H), showing a significant reduction of the accelerations on a control point for a specific positive mounting distance. Finally, housing sound pressure level (SPL) is compared for the selected scenarios, showing a significative improvement for the optimized mounting distance configuration.

Document	ISBN	Pages
21FTM11	978-1-64353-105-2	20

Design and Simulation of a Back-to-Back Test Rig for Ultra High Cycle Fatigue Testing of Gears Under Fully Reversed Load

J. Lövenich, M. Trippe, O. Malinowski, J. Brimmers, S. Neus, C. Brecher

Gear units for turbomachinery, especially in the aerospace sector, place high demands. In addition to the high power density, the demands are also increased regarding the operating temperatures compared to automotive applications. Furthermore, the high operating speed excites vibrations in the higher frequency range, which also poses challenges for the transmission design in terms of NVH. The high dynamics of over 12 000 rpm combined with the high number of load cycles under fully reversed load (N > 108) that an aviation planetary gearbox experiences makes load capacity tests with standardized back-to-back test rigs uneconomical or even impossible due to the extremely long testing times. To enable the Ultra High Cycle Fatigue (UHCF) testing, a high-speed back-to-back test rig was developed. In addition to the design, particular focus is placed on the thermal and dynamic simulation of the test rig. These two aspects are the basis for a safe commissioning and a successful testing. In the area of thermal simulation, the behavior of the test rig components in the operating temperature range from room temperature to T > 100°C is investigated regarding the thermal expansion and the resulting tolerances. The dynamic simulation deals with the vibration behavior of the test rig. Special focus is placed on the tooth mesh frequency and the natural frequencies of the components. As a result, the operating points for testing are defined and the operational safety is ensured. In addition, for providing a basis for the investigation of aircraft transmissions, the paper shows fundamental ideas for the design of high-speed back-to-back gear test rigs.

Document	ISBN	Pages
21FTM10	978-1-64353-104-5	13

Particle-Based Phyllosilicate-Additive for Efficiency Improvement and Surface Protection

Petr Chizhik, Stefan Bill, and Scott Gardiner

Croda Int Plc is a developer and manufacturer of an innovative phyllosilicate-based surface treatment additive technology for gears and bearings. The particles with a platelet shape use lubricants as a carrier and build through their adsorption a protective phyllosilicate-based coating on the surface. The modified surface has a significantly lower surface roughness, which ensures a better load distribution and lower local pressure. Additionally, due to the special layered material structure, the particles can be sheared in the tribological contact, which leads to a significant reduction in friction. All in all, when applying the products, treated systems can run better with reduced friction, wear, surface roughness and temperature. These effects lead to higher efficiency and longer lifetime.

Document	ISBN	Pages
21FTM09	978-1-64353-103-8	17

Algorithm-Based Optimization of Gear Mesh Efficiency in Stepped Planetary Gear Stages for Electric Vehicles

Christian Westphal, Jens Brimmers, Christian Brecher

The electrification of the automotive powertrain confronts the gearbox development with new challenges. High-speed concepts require higher gear ratios, which cannot be optimally achieved with simple cylindrical gear stages. For this reason, stepped planetary gear stages are increasingly used, as they offer high power density at high gear ratios. To increase range and energy efficiency, the gear mesh losses are of great importance and must be considered in the gear design.The design of the macro geometry of gears is usually focused on ensuring the load-carrying capacity. In the design of stepped planetary gear stages, there are constraints due to assembly restrictions as well as additional degrees of freedom, such as the division of the total gear ratio. Due to many adjustable geometry parameters and design combinations, manual optimization of the gear geometry would not be effective.In this paper, a method for an automated optimization of the macro geometry of stepped planetary gear stages to improve the gear mesh efficiency is presented, which considers the assembly restrictions. An FE based tooth contact analysis is used to evaluate the design objectives: NVH (Noise, Vibration, Harshness), load-carrying capacity, and efficiency. Since these objectives require different design strategies, a weighting of the objectives is necessary. A particle-swarm algorithm is used to optimize the gear geometry and the tool data. Tooth flank pressure, peak-to-peak transmission error, tooth root stress, and efficiency are evaluated. The influence of the weighting of the design objectives on the gear design is shown. The results of various optimizations are compared, and an efficiency-optimized variant is selected for a specific application.With the method presented in this paper, it is possible to design the macro geometry of stepped planetary gear stages using FE-based tooth contact analysis and to optimize the operational behavior for a given application.

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Defining The Tooth Flank Temperature in High Speed Gears

John Amendola and John Amendola III, Robert Errichello

In defining total contact temperature the tooth flank temperature is as significant in the calculation as the flash temperature. Work done in preparation to writing 19FTM24 revealed that the applied ksump multiplier value for applications with spray lubrication should be greater than > 1.2 for high speed gears when calculating a tooth flank temperature. This procedure is described in AGMA 925-A03, Section 6.3.1 equation (91). In order to have a comparable risk assessment with MAAG “63”, MAAG “83” and ANSI/AGMA 6011-J14, Annex B, it was determined a value of ksump = 1.42 is necessary otherwise AGMA 925 is not reliable for assessing scuffing risk for high speed gears. However, further investigation suggests variable values of ksump are required to accurately calculate the tooth flank temperature relative to pitch line velocity. Referenced documents, with supporting comprehensive test data and testing results of high speed gears both indicate a higher range of tooth body temperatures increasing with pitch line velocity. This is corroborated by field experience conducted by Artec Machine Systems. This paper improves the methodology for determining the tooth flank temperature. Two methods are proposed for assessing scuffing risk when applying AGMA 925 for high speed gears. Both methods provide similar results.

Document		ISBN	Pages
21FTM07		978-1-64353-101-4	13

Use of Duty Cycles or Measured Torque-Time Data with AGMA Ratings

Ulrich Kissling

Nowadays continuous torque measurement on gearboxes is increasingly popular, not only on very sensitive installations but also on many industrial gearboxes and wind turbines. When the transmitted load is not uniform, consideration should be given not only to the peak load and its anticipated number of cycles, but also to intermediate loads and their numbers of cycles. This type of load is considered a duty cycle and may be represented by a load spectrum. In such cases, the cumulative fatigue effect of the duty cycle is considered in rating the gear set. A method of calculating the effect of the loads under these conditions, such as Miner’s Rule, is not explained in AGMA rating methods (as AGMA 2001, 2101, 2003) but a reference is given to ISO/TR 10495 (nowadays replaced by ISO 6336-6:2019).In this paper the application of torque spectra in AGMA rating methods is described. Furthermore, a procedure to convert measured (or calculated by numerical simulation) torque data into a torque spectrum according to the definition in ISO 6336-6 is described. This task is simple if the torque is always positive, but quite complicated when also negative torque sequences happen.The torque spectrum must represent the load on each single tooth, therefore in a first step the continuous torque course has to be segmented in individual torque peaks applied on one tooth. If only positive torque occurs (no load reversal), the "Simple Count" method can be used. The method counts how often a torque value happens to be in a certain torque range. A tooth is always loaded by a torque value starting at zero to a peak, hence it is subjected to pulsating stress (stress ratio R=0). Tooth bending stress calculation according to AGMA is assuming pulsating stress, so the result of the “Simple Count” method can directly be used for the tooth bending strength verification. For complex loads, where the torque has both positive and negative signs, the “Rainflow method” (ISO 12110-2 [8]) should be applied. 'Rainflow Counting' is a method to determine the number of fatigue cycles present in a load-time history. The method is used in the analysis of fatigue data in order to reduce a spectrum of varying stress into an equivalent set of simple stress reversals. So, a tooth is loaded by cycles with a high and a low torque (respectively stress), having a variable stress ratio R ≠ 0. To comply with the rules of AGMA ratings, a reverse loading factor must be used to modify the admitted sat values for tooth bending. In ISO, this factor is the mean stress influence factor YM which must be defined for every bin of the torque spectrum.In the final part of this paper a practical application of the above method is presented.

Document		ISBN	Pages
21FTM06		978-1-64353-100-7	20

Bevel Gear Strength Rating – The Appropriate Combination of FE with Rating Standards

Jürg Langhart, Markus Bolze

Strength rating of bevel gears according to standards such as AGMA, ISO, etc. is executed based on virtual cylindrical gears, only modified by a few specific bevel gear factors. The rating method of these standards also includes the calculation of permissible stresses and finally resulting safety factors. Furthermore, the integrated S-N curves consider also an increased permissible stress during limited life and allow a lifetime prediction. The contact analysis for bevel gears allows a rating of the stresses. It allows the individual to consider flank modifications such as crowning, twist, etc., including the corresponding displacements. A lack of the contact analysis is the calculation of permissible stresses and hence no rating of safety and lifetime is available.To combine both methods, the standard requires a certain level of adaptation possibilities, to tune the major effects which influence the stresses. Whereas ISO 10300 (edition 2014) has factors that allow an adaptation, the AGMA 2003:C10 standard has little possibilities. Also, the bending stress numbers of AGMA 2003 are much lower and differ remarkably from the contact analysis values.The process to combine both calculation approaches increases the accuracy in the rating of bevel gears significantly. The first step is to determine the E, P, G and Alpha displacements for a sample bevel gear pair. By using the E, P, G and Alpha displacements, the largest possible contact pattern is developed, strictly avoiding any edge contact. Based on the stress numbers by the contact analysis, the relevant parameters of the rating standard are derived.As a next step, using the fast standard calculation, the bevel gear macro geometry is optimized by variation of the key parameters. All these solutions can be evaluated with various failures modes such as root bending, pitting, scuffing, and flank fracture.

21FTM05		978-1-64353-099-4	18

Double Differential for Electric Vehicle and Hybrid Transmissions – Sophisticated Simplicity

Hermann Stadtfeld, Haris Ligata

The fascination of the automotive differential has led to the idea to build a second differential unit around a first center unit. Both units have the same axes around which they rotate with different speeds.The potential of double differentials as ultrahigh reduction speed reducers is significant. Only the tooth-count of the gears in the outer differential unit must be changed to achieve ratios between 5 and 80 without a noticeable change of the transmission size.

Double differentials are well suited for high input speeds. The fact that the carrier rotates with about half of the input speed reduces the relative motion and with it the sliding velocity to 50% of the value of two conventionally meshing bevel gears which roll with the same input speed.Ground spiral bevel gears are recommended for the double differential application. Due to the load sharing of the two opposite planets, the torque of each gear is only 50% compared to a conventional bevel gear mesh. This effect results in very high-power density of this already very compact unit.Also, the efficiency of the double differential is high in contrast to the fact that always two pairs of gears are transmitting the rotation and torque. Double differentials show good efficiency results, which qualifies this new transmission type very well for the speed reduction and transmission in electric vehicles and hybrids.In addition to electric vehicles and hybrid cars, there are many other applications in the industry which require high ratios. Double differentials could be used in helicopters, wind turbines, agricultural equipment, and many other industrial applications.The objective of the paper is to compare a transmission concept, which is based on bevel gear technology, with cylindrical gear-based solutions, for designers and manufacturers of high reduction transmissions to have an additional technology available for their different applications.

Document	ISBN	Pages
21FTM04	978-1-64353-098-7	19

Effect of the ISO 6336 3:2019 Standard Update on the Specified Load Carrying Capacity Against Tooth Root Breakage of Involute Gears

Stefan Sendlbeck, Maximilian Fromberger, Michael Otto, and Karsten Stahl

Part 3 of the ISO 6336 standard contains a verified specification for calculating the tooth bending strength of involute gears. In November 2019, an update of the previous version from the year 2006 was issued, which includes more detailed calculation methods based on the most recent research findings. For an optimal gear design, gear engineers need to be aware of how the changes in the standard affect the overall calculation result, since the revised standard can yield a higher or lower safety factor against tooth root breakage.This paper provides a detailed summary of the key changes in ISO 6336-3:2019, outlines their overall effects on the basis of a calculation study, and presents a comparison of the results to the previous version of the standard, ISO 6336-3:2006. The key changes in ISO 6336-3:2019 are a new load distribution influence factor that accounts for the effects of high overlap ratios and a more precise consideration of the helix angle on the stresses. Furthermore, the standard now also covers the determination of the tooth root geometry of internal gears by means of a shaper cutter. To investigate these changes and their overall effect, we vary the contact ratio by using gears with different transverse contact ratios and overlap ratios as a basis for computing the specifications of the standard. In addition, by simultaneously varying the transmission ratio and the tool tip radius, we investigate the effect on the calculation of internal gears with different tooth root geometries. The findings of this research give a detailed insight into how the update enhances the ISO 6336 standard and how they affect the load carrying capacity calculation.

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21FTM03	978-1-64353-097-0	22

Tooth Flank Fracture – Design Process for a New Test Gearing and First Test Results

Daniel Müller, Thomas Tobie, and Karsten Stahl

Tooth flank fracture (TFF) is a gear fatigue failure mode. TFF differs from tooth root breakage and pitting in that the crack emerges below the hardened case of the active flank. However, like tooth root breakage, it leads to a total breakdown of the gears in contact and often in severe failure of the entire transmission. TFF recently has occurred more frequently, especially in larger sized gears. This makes it all the more important to investigate TFF failures. In order to avoid TFF in the future, a calculation method, that must be applicable in the design phase is needed and should be widely verified by experimental results. For the systematic investigation of TFF, smaller sized test gears are used. So far, only test gears for TFF with a center distance of 200 mm are commonly used. Although the gears are significantly smaller than those used in the relevant industrial applications, extensive experimental investigations still result in high costs. A smaller sized test gearing with a center distance of 91.5 mm would reduce the costs of manufacturing the test gears significantly and also offer more testing capabilities based on the use of standardized FZG back-to-back gear test rigs. Based on the experimental results of the test gears with a center distance of 200 mm, a calculation approach (ISO/TS 6336-4) was developed in the FVA 556 I research project. In this work, this practical approach is used to design a smaller sized test gearing with a center distance of 91.5 mm. The test gear pairing is tested with a back-to-back test rig and initial test results are shown and discussed. In addition, results of further investigations regarding microstructure, hardness and residual stresses are presented.

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21FTM02		978-1-64353-096-3	18

Transient Friction and Wear Simulation of Worm Gears During Running-In

K. Daubach, M. Oehler, B. Sauer

The load capacity of worm gears strongly depends on the size of the contact pattern. Worm wheels are often manufactured by using an oversized hob, which results in a relatively small initial contact pattern. Wear on the worm wheel with a softer material during the running-in process increases the contact pattern and thereby the load capacity. For the investigation of the continuous change of friction in the tooth contact during that process, a tribological simulation program is used. With a simplified model of the EHL-tooth contact, boundary as well as fluid friction are calculated locally, and the tooth efficiency is evaluated. The included wear model associates abrasive wear with solid friction energy occurring in the tooth contact and allows a time-dependent simulation by considering the wear-modified tooth flank in the tribological calculation.The simulative results are compared with experimental wear studies on the running-in of worm gears. Since various values are determined in the simulation model, the comparison covers different aspects to verify the model. However, for measurement reasons a comparison is taking place on the macro scale. The tooth friction is reflected by the measured efficiency of the gearbox on the test bench. Wear is on one hand a directly measured value, on the other hand it changes the geometry of the tooth flank and influences thereby the unloaded kinematics of the gears. Both aspects are considered for a verification of the wear calculation.

21FTM01		978-1-64353-095-6	20

Investigation of the Effect of Application of Non-Conventional Root Profiles for Reduction of Bending Stresses in Helical Gear Drives

Ignacio Gonzalez-Perez, Alfonso Fuentes-Aznar, Jose Calvo-Irisarri, Alfredo Fernandez-Sison, Harri Aurrekoetxea-Arratibe

The substitution of the conventional trochoid root profile in spur and helical gears by non-conventional root profiles, based on elliptical or Bèzier curves, to reduce the maximum bending stress at the gear root surfaces has been the subject of an intensive research recently. The application of finite element models in which the load is applied at the highest point of single tooth contact has been mainly used for those studies. However, a complete review of the stress field at the fillet surface and its variation along a cycle of meshing is still missing. The adjacent pair of teeth when it carries part of the load causes compressive stresses on the root area that deserves to be considered for a comprehensive study of the possible benefits of application of non-conventional root profiles. This paper focuses on the investigation of the variation of the normal stress in the perpendicular direction to the root line between adjacent teeth. Such variation will be obtained for two cycles of meshing by considering finite element models with five pairs of teeth, so that the effect of load sharing between adjacent pairs of teeth will be considered. This study will provide the variation of the alternating range normal stresses on the root surface in longitudinal direction of the gear teeth for tooth root profiles based on Hermite, elliptical, and Bèzier curves and their comparison in terms of the mentioned stresses with those obtained for conventional root profiles. Several numerical examples corresponding to an existing design of a helical gear drive show that the reduction of the maximum principal stress is possible using non-conventional root profiles, although an increment of the alternating component of the normal stress occurs, which may lead to the reduction of the expected fatigue life of the gear drive.

Document		ISBN	Pages
20FTM10		978-1-64353-088-8	15

Analysis of the Operational Behavior of a High-Speed Planetary Gear Stage for Electric Heavy-Duty Trucks in Multi-Body Simulation

Christian Westphal, Jens Brimmers, & Christian Brecher

Stricter emission limits accelerate the development of electric trucks, especially for urban distribution traffic. The use of electric motors instead of diesel engines confronts gearbox development with the challenge of higher engine speeds and higher requirements on transmission acoustics. Planetary gearboxes are often used for this purpose, as they allow high transmission ratios in reduced assembly space.Dynamic multi-body simulation (MBS) is used for detailed dynamic modeling of drive trains. The interaction of gears and shafts in planetary gearboxes requires, especially for NVH-analysis, advanced simulation methods due to the sophisticated kinematics and the more sensitive displacement behavior. Dynamic simulation methods for cylindrical gears usually describe the tooth contact based on analytical equations or consider only one rotational degree of freedom, which leads to uncertainties in the simulation results. Misalignments are therefore, either simplified or not considered at all. The authors developed a method that combines the advantages of the quasi-static FE-based tooth contact analysis with the advantages of an integrated approach in the MBS.In this paper the operational behavior of a high-speed planetary gear stage for electric heavy-duty trucks is analyzed in dynamic MBS. The method for the tooth contact analysis in the MBS is used for the simulation of planetary gearboxes. Different mesh sequences and model configurations for planetary gearboxes are compared and the effects on the operational behavior are evaluated. In addition to the dynamic transmission error, the dynamic tooth flank pressures are analyzed. Furthermore, dynamic misalignments in the tooth contact and the load sharing behavior in dynamic operating conditions are evaluated. In the simulation, the misalignment of the gears is directly taken into account by means of a penetration calculation in every time step. The presented method allows a well-founded prediction of the operational behavior of planetary gear stages, considering the dynamic interaction of the components.

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Single Tooth Bending Fatigue Testing at any R Ratio

Matthew Wagner, Aaron Isaacson, Kevin Knox, &Thomas Hylton

Single tooth bending fatigue (STBF) testing has long been used as a simple and cost effective alternative to running gear bending fatigue tests. In typical STBF testing, the test tooth root fillet is subjected to a cyclic tensile load until bending failure occurs, while the test load is reacted with an opposing tooth along the line of action. This results in a rather simple fixture design, however the typical STBF fixture design does not allow for any reversal of the loading in order to stress the tooth roots in compression. The test loads for this type of test vary from a maximum tensile value to a percentage of the maximum, resulting in a positive R-ratio (ratio of minimum to maximum load).It is well known that the root area of a gear tooth is subject to both tensile and compressive stresses as the tooth approaches and subsequently meshes with mating teeth. For a single pair of meshing gears, the loading experienced by the root fillet results in a slightly negative R-ratio in practice. For idler or epicyclic planet gears, the loading is fully reversed and the extreme case of a load ratio of $R = -1.0$ occurs.The Single Tooth Reversible Bending Fatigue (STRBF) test outlined herein overcomes previous limitations by allowing compressive loads to be applied to the test tooth root in any magnitude in conjunction with the typical tensile loads. This test setup involves three teeth of the test gear, with the upper and lower teeth providing the reactions in the up and down load directions and the test tooth being subject to test loads in both directions. Any R-ratio applicable to gear bending fatigue testing up to and including fully reversed loading ($1 > R \geq -1$) is possible. Non-dimensional examples of fatigue data from a recently completed fully reversed testing program are shown.

Document		ISBN	Pages
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Service Life of Cylindrical and Bevel Gears Under Variable Load and Stresses

Daniel Vietze, Josef Pellkofer, Michael Hein, & Karsten Stahl

Transmissions are usually loaded by variable external loads under real operating conditions. The decisive load for a gearbox is in most cases the applied torque. Commonly used allowable stress numbers σHlim/Flim (ISO) or σHP/FP (AGMA) for calculating the load carrying capacity of cylindrical, bevel and hypoid gears are usually derived from single stage tests carried out on pulsators or back-to-back test rigs. Variable loads can be considered in the calculation of the load carrying capacity by using application factors, overload factors or more complex standards like ISO 6336-6, which was recently revised. In case of variable loads, the calculation of the load carrying capacity of gears is quite different to bearings. According to ISO 6336-6, a safety factor is determined for gears and according to ISO 281, a service life is determined for bearings, respectively. Whereas all of these calculation methods only consider a global safety or lifetime, continuously progressing failures like micropitting or wear can – especially on bevel and hypoid gears – also lead to locally varying stresses even if only a constant external load is applied. This paper is intended to give a brief overview of currently applied methods to consider variable loads in the design process of cylindrical as well as bevel and hypoid gears. Therefore, the scope of application of these methods is shown and critically analyzed for the damage mechanisms pitting, tooth root breakage and tooth flank fracture. Especially the changes made in the revised version of ISO 6336-6 are shown in detail. Furthermore, the influence of locally changing stresses on the pitting load carrying capacity is explained on bevel and hypoid gears. A method to assess such influence is shown for constant external loads.

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Case Study of ISO/TS 6336-22 Micropitting Calculation

Robin Olson, Mark Michaud, & Jonathan Keller

ISO/TS 6336-22 (Calculation of load capacity of spur and helical gears — Part 22: Calculation of micropitting load capacity) is the ISO technical specification containing a proposal for a calculation for the risk of micropitting in gear sets. This document was originally published in 2010 as ISO/TR 14179-1 and added to the ISO 6336 suite of documents in 2018. It assesses micropitting risk through a safety factor that is calculated as the minimum specific film thickness in the contact zone divided by a permissible specific film thickness. A sliding parameter is used to adjust the film thickness in the contact zone to the region of highest sliding, which is where micropitting has been observed. The permissible specific film thickness is best determined through experience or testing, but there is an option to estimate it based on the lubricant's failure load stage in FVA-FZG micropitting testing. This paper is a case study to compare the results of the calculation to applications that have experienced micropitting in the field. For these examples, the method does not predict micropitting because of limitations in the Method B formulation.

Document		ISBN	Pages
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A New Approach for the Calculation of Worm Shaft Deflection in Worm and Crossed Helical Gear Drives

Philipp Norgauer, Gerhard Keinprecht, Michael Hein, & Karsten Stahl

Worm gear drives are characterized by a simple design, which allows the realization of a high gear ratio within one stage. Furthermore, they are characterized by low vibration and noise behavior. For these reasons, they are used both as power transmissions and servo drives in various drive solutions. The allowable load and the lifetime of the gearbox is usually limited by wear on the softer worm wheel. An influence factor on the wear as well as the NVH behavior of worm gear drives represents the stiffness and the associated worm shaft deflection.According to the current state of the art, the worm shaft deflection can be calculated accord-ing to AGMA 6022, DIN 3996 and ISO/TR 14521. In this paper, the current calculation status for worm shaft deflection is discussed. The underlying experimental results for the calculation of the worm shaft deflection according to DIN 3996 and ISO/TR 14521 are analyzed. A new approach for the worm shaft deflection calculation is developed. Therefor an analytical model for the bending stiffness of a worm shaft is developed. The model was validated through various FEM simulations. As a result, a new calculation method for the equivalent bending diameter of a worm as well as the formulae for the calculation of the worm shaft deflection are presented.The developed calculation method details the current state of the art, thus providing a basis for more optimized worm gear design. Furthermore, with this calculation it is now possible to calculate the bending stiffness of overhung worm shafts as well as worms of reduced tooth thick-ness, which are usually used in crossed helical gear boxes.The new calculation method is presented within this paper and compared to the current state of the art for calculating the worm shaft deflection according to AGMA 6022, DIN 3996 and ISO/TR 14521.

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Gear Sliding Losses

Parviz Merati, John Bair, Carlos Wink, & Farrukh Qureshi

Gearbox efficiency is becoming increasingly important for vehicle manufacturers to help achieve their overall fuel savings goals. Enhancing gearbox efficiency is also critical in saving the up-front cost and overall unreliability of gearbox cooling. It is well known that at high power levels, gear sliding losses dominate the overall gearbox losses. Therefore, accurately predicting frictional losses is critical for increasing overall gearbox efficiency. Previous work by these authors has shown that available closed-form calculations do not provide the range of important inputs or accuracy required to perform reliable design estimates of the sliding losses that are so important to the thermal and efficiency characteristics of the gearbox. This paper documents an approach used to incorporate the effect of lubrication characteristics, gear geometry, surface finish, and operating conditions into an algorithm that accurately predicts sliding losses over a range of operating conditions for a standard set of gears. This study provides a method for accurately calculating gear sliding losses based on all the important design variables early in the process, so that efficiency can be more easily assured. The methodology developed for simple contacts is used to predict gear sliding losses for much more complicated cases of spur and helical gears, where load and rolling and sliding speed of the contact patch varies at each roll angle during the mesh cycle.

Document		ISBN	Pages
20FTM04		978-1-64353-082-6	15

Effects of Different Shot Peening Treatments in Combination with a Superfinishing Process on the Surface Durability of Case-Hardened Gears

Dominik Kratzer, Johannes König, Thomas Tobie, & Karsten Stahl

Modern gearbox designs set increasing requirements on the surface durability of gears in light of calls for downsizing and performance optimization. Using additional manufacturing processes is one way to tackle these challenges. The increase in the compressive residual stress state due to shot peening and the decrease in the roughness of the gear flank surface due to superfinishing processes are two possible measures. While there have been extensive scientific studies in the past on the positive effects of shot peening and superfinishing, a detailed quantification of a calculation model of these two effects has not been subject to in-depth investigation yet. To address this gap in knowledge, a study was carried out to examine and evaluate different peening processes and the resulting residual stress profiles in combination with a superfinishing process. Experimental investigations showed significant differences in the gear flank load-carrying capacity due to the different surface treatments. In addition, a significant reduction in micropitting appearance was observed due to the superfinishing process, while the increased compressive residual stresses due to shot peening showed no significant influence on the development of micropitting. By correlating the pitting durability from the experimental investigations with existing calculation methods, it was possible to extend the surface factor ZR from ISO 6336 to a wider range of roughness values as well as to introduce a new factor ZS for different shot peening treatments. Based on the results of this paper, the positive effects of different shot peening processes as well as superfinishing processes can be taken into account for gearbox design and rating processes.

20FTM03		978-1-64353-081-9	11

Validation of a Generalized Formulation for Load Sharing Behavior in Epicyclic Gears for Wind Turbines

Yi Guo, & Jonathan Keller

In an ideal epicyclic gear set, every parallel gear path transmits the same amount of torque. However, it is well known that certain manufacturing variations result in unequal load sharing between the parallel gear paths. Previous works have developed and validated a general closed-form analytical model of this phenomenon that describes the load sharing characteristics of epicyclic gear sets from three to six planets at any torque level. More recently, this analytical model has been reformulated to include the effects of gravity, carrier bearing clearance, and external applied moments, all of which are relevant to most gearboxes and their mounting configuration in horizontal-axis wind turbines. In this paper, the reformulated model is compared to load measurements collected from two similar wind turbine gearboxes with three-planet epicyclic gear sets. The resulting load sharing values are also compared to the mesh load factor requirements in the AGMA 6006 and IEC 61400-4 wind turbine gearbox design standards. Load sharing factors as high as 1.16 at extreme rotor moments and 1.08 with no moment were measured for the gearbox with cylindrical roller bearings, but the load sharing factor remained below 1.10 for the gearbox with tapered roller bearings. Results show that in the wind turbine application, load sharing is not equal—even for three-planet systems with a floating central member because of the effects of gravity, rotor moments, and the resulting relative motions among the epicyclic gear components within the carrier bearing clearance.

Document	ISBN	Pages
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A Comparison of an Analytical and FEA Approach in Determining Thermal Lead Correction for High Speed Gears

Andreas Beinstingel, Burkard Pinnekamp, Michael Heider, Daniel Stierli, & Steffen Marburg

Especially for high-speed applications, gears of large dimensions and high power density are used. Temperature distribution in those rotors is much different in operation as compared to manufacturing. Therefore, the tooth contact as it can be validated by blue ink during assembly is not only affected by distortion and bending under load but also by non-uniform thermal growth. This influence has often been neglected in the past. As power density and specific load are continuously increasing over time, for highly sophisticated applications, this influence should be accounted for with suitable lead modification, as it is demanded by the latest version of API 613. For many years, RENK has been using empiric methods for thermal lead correction based on measurements and experience. Lately, the authors carried out complex finite element calculations to numerically investigate the influence of temperature distribution on tooth contact. This kind of detailed finite element modeling for tooth contact analyses requires a high effort with respect to FE meshing as well as extended computation time. Therefore, the numerical method was further enhanced. As a result, a simplified approach for quick and reliable heat analyses for thermal lead correction of high-speed gears was developed. The paper describes the theoretical background and gives a comparison of the results with the different calculation approaches.

Document	ISBN	Pages
20FTM01	978-1-64353-079-6	15

Quasi-Static Transmission Error Behavior Under the Composite Effects of Temperature and Load

Aitor Arana, Jon Larrañaga, Ibai Ulacia, Mikel Izquierdo, & Miren Larrañaga

Current demands for enhanced rotational speed in electric vehicle transmissions, aeronautical gearboxes and industrial machinery is known to affect the thermal behavior of mechanical parts by increasing their steady-state temperature. In geared transmissions, such condition is detrimental as the lubricating film is reduced thus increasing failure probability, furthermore, if temperature levels are sufficiently high thermal distortion can affect mesh behavior.Scientific literature review has shown that no experimental evidence on the composite effect of temperature and torque on transmission error exists up to date. Although some authors already pointed out that temperature influences positioning accuracy, no previous reference to peak to peak behavior has been found and comparisons to torque effects have not been performed. In this work, quasi-static transmission error behavior is experimentally analyzed under increased thermo-mechanical conditions. First, the development of a custom back-to-back test rig is described and test specimen geometries, operating conditions and measurement procedure are presented. Next, loaded transmission error tests are carried out in order to validate the expected mechanical behavior and then the influence of temperature is analyzed by heating up the system in a controlled manner. Composite effect of temperature and load are studied in terms of backlash, mean level of transmission error and its peak-to-peak value. Finally, experimental measurements are compared to analytical predictions, results are discussed and conclusions are withdrawn. It is shown that the effect of temperature and torque coexist in transmission error diagrams. Both parameters have a significant role in the mean level of transmission error while the influence of torque on peak to peak is prominent relative to that of temperature. Although the correlation between the change of mean level and that of backlash for increasing temperatures is clear, peak-to-peak variation due to temperature is not obvious.

Document		ISBN	Pages
19FTM26		978-1-64353-065-9	17

Sizing of Profile Modifications for Asymmetric Gears

Ulrich Kissling

Today, the benefits of asymmetric gears are being extensively discussed. They have yet to be widely adopted, but investigations are ongoing as to whether gear reducers can be improved with such techniques. The geometric definition of asymmetric gears is shortly described. The strength calculation of such gears can be calculated according to ISO standards, but the method for the bending stress must be adapted. This permits the power capacity of asymmetric gears to be calculated and compared with symmetric gears. In specific cases, when using asymmetric gears, the power capacity of a gear pair can be increased by up to 30%.The power capacity of a gear pair is critical, but the noise and vibration behavior is also highly relevant. With appropriate profile modifications, gears can be significantly improved. A modification of the gear profile will change the load distribution during a meshing cycle, therefore changing transmission errors, contact pressure and power losses. Additionally, with tip and/or root relief, the contact shock at the beginning and the end of the meshing can be removed, substantially reducing the vibration and noise of the gear mesh.The layout of profile modifications must be verified by a loaded tooth contact analysis (LTCA), which permits the analysis of the contact during a meshing cycle step by step. LTCA can be performed based on a finite element method (FEM) or with semi-analytical method (usually based on the Weber-Banaschek approach [1]). To get an optimum solution for a profile modification, it is very convenient to use a parameter variation technique. For example, tip relief and tip modification length are varied to find the best solution. For such a task with some hundreds of variants to check, the calculation time for an LTCA analysis becomes an issue, therefore, the use of the Weber-Banaschek approach is preferred. This approach was recently adapted for asymmetric gears to allow for efficient analysis.The selection process of a steel gear with asymmetric teeth is discussed in detail. With a well selected profile modification, the noise excitation and Hertzian pressure can be reduced. The behavior of the critical parameters was verified for different torque levels and for helix and profile errors due to manufacturing tolerances.

19FTM25		978-1-64353-064-2	23

Optimum Carburized and Hardened Case Depth

Robert Errichello, and Andrew Milburn

The optimum carburized and hardened case depth for each gear failure mode is different and must be defined at different locations on the gear tooth. Current gear rating standards do not fully explain the different failure modes and do not clearly define the different locations that must be considered. Furthermore, they use different hardness values to define effective case depth and provide different values for recommended case depth. This paper explains why case hardening is beneficial; the risks involved and compares the methods for calculating and specifying case depth per the ISO 6336-5 and ANSI/AGMA 2101-D04 gear rating standards, and guidelines presented in the MAAG Gear Handbook. The paper shows the three locations that the case depth needs to be specified and presents separate calculation methods to determine the optimum case depth to avoid the failure modes of macropitting, subcase fatigue, bending fatigue, and case/core separation. For each failure mode there is a minimum case depth below which the load capacity drops off. On the other hand, an excessively deep case decreases load capacity, increases cost, and has other detrimental effects that are explained.

Document	ISBN	Pages
19FTM24	978-1-64353-063-5	17

Calculated Scuffing Risk: correlating AGMA 925-A03, AGMA 6011-J14 and Original MAAG Gear Predictions

John Amendola, Sr., John Amendola III, and Robert Errichello

Predicting scuffing risk is a critical factor when designing high speed gears. In years past, scuffing risk was not calculated for gear tooth ratings for through hardened gears. Now, case hardened gears allow higher tooth loads making it necessary to calculate scuffing risk. AGMA and ISO application standards rate only macropitting and bending fatigue resistance. Both AGMA and ISO provide information sheets and technical specification reports, but neither provides a specific design standard for assessing scuffing risk.Scuffing is severe adhesive wear occurring on gear tooth flanks when oil film thickness is insufficient to prevent transfer of metal from one gear tooth surface to the mating gear tooth due to welding and tearing. It usually occurs during startup of new gears thereby requiring design modification, load adjustment, or lubricant change. Nevertheless, it can occur after years of service if the oil deteriorates or load distribution across gear tooth flanks changes.This paper compares three methods for calculating scuffing risk using performance data for real gears and presents a simplified method that assures accurate prediction of scuffing risk.

Document	ISBN	Pages
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New Standardized Calculation Method of the Tooth Flank Fracture Load Capacity of Bevel and Hypoid Gears

Josef Pellkofer, Michael Hein, Karsten Stahl, Tobias Reimann, and Ivan Boiadjiev

Bevel and hypoid gears are widespread in automotive, industrial, marine and aeronautical applications for transmitting power between crossed axles. Future trends show that the demands on bevel and hypoid gears for higher power transmission and lower weight are continuously increasing. A major aspect in the design process is therefore the load carrying capacity regarding different failure modes. Beside typical fatigue failures like pitting and tooth root breakage, which are the results of cracks initiated at or just below the surface, there are also failures caused by cracks starting in greater material depth in the area of the active flank that can be observed on bevel and hypoid gears. These cracks typically propagate to the tooth root area of the unloaded flank and to the surface of the active flank. The failure mode known as tooth flank fracture occurs particularly frequently on large spiral bevel and hypoid gears because this gear type shows larger equivalent radii of curvature compared to spur and helical gears. As a result of the larger equivalent radius of curvature the maximum shear stress occurs in a larger material depth, where the material of a case hardened gear shows a decreased strength. Important parameters influencing the tooth flank fracture load capacity are geometry, operating conditions, material and heat treatment of the gear set. Tooth flank fracture usually leads to the total breakdown of the gearbox and generally occurs suddenly and unexpected since the crack initiation and propagation takes place below the tooth surface and therefore cannot be identified within visual inspections.This paper will give an overview of the subsurface failure mode known as tooth flank fracture on bevel and hypoid gears. Further a newly developed standardized calculation method for determining the tooth flank fracture load capacity based on the geometry of virtual cylindrical gear according to the standard ISO 10300 (2014) will be explained in detail.

Document		ISBN	Pages
19FTM22		978-1-64353-061-1	24

Influence of the Load-Dependent Shift of the Center Distance of Cylindrical Gears on the Calculated Load Capacity and Noise Excitation Using an

Stoyan Radev

The nominal center distance in cylindrical gears is defined for the non-loaded state. The center distance changes under load conditions, which leads to a reduction of the plane of contact and respectively of the length of the effective path of contact. The effective total contact ratio is also shortened. This affects the load and pressure distribution on the flank and thus the load capacity of the gears. The transmission error is also mutated, which affects the noise excitation of the gear pair.For the analysis of these effects, we are using an analytical approach for the calculation of the local mesh stiffness. It is based on the Schmidt plate theory and the local gear tooth deformation approach according to Weber-Banaschek. We are evaluating the load capacity using the calculated pressure distribution on the flanks based on the static deformation analysis of the gear system. Shafts are modelled analytically as Timoshenko beams and bearings are considered as non-linear elements depending on the internal contact situation. In addition, the tooth root stresses are taken into consideration using a boundary element method (BEM). The noise excitation is evaluated using transmission error, force excitation, and other resulting characteristic values. These are formed using a Fourier transformation and level formation. This analytical approach allows excellent calculating precision while achieving high calculation performance. This paper shows the importance of considering the load-dependent change of the center distance for the calculation and layout of cylindrical gears. Furthermore, we show the advantages of using an analytical approach for calculating mesh stiffness.

19FTM21		978-1-64353-060-4	26

A Comparison of Surface Roughness Measurement Methods for Gear Tooth Working Surfaces

Matthew Wagner, Aaron Isaacson, Mark Michaud, and Matt Bell

Surface roughness is a critical parameter for gears operating under a variety of conditions. It directly influences friction and contact temperature, and therefore has an impact on various failure modes such as macropitting, micropitting and scuffing. Typically, gear tooth surface roughness is measured using a stylus profilometer, which yields a two dimensional cross section of the surface from which roughness parameters are taken.Stylus profilometry can produce inconsistent results if measurements are not executed correctly. Variables such as measurement parameters, stylus tip radius, and repeatability of stylus orientation relative to the gear tooth can all impact measurement results. This paper examines measurements from one “shop floor” and one “metrology lab” profilometer, both using two different stylus tip radii on the same gear teeth. Measurements from ground, shot peened and superfinished surfaces are compared.Although stylus profilometry is convenient, a limited amount of information regarding the surface topography of the tooth is retained. Tooth replicas subsequently evaluated with optical interferometry offer an alternative means to measure surface roughness, and allow for retention of a much more complete representation of the tooth surface for future evaluation. The three dimensional surface profile generated by optical interferometry can also highlight features that would be difficult to evaluate using stylus profilometry. This paper compares roughness measurements made using optical interferometry of gear teeth with optical interferometry of tooth replicas. Two different replication techniques are evaluated. The same teeth measured using stylus profilometry are used, thus the interferometry results are directly compared to the profilometry measurements. Lastly, when tooth replicas are taken and measured with optical interferometry, the reference frame of the gear from which the replica is taken is not immediately apparent. A method for correlating tooth replica coordinates to roll angle is also presented, which is shown to be useful for plotting roughness trends at points of interest over the active profile of the tooth.

Document		ISBN	Pages
19FTM20		978-1-64353-059-8	14

Rapid and Precise Manufacturing of Special Involute Gears for Prototype Testing

Christian Weber, Thomas Tobie, and Karsten Stahl

Due to the steadily increasing demands on the power density of mechanical transmissions, gears with special geometries are increasingly coming into focus and therefore the need for short-term availability of prototypes. Such special gear designs are e.g. asymmetrical gears with different normal pressure angles on the drive and coast flank. These are particularly suitable for use in gearboxes with preferred driving direction, whereby the loaded flank can be optimized with regard to load carrying capacity. While for symmetrical gears with normal pressure angles in the range of $\alpha n = 20°$ standardized calculation methods for gear design have been available for decades, mainly theoretical numerical investigations have been carried out on asymmetrical gears so far. For the qualification of any such designed asymmetrical gear geometry with increased load carrying capacity potential for use in industrial practice, however, reliable load carrying capacity values are required. Therefore, according to the current state of the art, prototype tests are indispensable to determine the actual gear strength. At the Gear Research Centre (FZG), such load capacity investigations are carried out using back-to-back test rigs and pulsator test rigs. The design and procurement of special tools for the production of such prototype gears is often time-consuming and expensive. In this paper, an alternative method for a fast and cost-efficient production of asymmetric gears for prototype tests is presented. The focus is on the grinding process from a full blank test specimen. This process was applied at the FZG in cooperation with Liebherr-Verzahntechnik GmbH in order to produce asymmetrical test gears for experimental investigations of the tooth root bending strength. Very good results were achieved with regard to gear quality and shape accuracy, especially in the tooth root area, which is then investigated. The results of this paper show therefore a suitable method for the fast, precise and cost-efficient production of special gears for prototype tests.

19FTM19		978-1-64353-058-1	19

Micro-skiving - (r)evolution of a Known Production Process

Pierre Falbriard, and Hervé Baour

Production of internally toothed gear wheels is possible in many different ways. Different techniques such as gashing, broaching, wire EDM or shaving make it possible to achieve these profiles. However, skiving seems to be the optimal solution for reducing production time of this type of gears when large production batches are required.This internal gear cutting technique has been known for several years and widely used in the industry for modules over 0.50 (DP>50).However, cutting an internal gear with a module below 0.50 (DP>50) is not an easy task. The profile becomes very small and requires an optimized cutting tool, which can only be manufactured on special grinding machines that can cope with micron (μm) accuracy.Micro-skiving has been developed allowing users to have access to the skiving technique for machining inner micro-teeth. The basic principle is similar to standard modules, with higher requirements in terms of shape, burr and surface finish. Modules as low as 0.15 have already been produced and the technical limits to go even lower are regularly crossed.These developments expand the possibilities for fast and high-volume production of parts with internal micro-teeth. The production of micro-subassemblies, medical micropumps or micro-reducers can now be considered without the current manufacturing challenges of cycle time and quality level.That being said, micro-skiving internal gear cutting requires suitable, high accuracy machines with fine adjustment options. In addition, a perfect synchronization between the spindles of the part and the tool is necessary. Once all these parameters mastered, machining times and therefore productivity are matchless.

Document		ISBN	Pages
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Influence of Manufacturing Variations of Spline Couplings on Gear Root and Contact Stress

Hareesh Kurup and Carlos Wink

Involute splines are widely used in mechanical systems to connect power transmitting gears to their supporting shafts. These splines are as susceptible as gears to manufacturing variations, which change their loading pattern and may eventually lead to failures. The influence of manufacturing variations of spline teeth on performance and failure mechanisms of spline couplings is available in the literature. Similarly, the influence of manufacturing variations of gear teeth on gear tooth stresses, and gear noise has been extensively studied. However, the effects of manufacturing variations of spline teeth on gear tooth contact, noise, and stresses remain unseen in publications. This study investigates how manufacturing variations of spline couplings affect gear performance. A parametric study was done on a spur gear set and a helical gear set to determine the amount of gear mesh misalignment caused by manufacturing variations of spline teeth. Spline parameters, such as tooth alignment and spline side fit were considered. The changes in gear contact and bending stress patterns were also investigated.

Document		ISBN	Pages
19FTM17		978-1-64353-056-7	14

Chamfering of Cylindrical Gears - New Innovative Cutting Solutions for Efficient Gear Production

Gottfried Klein

Cylindrical gear chamfering and deburring is a rather ‘unloved’ process that adds cost but without delivering readily apparent improvements in gear quality. However, the chamfer process, when performed correctly, provides significant advantages for downstream handling and processing. This is why manufacturers of automotive- and truck-sized gears are increasingly exploring new technologies to chamfer their gears.Two major chamfer technologies are used: forming and cutting. While chamfer rolling is a highly proven forming process that has been used for decades mainly in mass production, cutting chamfer technologies are of increasing market interest due to cost reduction and increased quality requirements; especially in dry cutting conditions.This paper will cover new chamfer cutting processes: Chamfer Contour Milling and Chamfer Hobbing and compare them with the existing chamfer roll technology.Chamfer Contour Milling uses a universal fly cutter tool with indexable carbide inserts. Chamfer angle and chamfer size depend on programmable machine movements. Therefore, this process provides highest flexibility for coarse pitch gears – even with different modules, pressure angles or number of teeth.Chamfer Hobbing has been developed for modern gear production focusing on low tool cost per part with dry cutting and short cycle times in mass production. As for the left and right gear flank, separate and dedicated chamfer hobs are used to meet most customer specifications in the market.By comparing the advantages and limits of the aforementioned chamfer processes in gear production for workpieces up to 400 mm diameter and module 8 mm, it is possible to select the right process depending on the specific requirements.

Document		ISBN	Pages
19FTM16		978-1-64353-055-0	21

Material Properties and Tooth Root Bending Strength of Shot Blasted, Case Carburized Gears with Alternative Microstructures

Karl Jakob Winkler, Christian Güntner, Thomas Tobie, Karsten Stahl, and Stefan Schurer

Case hardening is one of the most common heat treatment processes for highly loaded components such as shafts and gears. Due to numerous investigations and according to the material requirements for quality grade MQ and ME in part 5 of ISO 6336, a microstructure consisting of martensite with less than 30% retained austenite is favorable for a high load carrying capacity.A former research project focused on the load carrying capacity of carbonitrided gears with alternative microstructures. In this research project, the carbonitrided gears with an increased amount of retained austenite of up to 65% showed a higher tooth flank load capacity than standard case carburized gears. At the same time, the tooth root bending strength was not influenced in a negative way. The question arises, how different alternative microstructures influence material properties and thus affect the tooth root bending strength of gears.This report states the results of current investigations on material properties such as hardness depth profile, residual stress condition and amount of retained austenite as well as the tooth root bending strength of gear variants with different alternative microstructures. All gear variants are shot blasted after the heat treatment and made out of the materials 20MnCr5 and 18CrNiMo7-6.The tooth root bending strength in the high cycle fatigue regime of these gear variants is not inferior compared to standard case carburized gears. In the cycle regime of limited life, the tooth root bending strength can be increased as well as decreased by the alternative microstructures.As consequence, when regarding the tooth root bending strength, certain alternative microstructures, which are different to the recommendations of part 5 of the standard ISO 6336, can be tolerated. This means consequently, that if the tooth root bending strength is tested and acceptable, alternative microstructures can increase the tooth flank load capacity for shot blasted, case carburized gears.

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Performance and Properties of a New, Alternative Gear Steel

Lily Kamjou and Joakim Fagerlund

In the ongoing strive for light weighting or power densification, high-performance clean steels are showing a significant improvement. As a next step, gear steels that combine several properties, are now proving an interesting alternative. Traditional gear steels achieve their maximum hardness after carburizing and a fast quench. A fast quench usually results in distortion as the part is unavoidably unsymmetrically cooled/quenched. For many gear applications, distortion during heat treatment of final component, can add cost and unwanted hard machining operations. With many components being more sensitive to distortion, especially within electrical vehicles, where NVH becomes even more important, the potential to reduce distortion from heat treatment can be essential. With a new steel composition, that hardens by precipitation hardening (aging around 500°C/950F) low distortion can be attained as a fast quench such as an oil quench is not necessary. This type of steel can be both nitrided and carburized. Costly hard machining can therefore be reduced due to the low distortion. Other interesting properties of this new steel that will be presented in this paper are; good mechanical properties at elevated temperatures and good corrosion and oxidation properties compared to traditional gear steels.

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19FTM14	978-1-64353-053-6	10

4D High Pressure Gas Quenching - A Leap in Performance vs. Press Quenching

Thomas Hart and Dr. Maciej Korecki

Thermal processing and quenching of steels for hardening is a well-established practice performed by various techniques over the centuries. A common thread has been the unpredictable nature of the size change during the quenching process, which is known as dimensional change or distortion. Material distortion is the undesired trade-off between the development of proper mechanical property and the necessity of rapidly quenching the material from elevated temperatures into a quenching media (i.e. brine, water, polymer, oil, gas, molten salt, etc.). Due to this compromise, users have been attempting to reduce part distortion because once a component is hardened, it becomes very difficult and costly to remove excess material or form the part back into its original shape. When one looks at the bearing and gearing industries, materials typically are hardened via austenitizing and quenching. Not only do these components require high hardness and wear/corrosion resistance, they also require high dimensional precision to tight tolerances as well as repeatability of results. One of the most common way to reduce material distortion when quenching is a method by which a heated component is placed in a special fixture and a steady force is applied to the component, which allow the part to resist material deformation when the quenching media is applied. This method of quenching is known as “press quenching” and requires specialized equipment, manual or robotic handling, custom die sets and high maintenance as well as being operator dependent to achieve consistent results. It is well known that machining after heat treatment is one of the most costly and difficult tasks to complete in the entire manufacturing life cycle. This is why an extreme amount of engineering is devoted to the prevention of distortion of a component to ease the post heat treatment machining operations. With the ever prevailing desire to lower the cost of raw materials and still maintain proper mechanical performance, extreme amounts of pressure are applied to the heat treatment process to bring up the quality level of the low cost steel. When using these low quality steels, they are prone to high levels of distortion during the quenching process, such that they distort more than the allowable amount and either become too challenging to hard machine or are not able to be used all together. ~4% of the price for a hardened component is attributed to the removal of post heat treatment material to so that it meets the finished size requirements. When users can control distortion, they lower the overall cost of the component. This paper will introduce the latest achievements in the advancement of distortion control by way of 4D High Pressure Gas Quenching (HPGQ) versus press quenching. Both processes quench a single part at a time but the 4D HPGQ process does not subject a part to any clamping forces or issues associated with liquid quenching inconsistencies. The 4D HPGQ process results in every single part being heated and quenched identically the same at surprisingly low gas pressures thus producing extremely accurate dimensional variation with highly repeatable results. 4D HPGQ systems are easily integrated into current manufacturing environments and the process is a revolutionary advance in quenching technology, which has been shown to reduce or even eliminate the need for expensive & difficult post hardening manufacturing processes.

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19FTM13		978-1-64353-052-9	16

Tooth Root Testing of Steels with High Cleanliness

Moritz Trippe, Christoph Löpenhaus, Christian Brecher, Lily Kamjou, and Elias Löthman

The power density of gearboxes is continuously increased through different research activities. Besides new material developments, steel cleanliness comes to the forefront in order to meet future requirements regarding load carrying capacity of gears. The experimental quantification of load carrying potentials for high quality steels is the basis for introducing cleanliness as a design parameter.In this paper, investigations on the tooth root load carrying capacity of steels with different cleanliness levels are presented. The investigations are carried out on a pulsator test rig with a standardized FZG-C gear geometry. To determine and compare the different behaviors of the tested steels, correct force application in the test rig needs to be ensured. By this, it is possible to clearly separate the endurance strength for different cleanliness levels within the same steel grade composition.For the pulsator testing, an approach for checking and ensuring correct clamping of the gears is presented. Using this procedure, endurance tests on conventionally manufactured gears with different cleanliness levels are carried out. Resulting mean values of the tooth root strength as well as scattering of test results is evaluated, and the influence of higher cleanliness on an increasing mean value and decreasing scattering is proved. The confidence level of the mean value is discussed regarding the overall number of tests.As a conclusion, the impact of steel cleanliness on increasing endurance strength and decreasing scattering is separated from manufacturing and testing influences. A higher level of cleanliness takes into account the influence of the occurring failure mechanisms. Especially for applications with a high manufacturing and surface quality, high quality steels show a high potential for increasing the load carrying capacity and thereby the power density of the gearbox.

19FTM12		978-1-64353-051-2	16

Evaluation of Steel Cleanliness By Extreme Value Statistics and its Correlation With Fatigue Performance

Trishita Roy, Cassie L. Smith, Nikhil Deo, Carlos Wink, and Jason Carroll

Nonmetallic inclusions, primarily oxides play a significant role in the fatigue performance of components such as bearings and gears that undergo fatigue loading. This leads to an increased demand for cleaner steel for longer-life applications. Due to the advances made in steel making processes in the past decades, the oxygen level as well as inclusion size and distribution have been brought under remarkable control enabling production of high-quality steel. Consequently, the earlier inclusion rating methods such as ASTM A534, ASTM E-45 that use a comparison with standard micrographs are insufficient to render an effective comparison of cleanliness of steels from different heats or suppliers, especially for the cleaner heats. It thus becomes imperative to find a reliable method to predict the size of the largest inclusions present in a steel volume and to further correlate it with the fatigue limit of steel. This is another limitation of the existing inclusion rating methods. Extreme value analysis is a method that can surmount these limitations and it comprises of examination of a small area of steel by Optical or Scanning Electron Microscopy to predict the maximum size of inclusions which may inhabit a larger volume of steel.In this work, the effect of inclusion size distribution on fatigue performance is investigated from the experimental data obtained using ultrasonic fatigue testing. Extreme value analysis is used to predict the characteristic size of the largest inclusion based on the metallographic observations on polished surfaces and this inclusion size is then correlated with the fatigue limit measured by ultrasonic fatigue testing, making use of the Murakami approach.

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Opportunities of Efficiency Improvement by the Use of Hydro Lubricants

Matthias Pfadt, Elena von Hörsten, and Balasubramaniam Vendudusamy

The majority of industrial lubricants are still based on mineral oils due primarily to low cost and good compatibility with other oils, although different base fluid types exist in the market. However, despite their widespread use, conventional lubricants reach functional limits in various scenarios. In addition to the limitations of natural resources, their safe and environmentally sound handling, use and disposal often require considerable efforts. At the same time, industrial operators’ expectations towards innovative specialty lubricants are increasing. They range from operational and food safety to biodegradability, longer life cycles and reduced emissions and energy consumption.While searching for a material that meets all of these general and branch-specific requirements, water is a visionary but yet an obvious raw material available worldwide, non-toxic, non-combustible. The benefits are clear, but some challenges include its low viscosity, evaporation, freezing point, corrosiveness and sensitivity against microbiological growth.Hydro Lubricants unfold their innovative traits by using water either as a base oil or as an additive, hence the name ‘‘Hydro Lubes’’. Initial results indicate that it is a promising technology with a great potential to deliver high performance; some include high thermal and electric conductivity, superlow friction and good load carrying capacity on the FZG four-square test machine. Some key challenges of Hydro Lubricants like pour point, corrosion protection and microbiological growth have been solved by proper and advanced formulation. With the wide range of benefits, different Hydro Lubricants have been developed for applications like gears and hydrodynamic bearings.Hydro Lubricants offer a more sustainable solution and are potential candidates for a wide range of industrial applications that particularly demand for huge energy savings.

Document		ISBN	Pages
19FTM10		978-1-64353-049-9	10

Computing Gear Sliding Losses

Caleb Gurd, Carlos Wink, John Bair, and Claudia Fajardo

Accurately predicting frictional losses is critical for increasing gearbox efficiency. Whereas several empirical algorithms are available for numerically predicting coefficient of friction and gear sliding losses, a systematic evaluation of these is necessary to establish their accuracy and range of applicability. This paper evaluates nine different algorithms available in the literature for determining coefficient of friction and calculating gear sliding loss, and their applicability to commercial vehicle transmissions. Power loss results are compared initially to the experimental data from a standard FZG gear set, and then to two transmissions with helical gears for a range of operating torque, speed, and temperature. The differences between predictions and measurements are discussed for each algorithm evaluated and a recommendation is presented for improved accuracy within the application range investigated. The findings of this study might help gear engineers select the appropriate algorithm for calculating gear sliding losses, and ultimately increase gearbox efficiency.

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19FTM09	978-1-64353-048-2	17

Reduction of the Tonality of Gear Noise by Application of Topography Scattering for Ground Bevel Gears

Marcel Kasten, Christian Brecher, Christoph Löpenhaus, Andreas Lemmer, Werner Bläse, and Rolf Schalaster

The noise behavior of transmission is mainly caused by the excitation in the gear mesh. The standardized design and calculation methods for gears concentrate on the reduction of the excitation level. However, often the physical noise characteristics do not conform with the human noise perception. Thus, gear design rules and guidelines are required that are able to rate the excitation according to the perception. The effect of the targeted topography scatter generally described is the reduction of the gear mesh amplitudes with an increase of the background noise. In this report, the noise behavior of bevel gears is investigated with a targeted topography scattering. The excitation and noise behavior is analyzed from the excitation in tooth contact by transmission error measurements up to noise emission in the form of airborne noise. Finally, it is the objective to evaluate the impact of individual topography scattering on the dynamic noise behavior. The analysis of the noise behavior of two variants are compared regarding the difference in psychoacoustic parameters such as loudness and tonality. The potentials of the topography deviation for the optimization of ground bevel gears in terms of tonality reduction will be shown by test results. A test fixture for the evaluation of the operational behavior under loaded and dynamic conditions will be used. Finally, the method is applied to a vehicle transmission and the noise behavior on the test bench and inside of the vehicle is investigated and evaluated.

19FTM08	978-1-64353-047-5	11

Leveraging the Complementary Strengths of Orbitless and Planetary Drives

Leo Stocco

An Orbitless drive is a novel fixed-ratio epi-cyclic drive which includes a second carrier in place of a ring gear. It has been shown to have superior efficiency to a Planetary drive and is shown here to produce less vibration and noise at the expense of reduced torque capacity and ratio. A prototype 16mm Orbitless drive is constructed and compared to an off-the-shelf Planetary drive. Vibrations that occur at the Planetary tooth engagement frequency are absent from the Orbitless drive. A higher quality 32mm Orbitless prototype is evaluated in a multi-stage environment in both a stand-alone and multi-stage configuration. It is shown that sound levels are reduced, sound quality is improved, and it is concluded that an Orbitless primary stage may be mated with conventional technologies to minimize NVH levels in multi-stage gear drives.

19FTM07	978-1-64353-046-8	23

Phase Management as a Strategy to Reduce Gear Whine in Idler Gear Sets

Robert White and Pravin Patil

Gear whine is controlled by managing transmission error (TE). Transmission error forces in the mesh are reacted by the bearings supporting the shafts. These forces dynamically excite the housing and cause its walls to vibrate. The walls couple with the air, making pressure waves that travel to our ears which we hear as sound. Reducing the dynamic forces on the housing reduces noise. In idler gear sets, we have an opportunity to affect gear whine by phasing the meshes. Phase is determined by the number of teeth and tooth thickness of the idler. The TE forces acting on the idler from its two meshes add vectorially and sweep out an ellipse as the gears are advanced one tooth. The size of the ellipse (magnitude of force) is related to the noise generated by the gearbox. By cleverly selecting the number of teeth on the idlers, their tooth thicknesses and the idler location, the forces from transmission error force vectors that must be reacted by the idler bearings can be substantially reduced, thereby reducing the excitation on the gearbox that causes noise.

Document		ISBN	Pages
19FTM06		978-1-64353-045-1	12

Specific Dynamic Behavior of Planetary Gears

Burkhard. Pinnekamp, Michael Heider, and Andreas Beinstingel

Gear noise is a very important contribution to the overall performance of power transmission systems. The actual gear mesh is the most decisive criterion for noise generation with two aspects: a) impact of gears getting into mesh with the previous mesh being deflected under load resulting in premature mesh begin and/or mesh interference and b) mesh stiffness variation and hereby uneven angular velocity and torsional vibration excitation. Optimized lead and profile modification as well as high values for profile and overlap ratios are basic measures to reduce noise excitation.There are specific conditions for the multiple gear meshes in planetary gear systems. Focusing on the sun pinion, it can be distinguished between simultaneous and sequential meshing. Many planetary gears are spur gears with higher excitation level than helical gears due to the lack of overlap ratio.Theory of noise generation in a gear mesh and the specific application on planetary gear systems are described in this paper. The results are illustrated by an example with test bench measurements.

19FTM05		978-1-64353-044-4	12

Design of a Double Spiral Bevel Gearset

Horácio Albertini, Thiago Cardoso, Márcio de Souza, and Diego Alves

It is known that bevel gears are used to transmit rotary motion and torque between intersected axes in case there is no possibility of using a parallel axis gearset, which are of simpler manufacture. Their most common geometries are straight bevel gear, spiral bevel gear and helical bevel gear (skew bevel gear), and all these types of gearset subject the bearings to three types of force vectors, namely: axial, radial and tangential loads which consequently influence their dimensioning. Therefore, any attempt to minimize radial and axial loads will lead to a more economical solution for the bearing's sizes.Thus, the present study aims the development of a conical gearset designed with a double spiral, expecting that radial and axial loads decrease and hence impacts the design of power transmission units, reducing the stresses acting on the bearings, and consequently their weights.Similar geometry was proposed in the past (a herringbone face gear was manufactured by Citroen); however, the manufacturing processes of that time did not allow such geometry to be developed and applied on a large scale since, in most cases, casting processes were used without a subsequent surface finishing process. Nevertheless, with the development of CNC machines with 5 or more axes and additive manufacturing processes, the design of double spiral bevel gears becomes feasible with the possibility of being applied in a wide range of applications.

Document	ISBN	Pages
19FTM04	978-1-64353-043-7	13

Optimal Polymer Gear Design: Metal-to-Plastic Conversion

Alexander Kapelevich

Recent achievements in polymer development have inspired a tendency to replace metal gears with plastic ones in many moderately loaded mass-produced gear drives. This metal-to-plastic conversion takes advantage of the benefits of plastic gears, such as low production cost, reduced weight and inertia, low noise and vibration, zero corrosion and electric current conductivity, and the advantages of the injection molding process in producing complicated multifunctional parts. However, a simple material replacement is insufficient for a successful metal-to-plastic conversion. Some polymer material limitations — low strength and wear resistance, low thermal conductivity that reduces maximum operating temperature, sensitivity to operating conditions (temperature and humidity), limited injection molding process accuracy — must be compensated for by innovative gear design. Unlike machined metal gears, which are typically constrained by standard tooth proportions and hobbing rack generation technology, a polymer gear injection molding process allows for a deep optimization of gear tooth geometry. Such optimization of plastic gears for a particular custom application, essential for a metal-to-plastic conversion, is comprehensively covered by the Direct Gear Design method.The article describes the optimal selection of operating pressure angle and contact ratio to maximize load sharing between contacting tooth pairs, and root fillet optimization to minimize root stress concentration.The article presents a numerical example of a metal-to-plastic conversion, comparing a standard steel gear pair to its replacement polymer gears, whose optimal design utilizes all the advantages of polymer materials and compensates for their limitations. It outlines basic guidelines for optimal polymer gear design.

Document	ISBN	Pages
19FTM03	978-1-64353-042-0	24

Spline Centering, Piloting, and Toggle: Torsional Stiffness, Shaft Bending, and Centering of Moment Loads

Stephen McKenny and Dustin Eseltine

Common practice for a splined joint is to assume that the load is theoretically transmitted along the entire length of the tooth face, but several factors, including axial spline length and the ratio of hub to shaft torsional stiffness, can impact how the load is distributed along the tooth face. Previous papers have considered the effect of pure torque and combined torque plus radial load, but few have described the impact of splines loaded with torque plus both moment and radial load.A spline with short axial length, if sufficient torque is applied, can center a hub that is subjected to a radial load. A sufficiently long spline may be able to center a hub that has both radial and moment loads acting upon it – but if the hub torsional stiffness is much higher than the shaft stiffness there may not be sufficient torque transfer at the far end of the spline to center the hub against its moment load.This paper describes the behavior of spline interfaces in piloted (radially offset), full toggle, half toggle, and centered alignment states. These alignment states are created by a combination of part geometry and load conditions. Part geometry includes the influence of torsional stiffness of the hub relative to the shaft stiffness, and spline length to diameter ratio. Load conditions considered include combinations of torque, radial load, and moment load. Splines with a large length-to-diameter ratio are modeled as a set of two short splines to describe their alignment state. The amount of misalignment allowed in piloted, full toggle, and half toggle is calculated, and a chart of misalignment load factor vs. torque and stiffness ratio (hub to shaft) is provided.

Document		ISBN	Pages
19FTM02		978-1-64353-041-3	17

Misalignment Compensation Spline Design

Davide Marano, Mariano Lorenzini, Luca Mastrandrea, Francesco Pulvirenti, Massimiliano Turci, and Nicolas Fillault

Shaft misalignment is a significant problem in the design of spline joint transmissions. Involute splines with flank line crowned teeth are a solution to compensate shaft parallel misalignments avoiding interferences between shaft and hub teeth. A precise determination of the influence of misalignment on spline load capacity can be performed by FEM or other powerful numerical simulation.In this study a geometrical model of crowned spline joint for misalignment compensation is proposed. Flank line crowning is determined as a function of shaft misalignment and the minimum theoretical circumferential backlash.The proposed approach is adopted for the design of a spline joint, part of a high-performance automotive driveline. Finite element simulation has been performed to determine the spline loaded tooth contact pattern and optimize the theoretical crowning value. Experimental results are in good agreement with simulations.Keywords: Power transmission, Spline joint, Misalignment, Crowning, Pitch deviation, Analytical modelling, Concentration factor, Strength calculations.

19FTM01		978-1-64353-040-6	23

Electric Vehicle Transmission with Hypoid Gearset

Hermann Stadtfeld, and Hanspeter Dinner

Compact electric vehicles require a cost effective and compact solution for the location of the electric motor and the transmission. Yes, even small electric vehicles today require a transmission, if the maximal possible motor efficiency has to be available in the majority of drive conditions. Most of the existing solutions for front wheel driven electric vehicles place the eMotor and the transmission inline between the front wheels. This results in an asymmetric weight distribution as well as motor heat radiation towards one of the two front wheels. The paper presents a new design concept which utilizes a super reduction hypoid with a ratio between 7 and 15. The hypoid gearset rotates the eMotor away from the limited space between the front wheels and delivers a symmetrical weight distribution as well as a heat radiation away from the wheels. Due to the preferred one stage reduction, the proposed eDrive transmission is very compact and provides multiple possibilities for an optimal vehicle component packaging. The paper will discuss the variety of transmission designs, orientations and locations. The compact design as well as the fact that a one stage transmission minimizes the number of shafts, bearings and gears allows for a cost effective eDrive manufacture. Design and dimensioning of the transmission and its components was done with the KISSsoft system. In order to utilize a super reduction hypoid gearset for an automotive eDrive, not only the efficiency has to be high, but equally important is a high back driving efficiency. A good back driving efficiency allows recuperating maximal amounts of electrical energy for battery re-charging. To allow the optimization of the back driving efficiency the coefficient CBD (Back Driving Coefficient) is proposed. Furthermore, fundamental changes of the SRH geometry versus conventional hypoid gears had to be developed in order to achieve desirable values for CBD.

18SP1			27

Concepts in tooth thickness measurement AGMA 2002 –C16

John M. Rinaldo

Concepts in tooth thickness measurement AGMA 2002 –C16

Document		ISBN	Pages
18FTM26		978-1-64353-029-1	22

Reliability of Gears – Determination of Statistically Validated Material Strength Numbers

Michael Hein, Michael Geitner, Thomas Tobie, Karsten Stahl, and Burkhard Pinnekamp

This paper is intended to provide a review on the statistical reliability behavior of cylindrical gears with regard to pitting and tooth root breakage failures. A mathematical reliability approach was developed and drafted to expand standardized load capacity calculation methods. The deduced models and procedures allow the consideration and conversion of different reliability levels in the design process of cylindrical gears. Practical examples of the research are provided.

18FTM25		978-1-64353-028-4	15

Combining Ultra-High-Strength and Toughness for Affordable Power Densification in Steel Gears

E. Buddy Damm

In the last few years, improvements in clean steel technology have been coupled with development of new ultra-high-strength, high-toughness steels. These technologies provide affordable solutions for critical, power-dense components. This paper reviews and compares steel cleanness metrics between re-melted steels and steels that meet AGMA grade 3 cleanness. The new steels provide yield strengths ranging from 175-210 KSI, ultimate tensile strengths ranging from 230-250 KSI, and Charpy impact energies ranging from 35 to 50 ft.-lbs., allowing these grades to provide longer life, more power, and/or lighter weight. The higher fatigue strength of these steels is compared to more commonly used gear steels, and an analysis is presented that illustrates a potential for either a 30% reduction in gear set mass or a 45% increase in gear set torque capacity.

18FTM24		978-1-64353-027-7	13

Residual Stress Measurement of Case Hardened Steel Gears

David Easton

Aerospace gear components are required to demonstrate excellent load carrying and endurance characteristics. Case hardened steels are often utilized for these parts, but often residual stresses are developed. These residual stresses are known to have a significant effect on distortion during the heat treatment and machining processes. This paper presents research conducted on gears manufactured from two different starting points: as-received bar material and hot-forged billet. This paper will also discuss the results of the work and compare the two sets of spur gears.

18FTM23		978-1-64353-026-0	16

Lean Heat Treatment for Distortion Control

Volker Heuer and David Bolton

Controlling distortion is of key importance during the case hardening process in the production of gear components. By effective control of distortion and the variation of distortion, significant costs in post-heat treatment machining processes can be avoided. This paper focuses on new vacuum furnace designs that allow the treatment of small batches in a single layer of parts (2D treatment), which allows for easy automated loading and unloading of the fixture-trays. When performing case hardening, the components are Low Pressure Carburized (LPC) at high temperatures, followed by gas quenching. The treatment in single layers offers an optimum quality with temperature homogeneity; quench homogeneity; and distortion control.

Document	ISBN	Pages
18FTM22	978-1-64353-025-3	14

Integrated Approach for Gear Testing of High-Performance Clean Steels

Dieter Mevissen, Christoph Löpenhaus, Lily Kamjou, and Elias Löthman

The power density of gearboxes is continuously increased by different research activities. Besides new material developments, the cleanliness of steels comes to the forefront in order to meet future requirements regarding load carrying capacity of gears. This paper discusses an integrated approach for gear testing of steels. In order to determine the differences between steels of different cleanliness levels, the testing approach has to be improved as a whole.

18FTM21	978-1-64353-024-6	16

Integrating Non-Contact Metrology in the Process of Analysis and Simulation of Gear Drives

Alfonso Fuentes-Aznar and Ignacio Gonzalez-Perez

Non-contact metrology allows for a very fast collection of points on the measured gear tooth surfaces, with data rates that can be as high as millions per second. It is a wealth of information about the gears. This paper discusses using this data for reverse engineering, noise root cause analysis, or as a baseline for stress information for further gear design optimization. Also presented is an approach on integration of non-contact metrology to enhance current methodology of analysis and simulation of gear drives.

18FTM20	978-1-64353-023-9	14

Fully Automated Roughness Measurement on Gears, Even on the Shop Floor

Georg Mies, Klingelnberg

For many years, the focus of the design of precision components for transmissions has been on optimizing gear geometry. The work in this area has come so far that we are now seeing a shift from design to a concentration on surface quality of the functional surfaces. The roughness of highly stressed gear flanks has significant influences on noise, wear, and power loss. Thanks to new or improved machining technologies, extremely smooth surfaces can now be produced cost-effectively. The need now arises for reliable measurement of roughness of gears. This paper discusses the newest solution that enables fully automatic measurements of gear geometry and roughness in one clamping.

18FTM19	978-1-64353-022-2	14

Method for High Accuracy Cutting Blade Inspection

Haris Ligata and Hermann J. Stadtfeld

Inspection of the cutting blade is a crucial step in the manufacturing of bevel gears. The proper blade geometry ensures that the desired gear tooth form can be achieved. The accuracy of the process can be compromised when the blade consists of several small sections, or when dust particles, surface roughness, or floor vibration during the data acquisition occurs. This paper highlights a new method for improving the robustness of the inspection process in such cases. A proposal for using larger portions of the blades to evaluate the properties of the small features will be shown. The paper discusses the methods developed and provide several examples of gears made using these methods.

Document	ISBN	Pages
18FTM18	978-1-64353-021-5	13

Reducing Tool Wear in Spiral Bevel Gear Machining with the Finite Element Method

Fang Hou, Yantao Zhang, Syed Wasif, Pete Mattson, and Kerry Marusich

Due to the complexity of spiral bevel gear machining, the cutting tools can be a significant cost of gear manufacturing. Unlike the price of material which is fixed by the market, the cost of tooling and subsequent re-grinding can be reduced through reducing tool wear and increasing tool life. This paper discusses an alternative approach to physical testing for predicting and reducing tool wear using the finite element method. This virtual design approach utilizes real-world cutting tool geometry, automatically generated gear blanks, and known process kinematics to simulate the cutting process. Additionally, lessons learned, potential benefits and pitfalls of this approach to tool wear reduction and future work will be discussed.

18FTM17	978-1-64353-020-8	19

Generative Gear Milling

Yefim Kotlyar

This paper discusses Generative Gear Milling, an innovative software feature for gear cutting. The involute generative principle is based on an incremental positioning of a simple and inexpensive milling “disk” cutter with trapezoidal or parallel sides on the “line of action.” The paper outlines the needs for this procedure and the applications of generative milling. And, the author discusses the benefits of Generative Gear Milling, including improved efficiency; reduced cutter cost and delivery time; and expanded pitch range capability.

18FTM16	978-1-64353-019-2	23

Microgear Measurement Standards: Comparing Tactile, Optical and Computed Tomography Measurements

Stephan Jantzen, Martin Stein, Karin Kniel, and Andreas Dietzel

Microgears are widely used in industry, as they are essential components of gearboxes used in precision engineering, medical technology, and robotics. This paper discusses the development of a new internal involute microgear measurement standard for research and industry. A comparison between the tactile calibration performed using a micro coordinate measuring machine (μCMM) and the measurement results obtained by means of a computer tomography (CT) system and optical CMM will be presented. The new results, compared with the results of the comparison measurements of the external microgear measurement standard, are discussed. The results and discussion will provide an overview of the state of the art in microgear metrology.

18FTM15	978-1-64353-018-5	17

Potentials of Free Root Fillets in Planetary Gearbox Applications

Jonas Pollaschek, Christian Brecher, Christoph Löpenhaus

Planetary gear stages are commonly used in many different fields of application, including wind turbine and automotive gearboxes. This paper discusses the potential for increased root load carrying capacity at the planet gear of a planetary gear application. The approach considers local material characteristics such as hardness, fatigue strength, and mean stress sensitivity, as well as residual stresses and different stress rations that result from the mesh with the sun and ring gear. It offers a detailed tooth contact analysis based on the Finite Element Method. The result of this work allows for the possibility of changes in the gear design.

Document	ISBN	Pages
18FTM14	978-1-64353-017-8	12

Fatigue Life Predictions of Spherical Gear Couplings

Ibai Ulacia, Jon Larrañaga, Aitor Arana, Aurea Iñurritegi, and Julen Elizegi

Spherical gear couplings are mechanical components that allow transmitting torque by means of equally spaced teeth. Modern roll-leveling machines are characterized to level high-strength steels by using small rolls under high torque requirements. The small size of the rolls decreases the space between the spline couplings, causing misalignments up to 7 degrees. This paper discusses a geometry-generating procedure that has been developed for both the hub with internal teeth and the crowned teeth shaft in spherical gear couplings. A finite element model has been developed to study the effect of backlash and misalignment on the number of teeth in contact and root stresses. Finally, fatigue tests are performed, and numerical predictions are correlated with experimental results.

Document	ISBN	Pages
18FTM13	978-1-64353-016-1	9

Impact of Root Geometry Manufacturing Deviations from a Theoretical Hob Rack on Gear Bending Stress

Rahul V. Nigade and Carlos H. Wink

Gear reliability is a key requirement of any automotive transmission. Two common failure modes of gears are pitting and bending fatigue. So, the total gearing reliability depends upon the bending and pitting reliability. This paper discusses a comparison of a theoretical root fillet geometry generated by the hob racks of gear drawings to an actual measured tooth fillet geometry of manufactured gears, which determines the impact of the different root fillet geometries on tooth bending stresses. An emphasis is placed on the importance of using a root fillet geometry truly representative of the actual gears in production for the bending stress calculation so that the required bending reliability can be achieved in the field.

Document	ISBN	Pages
18FTM12	978-1-64353-015-4	18

Load Intensity Distribution Factor Evaluation from Strain Gauges at the Gear Root

José Calvo Irisarri, Unai Gutierrez Santiago, Alfredo Fernández Sisón, and Pedro Olalde Arce

Strain gauges are commonly used to obtain the load intensity distribution on the flank of a gear mesh. To get the load distribution on the flank, the strain data must be processed and changed into load intensity distribution on the tooth flank. Research has been conducted on the best methodology to place strain gauges when calculating load intensity distribution on the flanks of a gear. This paper discusses these research methods that use FEM models and his analysis of how to deal with the effect of strain gauge positioning errors, in order to find the optimal placement.

Document		ISBN	Pages
18FTM11		978-1-64353-014-7	21

Optimization of Power Density by Local Gear Failure Modeling

Marco Kampka, Christian Brecher, Christoph Löpenhaus

Power density is a key factor in gear design. Increasing the power density enables engineers to use smaller gears for their applications, which leads to smaller and lighter gear boxes. The most common way to design gears is using industry standards in which material strength can be obtained either from fatigue limit tables or by means of empirical formulae. Due to limited empirical data, a lot of averaging and approximations are used to make the available standards applicable to a wide range of applications. To design the gear closer to the power density limit, a high level of information is necessary. The paper shows how local FEA-based calculation approaches can be used to design gears closer to their power density limits for pitting, tooth root breakage, and flank fracture. The calculation results will be validated in running tests on different test rigs.

18FTM10		978-1-64353-013-0	17

Experimental Study on the Pitting Detection Capabilities for Spur Gears Using Acoustic Emission and Vibration Analysis Methods

Mateusz Grzeszkowski, C. Gühmann, P. Scholzen, Christoph Löpenhaus, S. Nowoisky, and G. Kappmeyer

This paper discusses an experimental investigation on spur gears to characterize the pitting degradation process using monitoring features. Previous investigations have revealed that pitting has an impact on the gear vibration behavior. But is it possible to detect pitting at an early stage using acceleration sensors and acoustic emissions (AE) sensors to avoid consequential damages and subsequent correction activities? The paper will discuss this experimental investigation on spur gears to characterize the pitting degradation process using monitoring features. Also included is a discussion of the results of the investigation, including how the results show that a detection of pitting is possible several hours before complete gear failure, and more.

18FTM09		978-1-64353-012-3	15

Application of Finite Element Analysis for the Strain Wave Gear Tooth Surfaces Design and Modifications

Zhiyuan Yu and Kwun-Lon Ting

This paper is on a rigorous definition and parametric study of tooth surface modification of the strain wave gear. You will see that optimal modification for a sample strain wave gear is found from FEA and tested by contact pattern, transmission error, and life cycling experiments. The resulting innovative design with modified fully conjugate tooth surface improves accuracy, backlash, and the life of the existing design.

18FTM08		978-1-64353-011-6	17

Oil-Off Characterization Method Using In-Situ Friction Measurement for Gears Operating Under Loss-of-Lubrication Conditions

Aaron C. Isaacson and Matthew E. Wagner

The oil-off performance evaluation of gears is of significant interest to the Department of Defense and various rotorcraft manufacturers, so that the aircraft can safely land in an accidental loss-of-lubricant situation. However, unlike typical gear failure modes, gear failure in an oil-off situation is very rapid and likely catastrophic. This paper describes the procedure and instrumentation utilized for an oil-off test to measure the frictional loss in the test gear mesh and the “air” temperature just out of mesh. Sound and vibration data was also recorded during testing. Data from typical failures showing the detection of scuffing onset and its progression to catastrophic failure for gears made from several aerospace alloy steels is presented.

Document		ISBN	Pages
18FTM07		978-1-64353-010-9	13

Influence of Thermal Distortion on Spur Gear Tooth Contact

Jon Larrañaga, Ibai Ulacia, Aurea Iñurritegi, Aitor Arana, Jon German, and Julen Elizegi

The reduction of component size and oil volume of current automotive and aeronautical transmissions, along with the increasing input speeds, are pushing gear teeth bulk temperatures to their scuffing limit. Even with development of new lubricant additives and coatings, high temperatures may produce other issues. This paper analyzes the effects of thermal distortion on the profile geometry and tooth contact parameters in the transverse plane of a spur gear by calculating the steady-state temperature distribution relevant to immersion depth, sump temperature, and lubrication regime in the contact area. Then, thermally distorted geometry and tooth contact analysis is computed by means of a 2D finite element model where load distribution, transmission error, backlash, and other parameters will be analyzed. The results of the study will allow one to set the limits of design backlash to avoid gear jamming and to size the initial profile shift or tooth modifications to reach the desired contact behavior.

18FTM06		978-1-64353-009-3	17

Design and Optimization of a Hybrid Vehicle Transmission

Massimiliano Turci

Hybrid vehicles seem to be the fastest solution for the containment of consumption and of pollution for personal transport. The designer of a hybrid transmission has to address additional issues with respect to the classical cases, in particular the high speed of the electric unit and the bidirectional motor/generator operation. In this case, a lot of attention should be paid to how to consider the four combinations of signs for torque and speed in the load spectrum. This paper discusses several approaches for the alternating bending factor, the effects of the asymmetric crowning (especially the helix modification tapered or parallel) and how to consider the housing stiffness in the TCA. Also included is an interesting solution from the kinematic point of view, the compound planetary, relatively well-known in the automotive, but much less so in industrial gearbox design.

18FTM05		978-1-64353-008-6	10

Increasing Static Friction with Laser

Gerhard Flores

Flat and curved surfaces with the functionality of high static friction are increasingly needed for force-fitted nonslip power transmissions. This is especially true for con rod and cam structuring for high torque resistance or front face connections of sprockets, gears, or cam shaft adjustments. Expensive solutions such as diamond layers, diamond coatings, or form fitting design are increasingly being substituted. A modified laser process with defined exposed micro structures is the alternative for innovative manufacturing. Exposed micro melting burrs of smaller micrometer height with martensitic material structures are the precondition for the required high friction. So, such high static friction surfaces can be produced economically with repeatability of small tolerances in high-volume productions.

Document	ISBN	Pages
18FTM04	978-1-64353-007-9	20

Gearbox Development for the Food and Beverage Processing Industry

Sandeep V. Thube

Industry-specific power transmission needs can be efficiently served by a streamlined product development process. The 'Food and Beverage' industry has a variety of gearbox applications which are regulated by governmental industry standards, such as NSF and FDA. The scope of this paper is to design and construct a gearbox in compliance with these standards, which may be substantially different from typical industrial requirements.The paper discusses details of a gearbox development for food and beverage applications. It mainly includes stainless steel housing and shaft designs, as well as oil seal, bearing and lubricant selections. The development process utilizes tools, viz. Quality Function Deployment (QFD), Failure Mode Evaluation Analysis (FMEA), computational 'Finite Element Analysis' (FEA), and 3D printing followed by prototype testing. QFD is used to prioritize features to be included in the product. Potential failures of the gearbox are identified with FMEA. The structural and thermal optimization of the newly designed housing is performed using FEA. 3D printing is utilized to find design defect at early stage, and validate the gearbox assembly procedure. Minimizing the number of physical prototype testing and iterations is the primary objective for the utilization of these tools.

18FTM03	978-1-64353-006-2	13

Optimization of a Rack and Pinion Design for Offshore Jack-Up Applications

Adrian Nowoisky

Lift boats or Jack up oil rigs are essential for the oil and gas industry. One offshore jacking system is pinion and rack to elevate legs and hull in operation. It is well known that rack and pinion of such applications exceed the permissible contact stress by the factor of 2 to 5. The design and evaluation of such systems is still a technical challenge. The pinion will be typically highly modified and analyzed based on the Hertzian contact stress theory of two cylinders in contact. This method will show how to start with a basic rack and pinion design. The true involute profile of the pinion will be replaced with a multi radii profile. In a second step, the pinion design will be analytical optimized to reduce the contact stress and improve the life expectation. The influence of major gear parameter such as module, profile shift coefficient as well as the pressure angle will be analyzed and explained. The results of the final pinion will be compared with an existing pinion design to evaluate and discuss a reuse of existing hardware. The results of the final designs will be verified by a numerical method. This paper demonstrates the impact of major gear parameters for a pinion design and their impact on the life expectation. The benefit of a custom pinion design and how much improvement can be achieved with emphasizing the design process properly will be shown. Furthermore it shall serve as a guideline for best practice to design a rack and pinion for offshore jacking applications.

18FTM02	978-1-64353-005-5	16

Methods to Determine Form Diameter on Hobbed External Involute Gears

Shuo Zhang

Two mathematical methods have been developed to be used for the calculation of true involute form diameter when specialized software or original gear designer information is not easily accessible. These methods are designed for external involute gears produced by the hobbing process, possibly followed by a finishing operation. Method A is a more precise match, but it requires special inputs that may be time consuming without special software. Method B, although not as accurate, still has relative error of TIF diameter below 0.1% over wide ranges of gear design parameters. Method B is also easy to apply and can be integrated into most existing gear design programs.

Document	ISBN	Pages
18FTM01	978-1-64353-004-8	15

Filling Some Gaps in Spline Design Guidelines: Centering, Friction, and Misalignment

Stephen McKenny

International spline standards and other widely used published documents have detailed definitions of two-dimensional spline geometry, and while they cover basic axial effects and stresses, more can be provided for design engineers. Results from an analytical study of misalignment factors and an experimental study of centering forces are discussed to provide information to help refine calculation methods. These include: how to calculate the effective pressure angle of straight-sided splines that must be used to accurately determine normal and radial loads; how to calculate the effective centering force of a spline pair; how to calculate the centering moment of a spline with ‘topping’; an update to current publications; and an update to the calculation of the maximum axial force that a spline can transmit via friction.

Document	ISBN	Pages
17SP4		24

Reverse Gear System Engineering. Why, When, How & What. Avoiding Pitfalls...& Litigation! A Practical Guide for the Design Engineer

Raymond J. Drago, P. E.

Reverse Gear System Engineering. Why, When, How & What. Avoiding Pitfalls...& Litigation! A Practical Guide for the Design Engineer

Document	ISBN	Pages
17SP3		45

Gear failure analysis and lessons learned under unanticipated loadings conditions

Anngwo Wang

Gear failure analysis and lessons learned under unanticipated loadings conditions

Document	ISBN	Pages
17SP2		29

On the Link Between Steel Cleanness Metrics and Component Performance

Dr. Peter C. Glaws

On the Link Between Steel Cleanness Metrics and Component Performance

Document	ISBN	Pages
17SP1		44

Indexing Error and Dynamic Factors of Spur Gears

David Talbot

Indexing Error and Dynamic Factors of Spur Gears

Document		ISBN	Pages
17FTM23		1-55589-764-2	19

The Influence of a Grinding Notch on the Gear Bending Strength Rating

Ulrich Kissling, Ioannis Zotos

To achieve the requested quality, most gears today are ground. If the gear is premanufactured with a tool without protuberance, then at the position where the grinding tool retracts from the flank, a grinding notch in the tooth root area is produced. A review of the formulas to calculate the effects of the grinding notch is necessary. A 3D-FEM analysis that was used to deduce an improved formula will be presented.

17FTM22		1-55589-763-5	14

Full Contact Analysis Versus Standard Load Capacity Calculation for Cylindrical Gears

Michael Otto, Uwe Weinberger, Karsten Stahl

In this paper, local tooth contact analysis and standard calculation are used to determine the load capacity for the failure modes pitting, tooth root breakage, micropitting and tooth flank breakage. Analogies and differences between both the local and the standard approaches are shown. The example presented demonstrates a valid possibility to optimize the gear design by using local tooth contact analysis while satisfying the requirement of documenting the load carrying capacity by standard calculations.

17FTM21		1-55589-762-8	22

Calculation of Tooth Flank Fracture Load Capacity – Practical Applicability and Main Influence Parameters

Michael Hein, Thomas Tobie, Karsten Stahl

Due to improved material qualities, new surface finishing methods, and increased heat treatment process reliability, flank surface damages, such as pitting or micropitting, can increasingly be prevented in a reliable manner. At the same time, this may result in an increase of unexpected flank damages such as tooth flank fracture. A computer-aided calculation of the risk of tooth flank fracture damages will be presented.

17FTM20		1-55589-761-1	18

Influences of the Residual Stress Condition on the Load Carrying Capacity of Case Hardened Gears

Christian Güntner, Thomas Tobie, Karsten Stahl

Compressive residual stresses, such as those generated by shot peening, result in an increased tooth root bending strength. The author’s investigations show that shot peening can increase the load carrying capacity of case hardened gears significantly. Correlations between the residual stress state and the load carrying capacity limits were determined. This paper will give an overview of the main results of different investigations and discuss influences of the residual stress condition on different failure modes of case hardened gears.

Document	ISBN	Pages
17FTM19	1-55589-760-4	17

Sensitivity Study of Press Quench Process and Concept of Tooling Design for Reduced Distortion by Modeling

Zhichao (Charlie) Li, B. Lynn Ferguson

The press quench process includes parameters such as heating rate, austenitization temperature, applied load type, load amount, load locations from the tooling, friction between the tooling and the gear, and the quench rate. All these factors can lead to inconsistent distortion, especially for the radial size of thin-wall gears. In this paper, the effects of several critical factors on the dimensional inconsistency and tooling design are analyzed by heat treatment modeling software.

Document	ISBN	Pages
17FTM18	1-55589-759-8	23

Effect of Non-metallic Inclusions on Bending Fatigue Performance in High Strength 4140 Steel

Michael Burnett

This paper studies the fatigue performance of three sets of quench and tempered 4140 steel samples, representing three distinctly different inclusion populations. The inclusion populations for each of the sample sets were characterized using both an SEM-based image analysis system, primarily for the micro-inclusions, and a high-resolution UT system for the macro-inclusions. The sample sets were also evaluated using both longitudinal and transverse specimens in all the bending fatigue tests. The results of these tests will be presented.

Document	ISBN	Pages
17FTM17	1-55589-737-6	10

Four Ways Polyketone Polymers Can Improve Gear Performance

Tim Morefield

Historically, the most commonly specified resins for plastic gears have been acetal (POM), nylon (PA 66) and polyester (PBT), with or without modifiers (PTFE, carbon fiber, glass fiber, silicone or combinations thereof) to reduce friction and wear. Polyketone offers engineers four distinct advantages relative to other materials in meeting design challenges: 1) superior wear properties, 2) better dimensional control / stability, 3) superior creep rupture performance, and 4) quieter operation.

Document	ISBN	Pages
17FTM16	978-1-61481-400-9	14

Predicting Life on Through Hardened Steel Rack and Pinion for Jacking Applications in the Offshore Industry

Adrian Nowoisky

It is well known in the industry that, according to AGMA and ISO gear calculation methods, the contact stresses in rack and pinion systems for jack up applications exceed the permissible limits by a factor of 3 to 6. However, these applications have been in service without any failures for more than 20 years. This paper will outline the process of the analytical evaluation of a specific design and validate it with systems currently in service.

Document		ISBN	Pages
17FTM15		1-55589-664-5	16

Fatigue Performance and Cleanliness of Carburizing Steels for Gears

Joakim Fagerlund, Lily Kamjou

The cleanliness of steels used for gears is of great importance when looking to improve life of gears or increase loads. In this paper, carburizing steels with the same basic chemical composition, but with a varying cleanliness level, are compared. The investigation showed a good qualitative correlation between the fatigue performance and the inclusion assessment made by ultrasonic evaluation and SEM. The results also show that traditional micro-inclusion rating methods are not sensitive enough to give a good indication of material performance.

17FTM14		1-55589-628-7	21

Prediction of Dynamic Factors for Helical Gears in a High-Speed Multi-Body Gearbox System

Niranjan Raghuraman, Chad Glinsky, Sharad Jain

This paper will analyze the influence of operating speed, torque, system dynamics, and gear micro-geometry on the dynamic factors of a high-speed gearbox. It will show that the dependence of dynamic factor on torque is significant and must not be ignored, and that the presence of system resonance modes increases dynamic factors. The dynamic factors calculated in this study are compared with the dynamic factor values suggested by ISO and AGMA standards.

17FTM13		1-55589-627-0	45

A Comparison of Current AGMA, ISO and API Gear Rating Methods

John M. Rinaldo

There are many different gear rating methods in use today, and they can give substantially different results for any given gear set. This paper will make it easy to understand the choices and the impact the choices have on gearbox design. The eight standards examined are AGMA 2001, AGMA 6011, AGMA 6013, ISO 6336, API 613, API 617, API 672, and API 677. This paper will provide a useful aid to customers who are unsure of the differences between the standards.

17FTM12		1-55589-618-8	17

Reliability, Lifetime and Safety Factors

Stefan Beermann

This paper uses several examples to show the practical differences in using safety factors versus reliabilities. The failure probability of all components for a specific lifetime is calculated to provide the reliability of the whole gearbox as a system of components. This provides the engineer an easier method to compare designs and identify the critical components.

Document		ISBN	Pages
17FTM11		1-55589-616-4	17

FE-Based Method for Design of Robust Tooth Flank Modifications for Cylindrical and Planetary Gear Stages Regarding Manufacturing Tolerances

Christian Brecher, Christoph Löpenhaus, Julian Theling, Marius Schroers, Daniel Piel

The authors present a method to evaluate the quality and stability of flank modifications regarding manufacturing tolerances during the design process, using an FE-based tooth contact analysis. The presented design process provides a method to examine and simulate characteristics of the excitation behavior and durability of a gear pair. This enables the engineer to choose the most robust micro-geometry in terms of quality and stability already in the design process.

17FTM10		1-55589-613-3	19

Psychoacoustic Methodology for the Noise Reduction of Bevel Gears

Hermann J. Stadtfeld

A rather exciting conclusion from the psychoacoustic research is the proposal of a gear transmission graph which is a hybrid that connects different mathematical functions within the one pitch long contact area and the outside of this area. The results show that the hybrid transmission function dramatically changes the way bevel and hypoid gearsets will be optimized in the future for silent operation.

17FTM09		1-55589-580-8	8

Standard Samples for Grinder Burn Etch Testing

Jonathan R. Crow, Michael A. Pershing

This paper discusses a unique method for producing a standard sample of an acid etch system that has a consistent amount of thermal damage. Multiple degrees of burn are applied to the sample to ensure that the etch inspection can detect all levels of potential burn on the piece parts. The sample can then be reliably used to test an acid etch system and its method to ensure the proper amount of contrast for threshold levels of thermal damage.

17FTM08		1-55589-578-5	15

Areal Evaluation of Involute Gear Flanks with Three-Dimensional Surface Data

Yue Peng, Kang Ni, Gert Goch

This paper presents the benefits of areal evaluation of gear flanks, mathematical approaches for areal description of involute surface, deviations and modifications, and the characterization of areal data with “3D gear deviation parameters”. Approximation and orthogonal polynomial decomposition methods are applied for surface reconstruction and parameter calculation. Both simulated and measured gear data are analyzed, and comparisons with conventional evaluation results are presented.

Document	ISBN	Pages
17FTM07	1-55589-570-9	11

Magnetic Barkhausen Noise as an Alternative to Nital Etch for the Detection of Grind Temper on Gears

James Thomas, Stephen Kendrish

Magnetic Barkhausen Noise (MBN), is quantitative, repeatable, and non-destructive. Further, the MBN method is easily automated thus removing operator influence, as seen with Nital Etch, as a variable. Using a sample set of carburized spur gears ground to varying conditions of grinding burn, the MBN method is demonstrated to match or exceed the detection effectiveness of traditional Nital Etch. Residual stress depth distributions measured with x-ray diffraction and electrochemical layer removal are utilized as a quantitative verification method.

Document	ISBN	Pages
17FTM06	1-55589-568-6	20

The Effect of Asymmetric Cutter Tip Radii on Gear Tooth Root Bending Stress

Abdullah Akpolat, Nihat Yildirim, Burak Sahin, Omer Yildirim, Bulent Karatas, Fatih Erdogan

The tooth root fillet is where the maximum bending stress concentration region is located during torque transmission via gear pairs. An increase in gear root fillet radius provides a smooth transition from involute to trochoid, increases root critical section thickness, and the moment of inertia against bending of tooth. A 10-11% reduction in bending stress is obtained by using asymmetric cutter tip radii coefficients for two sides of the gear tooth profile with standard center distance and no tooth interference.

Document	ISBN	Pages
17FTM05	1-55589-567-9	11

Complete Measurement of Gearbox Components

Christof Gorgels

In today's production environment, a variety of different measurement devices, such as CMMs, gear checkers, form testers, and roughness testers, are used to assess the quality and accuracy of workpieces, many of which require specialized training and environments. This paper describes how a Circular CMM (CCMM) can be integrated into a production environment. The benefits and challenges of the use of a CCMM will be discussed.

Document	ISBN	Pages
17FTM04	1-55589-547-1	15

The Effectiveness of Shrouding on Reducing Meshed Spur Gear Power Loss – Test Results

Irebert R. Delgado, M. J. Hurrell

Reducing power losses to rotorcraft gearboxes, due to windage drag and viscous effects on rotating, meshed gear components would allow gains in areas such as vehicle payload, range, mission type, and fuel consumption. One method used in rotorcraft gearbox design attempts to reduce losses is to use close clearance walls to enclose the gears in both the axial and radial directions. This paper examines using meshed spur gears at four shroud configurations and compares the data to available data.

Document		ISBN	Pages
17FTM03		1-55589-537-2	18

Gear Tooth Strength Analysis of High Pressure Angle Cylindrical Gears

Alfonso Fuentes-Aznar, Ignacio Gonzalez-Perez

In this paper, the gear tooth strength of high pressure angle gears is studied and compared with that of conventional pressure angle gears. The comparison will be performed regarding contact pressure, contact and bending stresses, loaded function of transmission errors, and comparison of errors of alignment and shift of contact pattern when mounted in similar shafts.

17FTM02		1-55589-529-7	15

Understanding the Dynamic Influences of Gear Oils and Radial Shaft Seals

Matthias Adler, Joe Walker, Sascha Grasshoff, Craig Desrochers, Matthias Pfadt

Approximately 40 percent of long-term gearbox leakages can be traced back to poor interaction between the Radial Shaft Seal (RSS) and the lubricant. This paper highlights the most critical interactions between the industry’s most commonly used gear oil formulations, with emphasis on synthetic oils with Nitrile- and Fluoroelastomers. Through an ideal combination of base oil and additives, the demand of life expectancy on the radial shaft seals can be met.

17FTM01		1-55589-527-3	14

CFD Simulation of Power Losses and Lubricant Flows in Gearboxes

Franco Concli, Carlo Gorla

This paper describes the application of Computational Fluid Dynamics simulation of power losses and lubricant flows in gearboxes based on an original global re-meshing technique. This enables accurate predictions in relatively short simulation times, compatible with the industrial design practice. The results of the practical applications used for the validation are also included and discussed in the paper.

16SP1			19

Flank Fracture as an Example of International Standardization of German Drive Technology Applications

Dipl.-Ing. Norbert Haefke

Flank Fracture as an Example of International Standardization of German Drive Technology Applications

16FTM23		1-55589-234-0	20

A New Approach to Repair Large Industrial Gears Damaged by Surface Degradation – The Refurbishment Using the Modification of Both the Profile Shift

Horacio Albertini, Carlo Gorla, Francesco Rosa

Superficial degradation of industrial gears, and a lack of approaches to repair them, have resulted in many gears being discarded prematurely. This paper presents a computer program and method for repairing industrial gears, enabled by the recent advances in multi-axis CNC machine centers, and gear grinding, that considers the modification of both the profile shift coefficient and the pressure angle.

Document	ISBN	Pages
16FTM22	1-55589-497-9	19

Comparison of Tooth Interior Fatigue Fracture Load Capacity to Standardized Gear Failure Modes

Baydu Al, Paul Langlois, Rupesh Patel

This study aims to improve the existing understanding of Tooth Interior Fatigue Fracture (TIFF) load capacity and compare calculated load capacity to the allowable loading conditions for bending and pitting fatigue failure, based on standard calculation procedures. Possible methods that could be used to mitigate TIFF risk are presented, and the effect of these methods on the performance with respect to the other failure modes are quantified.

Document	ISBN	Pages
16FTM21	1-55589-480-1	19

Influence of Contact Conditions on the Onset of Micropitting in Rolling-Sliding Contacts Pertinent to Gear Applications

Dr. Amir Kadiric & Dr. Pawel Rycerz

Recently, increased sliding has been one of the factors suggested to be responsible for the onset of micropitting, with the proposed underlying mechanism being the potential reduction of film thickness through increased sliding speed. This paper attempts to shed light on the tribological conditions that may lead to the onset of micropitting in lubricated, concentrated contacts representative of those occurring between gear teeth. In particular, the effect of slide-roll-ratio, surface roughness and film thickness is studied.

Document	ISBN	Pages
16FTM20	1-55589-176-3	14

Influence of the Defect Size on the Tooth Root Load Carrying Capacity

Jens Brimmers, Christian Brecher, Christoph Löpenhaus, and Jannik Henser

Conventional calculation methods for the flank and tooth root load carrying capacity are well-established, but models that consider the defect size on the tooth root strength have not yet been applied in fatigue models for gears. This paper will introduce a method for calculating the tooth root load carrying capacity for gears while considering the influence of the defect size on the endurance fatigue strength of the tooth root.

Document	ISBN	Pages
16FTM19	1-55589-123-7	17

Numerical Thermal 3D Model to Predict the Surface and Body Temperature of Spur and Helical Plastic Gears

Niranjan Raghuraman, Donald Houser, and Zachary Wright

Tooth surface wear is an important failure mode in plastic gears and this primarily caused by the surface temperature increasing to a value close to the melting point of the material. Thus, it is critical to compute the temperature of the gear pair in an accurate fashion. This paper will focus on the prediction of gear temperature of plastic gears using a numerical heat transfer model based on 3D finite difference method.

Document	ISBN	Pages
16FTM18	1-55589-122-0	25

An Experimental and Analytical Comparison of the Noise Generated by Gears of Austempered Ductile Iron (ADI) and Steel Materials

Dr. Donald Houser, Samuel Shon, Kathy Hayrynen, Justin Lefevre

Many have made claims concerning the relative noise performance of Austempered Ductile Iron (ADI) versus steel as a gearing material. Predictions based on measured tooth topographies of the transmission error and "sum of forces" gear noise metrics show that the iron gears should be slightly quieter than the steel gears at loads beneath the transmission error optimization "notch" torque and slightly louder above this torque. This paper presents results from a systematic experimental study to ascertain these differences.

Document	ISBN	Pages
16FTM17	1-55589-121-3	16

Analysis of Excitation Behavior of a Two-Stage Gearbox Based on a Validated Simulation Model

Marius Schroers, Christian Brecher, and Christoph Löpenhaus

In order to reduce development and production costs of a gearbox, simulation models have been set up to predict the noise and vibration behavior of a gearbox before the prototype phase. A simulation model, verified by experimental results, is presented that is able to calculate the dynamic excitation behavior of a two-stage gearbox.

Document	ISBN	Pages
16FTM16	1-55589-120-6	14

Developing an Energy-Efficient Industrial Gear Oil

Shubhamita Basu, Daniel Wilkerson, and James Vinci

This paper describes a laboratory test rig, test procedure, and results that are focused on quantifying increased operating efficiency with various synthetic lubricant formulations. Fluid evaluations were conducted in an industrial-scale worm gear efficiency rig. Operating under a wide range of speeds and loads, the rig produced sharp differentiation among fluids for their impact on power loss and operating temperature.

Document	ISBN	Pages
16FTM15	1-55589-119-0	20

Surface Structure Shift for Ground Bevel Gears

Sebastian Strunk

A process is presented that improves the excitation behavior of a ground bevel gear set by altering the surface structure of a generated member along the path of contact from slot to slot. This process addresses this objectionable harmonic excitation by influencing each axis position in each line of the axis position table with small predetermined or random amounts.

Document		ISBN	Pages
16FTM14		1-55589-118-3	12

Impact of Surface Condition and Lubricant on Effective Gear Tooth Friction Coefficient

Aaron Isaacson, Matthew Wagner, Suren Rao, and Gary Sroka

Using a four-square, power re-circulating gear test rig with high accuracy torque transducers, losses due to operating speed, surface roughness, and torque level, including two different lubricants, were compared, and measurements of the effective coefficient of friction at the gear tooth flanks are provided. This paper summarizes the results obtained.

16FTM13		1-55589-114-5	22

Designing Very Strong Gear Teeth by Means of High Pressure Angles

Richard Miller

This paper will show a method of designing and specifying gear teeth with much higher bending and surface contact strength than that of conventional gear teeth. The primary means of achieving this is by specifying gear teeth with significantly higher pressure angles. This paper will show calculation procedures, mathematical solutions, and the theoretical background and equations to achieve this.

16FTM12		1-55589-113-8	14

Determination of Load Distributions on Double Helical-Geared Planetary Gear Boxes

Dr. Tobias Schulze

The optimization and effective utilization of planetary gearbox designs require a detailed consideration of the loads on the gears. This paper presents a computer aided calculation method that has been developed for planetary gearboxes with spur and helical gears that considers the most important influences on the load distribution. Using this information, a detailed load distribution is possible to reach the maximum capability of the gears.

16FTM11		1-55589-112-1	18

Contact Fatigue Characterization of Through-Hardened Steel for Low-Speed Applications Like Hoisting

Dr. Michel Octrue, Antoine Nicolle, and Remy Genevier

Lubrication by grease is often employed on open gears that transmit power at low speeds. The rating methods found in ISO 6336 has shown that ISO is very conservative for grease lubricated, through hardened steel gears running with case hardened pinions, specifically when considering service life. Fatigue SN curves resulting from tests will be compared and discussed with values given in ISO and AGMA gear rating standards.

16FTM10		1-55589-111-4	21

Computerized Design of Straight Bevel Gears with Optimized Profiles for Forging, Molding, or 3D Printing

Alfonso Fuentes, Ignacio Gonzalez-Perez, and Harish Pasapula

Research will be presented on whether there is a reference profile that will yeild the same advantages for bevel gears as the involute for cylindrical gears. The spherical involute and octoidal profiles will be studied, and the virtual generation of bevel gears with the different profiles will be developed, and simulated, using advanced tools such as tooth contact analysis and finite element analysis.

Document	ISBN	Pages
16FTM09	1-55589-069-8	14

Development of High Hardness-Cast Gears for High-Power Applications in the Mining Industry

Fabrice Wavelet

Multiple solutions are available to increase the transmissible power of girth gears, including using a larger module, increasing the gear diameter, enlarging the face width, and increasing the hardness of the base material. Base material hardness, the only parameter that is not limited by cutting machine size, is being increased to meet higher power needs. This paper will review the related design and manufacturing impact of the high-hardness gears needed to meet today's industry demands.

Document	ISBN	Pages
16FTM08	1-55589-068-1	17

Gear Design Relevant Cleanness Metrics

Dr. E. Buddy Damm, Peter Glaws

This paper describes the methods used to characterize premium quality clean steels through the use of statistics of extreme values (SEV), and the use of these data to perform gear design relevant engineering analysis of the potential for a gear failure due to bending fatigue in the root or flank. Literature evaluation, modeling results, and experimental results are presented in order to validate the approach.

Document	ISBN	Pages
16FTM07	1-55589-067-4	16

Performance and Machining of Advanced Engineering Steels in Power Transmission Applications – Continued Developments

Lily Kamjou, Nicklas Bylund, Brent Marsh, Joakim Fagerlund, Thomas Björk

This paper discusses the potential gain for the power transmissions industry by making use of the material properties of Advanced Engineering Steels to support more demanding applications. Machining the Advanced Engineering Steels is discussed based on a number of recent studies. All studies indicate that by optimizing machining parameters and tools, the productivity and efficiency of these processes can be maintained, or even improved.

Document	ISBN	Pages
16FTM06	1-55589-066-7	10

Pre-Nitriding: A Means of Significantly Increasing Carburizing Throughput

Thomas Hart

Higher carburizing temperatures allow end users to use shorter cycle times and significantly increase production rates, but can lead to grain growth. Pre-nitriding is a relatively new technology that addresses grain growth and allows carburizing end users to carburize at higher temperatures. Real life case studies show how carburizing productivity has doubled, and sometimes tripled, using pre-nitriding.

Document	ISBN	Pages
16FTM05	1-55589-065-0	11

Review of Microstructure and Properties of Non-Ferrous Alloys for Worm Gear Application and Advantages of Centrifugally Cast Gears

Giri Rajendran & Jason Hassen

This paper reviews the microstructure and properties of tin bronze, manganese bronze, and aluminum bronze material that make them suitable for specific wormgear applications. The advantages of centrifugally cast bi-metal gear blanks, and some common causes of worm gear failures are discussed.

Document	ISBN	Pages
16FTM04	1-55589-064-3	13

Twist Control Grinding (TCG)

Walter Graf

This paper introduces the latest process developments for the hard-finishing of gears in regards to controlling flank twist. Flank twist occurs as a matter of course when machining helical gears that feature lead modifications, and is brought about by the geometries and kinematics inherent in the continuous generating grinding of helical gears. Controlling the flank twist on gears, using twist control grinding (TCG), can either eliminate twist completely, or introduce a counter-twist to counteract the deformation of gears under load.

Document	ISBN	Pages
16FTM03	1-55589-063-6	15

Worm Screw High-Speed Manufacturing

Jean-Laurent Feutren

The conventional set-up of on a gear hobbing machine for the production of helical gears has the hob axis perpendicular (±30°) to the workpiece. This set-up does not allow for conventional manufacturing of wormgears. To solve this problem, a high speed method will be presented that reverses the axis between the workpiece and tool, and utilizes a high speed spindle (up to 16 000 rpm). This method can produce wormgears eight times faster than conventional methods.

Document	ISBN	Pages
16FTM02	1-55589-061-2	22

The Whirling Process in a Company that Produces Worm Gear Drives

Dr. Massimiliano Turci, Dr. Giampaolo Giacomozzi

This paper looks at the benefits that can be realized with the introduction a whirling machine into the wormgear manufacturing facility. The benefits include time and cost savings, especially in regard to the need for grinding, increased quality, and environmental considerations due to not needing cutting oils.

Document	ISBN	Pages
16FTM01	1-55589-060-5	13

Efficient Hard Finishing of Asymmetric Tooth Profiles and Topological Modifications by Generating Grinding

Andreas Mehr & Scott Yoders

New possibilities of modifications with the continuous generating grinding method will be presented, such as Deviation Free Topological grinding (DFT), Generated End Relief (GER), Noise Excitation Optimized modification (NEO), and hard finishing of asymmetric gears. The focus is on the explanation of the technical challenges, their solutions, and the principle function of the dressing and grinding processes.

Document		ISBN	Pages
15FTM29		1-55589-043-8	11

Tooth Flank Fracture – Influence of Macro and Micro Geometry

Stefan Beermann

In this paper, the method to calculate the risk of tooth flank fracture, which is defined in the current draft of ISO DTS 19042-1, is investigated and discussed. Part of this investigation is a sensitivity analysis with respect to the main gear parameters. Therefore, parameters including pressure angle, helix angle, normal module, hardness depth, tip relief, and crowning were systematically varied and the respective safety factor against tooth flank fracture was calculated.With this method, it can be shown that the risk of tooth flank fracture and the risk of pitting might have opposite trends. It is also shown that a tip relief on spur gears typically has no effect or might even increase the risk of tooth flank fracture. On helical gears, the situation is more complex. For lead modifications, a certain beneficial effect is seen by compensating misalignments of the flanks; however, if the modification chosen is too large, it will increase the risk of tooth flank fracture. In the first part of the paper, some formulas of the draft are discussed. There, it is shown that the definition of the material factor and the calculation of the course of the hardness into the depth of the material could be improved.

15FTM28		978-1-55589-042-1	10

Application of Advanced Mesh Analysis to Eliminate Pinion Failures

Terry Klaves

This paper will walk through a case study involving pinion failures on plastic extruder drives. It will cover failure analysis, gear rating review, application of advanced mesh analysis to define component deflections causing loaded mesh misalignment, and reduced tooth contact/high stress concentration resulting in tooth macropitting. The paper will demonstrate the capability and benefits of advanced mesh analysis, including design of optimized microgeometry and application of said microgeometry through precision tooth form grinding, with recommendations on types of microgeometry which are most effective, easiest to apply, inspect, and document in a production gear manufacturing environment. The summary will review tools which are commercially available to perform advanced mesh analysis, design, manufacture, and inspect optimized microgeometry—which compensates for tooth deflection, shaft bending, torsional windup, and bearing deformation in order to improve gearing mesh alignment and tooth contact under load for quiet running and longer life gearing. This tool can be applied proactively at the design phase to optimize gearing performance or reactively to identify root cause of failures and recommend corrective action.

Document		ISBN	Pages
15FTM27		1-55589-039-1	15

Wear: A New Approach for an ‘Old’ Failure Phenomenon of Gears

Ulrich Kissling, Sandro Hauri

Wear is a well-known criterion of failure for gears. Wear is a result of metallic contact between the tooth flanks. But when a lubricant is involved, the wear-generating mechanism can be quite different. If the pitch line velocity is 0.5 m/s or higher, the lubrication film still has a dominant effect, the metallic contact is only partial, and the gears are running in the mixed-film or full EHL regime. At very low pitch line velocities (less than 0.5–1.0 m/s), the boundary lubrication prevails, and the metallic contact is dominant. The wear behavior in this case is completely different from wear occurring in mixed-film regime. Wear occurring at very slow speed is called in U.S. literature ‘slow-speed wear’ or ‘adhesive wear’ [1]. In German literature also, the term ‘cold wear’ [2] (in contrast to scuffing, which is sometimes called ‘hot wear’) is used. In this paper, slow-speed wear will be discussed, defined as the following: wear occurring either on lubricated gears at very low pitch line velocity or on dry-running gears.Wear on gears is not an intensely researched topic, so little literature can be found. When compared with the exhaustive investigations carried out on other phenomena such as macropitting, scuffing, micropitting, or tooth flank breaking, it seems that slow-speed wear has literally been left out! But despite this, there are applications in heavy gear applications where wear is a criterion that cannot be ignored.Worldwide, until 2014, only one standard existed, AGMA 925 [3], which describes wear and proposes a method to evaluate the risk of wear. As will be discussed further on, the wear described by AGMA 925 is the wear occurring in the mixed-film regime; wear at very slow speed is not covered by AGMA 925. In a quite different area of application, wear is a very important topic—for dry running plastic gears.
Over the past few years, the authors have worked closely with a number of manufacturers of plastic gears and the University of Erlangen (Germany) to investigate the problems of gear wear in detail. A calculation method could be developed that can be used to predict where and when local wear will occur on a tooth flank. Parts of these findings have also just been published in the final version of the German standard VDI 2736 [4].The basic mechanics of slow-speed wear of metallic gears is the same as for dry-running plastic gears. However, the wear coefficients to be applied in each case are very different, and the influence of the lubricant (in particular, the effect of the lubricant additives) is crucial. In 1980, at the FZG in Munich, Plewe [5] published investigations of the adhesive wear behavior of lubricated metallic gears (pitch line velocities 0.007–1.0 m/s). The wear coefficients were determined for additive-free oil. However, a "factor for the influence of lubrication" is required before Plewe's data can be used for a modern gear lubricant, and up to now, very little is known about these factors.If the wear coefficient is known, the distribution of wear can be defined over the tooth contact area in the contact analysis. If the step-by-step change in the tooth flank (due to wear) is then also taken into account, a realistic prediction of the progression of wear and its effects on noise and vibrations can be made.

15FTM26		1-55589-038-4	16

Calculating the Risk of Micropitting Using ISO Technical Report 15144-1:2014 – Validation with Practical Applications

Burkhard Pinnekamp, Michael Heider

Micropitting is a surface fatigue phenomenon on highly loaded gears with case-hardened gear flanks. Main contributors are local stress, surface roughness, sliding speed, and lube oil properties. General influence factors, testing, and earlier calculation methods were described in 11FTM15 [1]. Meanwhile, a new version of the ISO Technical Report, TR 15144-1:2014 [2], was issued. It is intended to become an ISO Standard within the next years.

This paper describes the definition of micropitting, the actual calculation method, and its application to practical examples where micropitting has either occurred or not. The examples give evidence that the Technical Report reliably predicts the risk of micropitting where it is later found on the gear flanks.
For cases where no micropitting occurs, the calculated safety factors are sufficiently high. Operating conditions for some examples are out of the validated range of the Technical Report.

Document	ISBN	Pages
15FTM25	1-55589-037-7	18

An Experimental Evaluation of the Procedures of the ISO/TR 15144 Technical Report for the Prediction of Micropitting

Donald R. Houser, Samuel Shon

This paper presents the results of several experimental analyses to explore some of the features and methodologies of ISO 15144. A summary of ISO 15144 is first discussed, as is a spreadsheet that has been written, to accept contact stresses calculated from load distribution analyses. Sample load distribution analyses and subsequent ISO predictions are made for several experimental results that are reported in the literature. Following these analyses, a series of experimental durability tests were run using the AGMA tribology gears running with Dexron 6 automatic transmission fluid as the lubricant. An FVA 54 test was run to obtain the lubricant pass/fail level and the permissible value of Lambda needed to calculate the safety factor for micropitting.

Document	ISBN	Pages
15FTM24	1-55589-036-0	13

Tribological Coating Wear and Durability Performance Guideline for Gear Applications

Randy Kruse, Carl Hager, Ryan D. Evans

Diamond-like carbon (DLC) tribological coatings have demonstrated the ability to provide gear and bearing performance enhancements in an initially narrow but increasing range of applications. These experiences have heightened awareness and curiosity in industry about the potential of DLC coatings to enhance the performance of gear train systems. Valuable benefits may include reducing the probability of micropitting wear and increasing scuffing resistance, perhaps even to enable improved oil-out performance in aerospace applications. The application of these coatings may be used to increase gearbox efficiency, not by reducing friction within tooth contacts, but by increasing tooth surface durability to allow for less viscous lubricants and reduced lubricant quantities.It is generally known that extreme contact pressure and sliding velocity operating conditions can lead to coating wear. However, a better understanding of the thresholds that constrain coating durability and usefulness are needed so that gear and bearing engineers can more accurately specify and predict system life. This paper reports the results of testing a tungsten carbide-reinforced diamond-like carbon coating (W-DLC) as applied to AISI 4320 and AMS6308 gear materials using a rotating ball-on-disk tribology test rig under a range of conditions that simulate the contact stresses and sliding velocities of gears.

Document	ISBN	Pages
15FTM23	1-55589-035-3	22

Noise Reduction in an EV Hub Drive Using a Full Test and Simulation Methodology

Owen J. Harris, P.P. Langlois, G.A. Cooper

With the current trend towards Electric Vehicles (EVs), there is likely to be increasing focus on the noise impact of the gearing required for the transmission of power from the electric motor (high speed) to the road. Current automotive Noise, Vibration and Harshness (NVH) understanding and methodologies for total in-vehicle noise presuppose relatively large Internal Combustion (IC) contributions compared to gear noise. Further, it may be advantageous to run the electric motors at significantly higher rotational speed than conventional automotive IC engines putting the gear trains into higher speed ranges. Thus, the move to EV or Hybrid Electric Vehicles (HEV) places greater or different demands on gear train noise.This work combines both a traditional NVH approach (in-vehicle and rig noise, waterfall plots, Campbell diagrams, and Fourier analysis)—with highly detailed transmission error measurement and simulation of the complete drivetrain—to fully understand noise sources within an EV hub drive.The transmission error testing has been performed on both the full assembly with the three-stage gear train and on individual gear pairs using a dedicated transmission error measurement rig. Highly accurate rotary encoders are used to measure transmission error through different stages of the gear train in order to identify sources of excitation. For comparison, a full Computer-Aided Engineering (CAE) model has been built, which includes the flexibilities of all components, gears, shafts, bearings, and casing. Standard analysis is used to simulate the system deflection under input loads with corresponding gear misalignments, contact patches, and transmission errors. Contact patches are compared to tooth marking test results. Further, a novel advanced calculation is performed which iteratively couples deflections of the full system model with detailed tooth contact analysis at the gear meshes. This analysis shows how the gear meshes and the deflections of the full transmission change through the gear meshing cycles. This analysis can include detailed, measured, manufactured gear geometry, and various tolerances and errors within the system and calculate both the associated individual mesh and system transmission errors and their harmonic content.Detailed test and simulation identifies the noise sources to be the meshes of the three gear sets and captures a full understanding of them. Methods are presented to accurately derive and compare the individual gear mesh transmission errors from test and simulation of the complete unit. Further analysis of the individual results indicates both gear design and manufacturing considerations to be optimized to reduce noise. The results of prototype testing of design changes are given showing significant in-vehicle noise reductions.A detailed methodology is presented, combining both a full series of tests and advanced simulation to troubleshoot and optimize an EV hub drive for noise reduction.

Document		ISBN	Pages
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A New Class of Industrial Gear Oil

David B. Gray, René Koschabek, Aidan Rose

Industrial gear oils are a critical component in the efficient operation of modern equipment. More than 800 000 tons of these industrial gear oils are sold each year, which accounts for 5–6% of the total industrial lubricants market. While industrial gear oils have not traditionally been the leading focus for lubricant development, the recent strong growth of wind turbines and field service performance has shifted the focus significantly in the direction of the industrial gear oils.The challenging application for gearboxes in wind turbines has created demand for new high performance synthetic gear oils that provide both good equipment protection and longer drain intervals. While recent years have seen lubricant performance improvements, the highly fragmented landscape of OEM requirements and the complex approval processes have limited the application’s attractiveness to those developing new lubricant formulations. Today, however, the leading synthetic gear oils are based principally on polyalphaolefins (PAO), and while these lubricants are very effective and durable, they come at a significant cost penalty when compared to conventional mineral oils. This has created an opportunity for a new class of industrial gear lubricants, based on alternative synthetic materials. These new industrial gear oils have been developed to satisfy critical market performance expectations, ensure global supply chain security, and to address economic as well as performance challenges. This paper describes the technical aspects of this novel synthetic gear oil lubricant approach.

Document		ISBN	Pages
15FTM21		1-55589-033-9	13

Polish Grinding of Gears for Higher Transmission Efficiency

Walter Graf

This paper introduces a new gear polish grinding process and describes its multiple benefits to makers of automotive transmissions. First, based on independent scientific studies and customer trials, it will be shown that improved surface finishes increase the overall efficiency of transmissions, which translates into a reduction in torque loss, lower fuel consumption, and lower CO2 output. The resulting higher bearing ratios reduce micro-pitting, and thus increase the longevity of gears. Secondly, the paper introduces a cost-efficient manufacturing method adapted for large-scale manufacture, as automotive transmission manufacturers need a more suitable method than the time-consuming vibration finishing used in aerospace applications today.

Document		ISBN	Pages
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Efficiency of Worm Gear Drives

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Due to a wide range of properties, worm gears are an indispensable element on the current transmission market. Next to a huge gear ratio field in one gear stage of i = 5 to i = 80, operation with low noise and vibration is realizable. Furthermore, worm gears provide the opportunity of self-locking, respectively self-braking. Despite these benefits, as a result of greater energy awareness, the efficiency of worm gears is in the focus. Because of high sliding velocities, especially at high gear ratios, gearing losses are a main topic of interest. Other gearbox concepts with combined spur and bevel gear sets show smaller gear ratio fields, and therefore the realization of high gear ratios in only one stage is not possible. Consequently, fewer components are necessary for worm gearboxes, which allows savings of assembly and maintenance costs.In the scope of recent research projects, the efficiency and the load-carrying capacity of worm gears is examined. Therefore, experimental investigations on different worm gears were conducted on several test rigs. Generally, the pairing of bronze worm wheel with case-hardened worm is used in center distances between a = 65 and 315 mm. Additionally, the influence of different gear ratios, worm wheel materials, lubricants, and contact pattern on efficiency and load-carrying capacity are considered. In the course of these investigations, overall worm gearbox efficiencies of up to η = 96% are reached.The paper describes the conducted tests in detail and shows basic examples of experimental test results. On the basis of the experimental investigations and theoretical examinations, recommendations for an increase in efficiency are given.

15FTM19		1-55589-031-5	15

Worm Gear Efficiency Estimation and Optimization

Massimiliano Turci, E. Ferramola, F. Bisanti, G. Giacomozzi

This paper outlines the comparison of efficiencies for worm gearboxes with a center distance ranging from 28 to 150 mm that have single reduction from 5 to 100:1. Efficiencies are calculated using several standards (AGMA, ISO, DIN, BS) or by methods defined in other bibliographic references.It also deals with the measurement of torque and temperature on a test rig, required for the calibration of an analytical model to predict worm gearbox efficiency and temperature.There are also examples of experimental activity (wear and friction measurements on a block-on-ring tribometer and the measurements of dynamic viscosity) regarding the effort of improving the efficiency for worm gear drivers by adding nanoparticles of fullerene shape to standard PEG lubricant.

Document		ISBN	Pages
15FTM18		1-55589-030-8	15

Rating of Asymmetric Tooth Gears

Alexander L. Kapelevich

The benefits of gears with asymmetric tooth profiles for unidirectional torque transmission are well known. The design objective of asymmetric tooth gears is to improve performance of the primary drive flank profiles at the expense of the opposite coast profiles' performance. The coast flanks are unloaded or lightly loaded during a relatively short work period. Asymmetric tooth profiles make it possible to simultaneously increase the contact ratio and operating pressure angle of drive tooth flanks beyond those limits achievable with conventional symmetric tooth gears. The main advantage of asymmetric tooth gears is drive flank contact stress reduction, which allows one to considerably amplify power transmission density, increase load capacity, and reduce size and weight. However, asymmetric tooth gears and their rating are not described by existing gear design standards.This paper presents a rating approach for asymmetric tooth gears by their bending and contact stress levels in comparison with symmetric tooth gears, whose rating is defined by standards. This approach applies finite element analysis (FEA) for bending stress definition and the Hertz equation for contact stress definition. It defines equivalency factors for practical asymmetric tooth gear design and rating.The paper illustrates the rating of asymmetric tooth gears with numerical examples.

15FTM17		1-55589-029-2	17

Homogeneous Geometry Calculation of Arbitrary Tooth Shapes – Mathematical Approach and Practical Applications

Maximilian Zimmer, M. Otto, Karsten Stahl,

As an extensive machine element to transfer and convert rotational movement, gears meet high requirements for construction and assembly. Due to existing modern production techniques, more sophisticated gear types can be produced with high precision and maintainable financial effort. The benefits of traditional gear profiles, such as an involute, are thus no longer of major importance. In particular, for gear types such as bevel, worm, and hypoid gears, but also for non-standard gear types (e.g., beveloid gears, crown gears, or spiroid gearings), modern gear production systems ensure high quality and reliability to the operator. Depending on the context of application, different gear types have advantages and disadvantages concerning load carrying capacity, effectiveness, or noise excitation. Supported by various calculation software tools for the particular gear type, it is possible to create the optimal gear design, depending on the respective application. A homogeneous calculation software for ubiquitous gear geometries—irrespective of the gear type, and especially for analyzing non-standard gears—would be preferable.This paper provides a mathematical framework and its implementation for calculating the tooth geometry of arbitrary gear types, based on the basic law of gear kinematics. The rack or gear geometry can be generated in two different ways: by calculating the conjugate geometry and the line of contact of a gear to the given geometric shape of a known geometry (e.g., a cutting hob), or by prescribing the surface of action of two gears in contact and calculating the correspondent flank shapes. Besides so-called standard gears like involute spur and helical gears, bevel or worm gears, it is possible to analyze the tooth geometry of non-standard gears (e.g., non-involute spur, conical, or spiroid gears). Depending on the type of gear, a distinction is made between tool-dependent and tool-independent geometry calculation.The described mathematical algorithms are summarized in implemented software modules for the particular gear types. Two practice-oriented examples are presented to illustrate the calculation model: beveloid gears for use in vehicle or marine gear boxes as well as rack-and-pinion meshing with variable ratio, as it is used for steering systems on automobiles. Since the geometry is exported as a point cloud, a further analysis of the generated gear types is possible, e.g., by computer-aided design or finite-element software tools as well as manufacturing on 5-axis CNC or forging machines. Thus, a detailed analysis—especially of non-standard gears—is feasible that currently cannot be calculated and evaluated with common industrial gear calculating software.

Document		ISBN	Pages
15FTM15		1-55589-028-5	15

New Refinements to the Use of AGMA Load Reversal and Reliability Factors

Ernie Reiter

AGMA standards use load reversal and reliability factors in the calculation of the rated load capacity for gear teeth. ANSI/AGMA 2101-D04 recommends the use of a load reversal factor of 1.0 for most gears which see one-way bending, and 0.7 for gears such as idler gears and planet gears that see a fully reversing bending condition. Likewise, the standard uses a table format to assign a reliability factor based on a desired reliability level in an application.This paper suggests two ways to calculate a load reversal factor which would be material specific, based either on Modified Goodman or Gerber Failure Theories. This paper further provides a method of calculating the reliability factors which very closely match the AGMA tables found in ANSI/AGMA 2101-D04.

15FTM14		1-55589-026-1	7

Gear Backlash Analysis of Unloaded Gear Pairs in Transmissions

Carlos Wink

A best practice in gear design is to limit the amount of backlash to a minimum value needed to accommodate manufacturing tolerances, misalignments, and deflections, in order to prevent the non-driving side of the teeth to make contact and rattle. Industry standards, such as ANSI/AGMA 2002 and DIN3967, provide reference values of minimum backlash to be used in the gear design. However, increased customers' expectations in vehicle noise reduction have pushed backlash and allowable manufacturing tolerances to even lower limits. This is especially true in the truck market, where engines are quieter because they run at lower speeds to improve fuel economy, but they quite often run at high torsional vibration levels. Furthermore, gear and shaft arrangements in truck transmissions have become more complex, for an increased number of speeds and to improve efficiency. Determining the minimum amount of backlash is quite a challenge. This paper presents an investigation of minimum backlash values of helical gear teeth applied to a light-duty pickup truck transmission. An analytical model was developed to calculate backlash limits of each gear pair when not transmitting load, and thus susceptible to generate rattle noise, through different transmission power paths. A statistical approach (Monte Carlo) was used since a significant number of factors affect backlash, such as tooth thickness variation, center distance variation, lead, runout and pitch variations, bearing clearances, spline clearances, and shaft deflections and misalignments. Analytical results identified the critical gear pair, and power path, which was confirmed experimentally on a transmission. The approach presented in this paper can be useful to design gear pairs with a minimum amount of backlash, to prevent double flank contact and to help reduce rattle noise to lowest levels.

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15FTM13		1-55589-025-4	12

Thermal Capacity of a Multi-Stage Gearbox

Albertus Willem Wemekamp, A. Doyer

In many industrial gearbox applications, thermal rating is a key factor in the practical utilization of the gearbox. The thermal capacity is affected by the efficiency (power loss) of the gearbox and heat dissipation within the environment. Methods, as found in ISO Technical Reports (ISO/TR 14179), help to estimate quasi-stationary temperature in the oil sump.To further increase the understanding, SKF has incorporated power loss prediction and thermal equilibrium in its validated simulation tool. It goes beyond ISO methods: it includes the interaction between heat losses, thermal expansions, and (bearing) pre-loading. With this simulation tool, all these interactions can be analyzed by solving the mechanical and thermal problem simultaneously. When changing operating conditions (e.g., during starting up), temperature differences between rotating parts (e.g., shafts) and the exterior parts (e.g., housing) may differ considerably from the steady state conditions. These effects are extremely difficult to anticipate, or complex measurements would be required. The developed method allows engineers to perform transient calculation in which the momentary temperature differences (affecting the bearing loading) are taken into account. In this way, the whole gearbox behavior can be analyzed in more detail.In the paper, the methodology used to obtain the interaction between mechanical and thermal equilibrium will be explained. Using the simulation tool capabilities, the performance of the bearings and gears in a multi-stage gearbox will be analyzed and presented.

15FTM12		1-55589-023-0	11

Simulation of Hobbing and Generation Grinding to Solve Quality and Noise Problems

Günther Gravel

Due to increasing tolerance requirements for gearboxes and gears, it has become more and more important to establish quality circles in production. A quick detection and correction of the causes of tolerance violation is essential for high quality. This paper shows the possibilities and procedures of searching for the root cause in general, especially with problems in hobbing and generation grinding using multi-start tools. A new simulation tool has been developed, which allows for the simulation of typical faults that occur during hobbing and generation grinding. The calculated contour on the workpiece is treated as a measured curve, making it easy to compare workpiece measurements and simulations. In this way, possible error causes can be simulated and compared with the real gear surface.This paper uses practical examples to demonstrate the following applications for simulation. The influence of the tool parameter’s "number of starts" and "number of flutes" on the cutting result is shown in connection with the axial feed parameter. Protuberance and tooth tip rounding on the tool influence the profile form generated on the workpiece. Wobble and eccentric in the tool clamping creates an s-shaped pattern on the profile, based on the number of starts on the tool. The form of the pattern changes with different parameters. In high-speed gearboxes, ripples on the gear surfaces are frequently the cause of noise problems. Simulation of a tool error and a subsequent evaluation of the ripples enable conclusions to be drawn about the excitations caused by the tool error during the cutting process. A practical comparison between the ripple measurement of a hobbed and subsequently honed gear and the simulation shows that the noise-related ripples on the finished part arises already in the pre-machining stage.The applications presented in this paper show that the results of the simulation are a very good match with practical tests. Thus, the simulation software is a highly precise tool for determining and eliminating the causes of deviations in production. At the same time, design engineers and planners can quickly and easily develop new process and tool designs, thereby significantly reducing the costs involved in testing.

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Selecting the Proper Gear Milling Cutter Design for the Machining of High Quality Parallel Axis, Cylindrical Gears and Splines

Brent Marsh

Gear milling cutters offer a versatile and timesaving solution for milling of high-quality gear profiles. Application methods vary. There are many ways to utilize these cutters. Machines range from traditional gear hobbing machines with single indexing capability to horizontal and vertical CNC machining centers with 4- or 5-axis capability, modern multi-task turning and milling centers, CNC lathes with live milling capability, and dedicated special-purpose machines.Tool selection will depend on a number of factors, such as module size, work piece material, gear quality level desired, spur or helical design, tooth count, size of gear blank, and available equipment options. The desired post-milling operations needed—such as hardening, grinding, honing, and shaving—also have an influence on the milling tool design.When planning for successful process methods, rigidity, tool holding (arbor supported vs. unsupported), and material removal rate, all must be addressed.Power and torque requirements as related to gear material, number of passes, cutter design, and diameter, are very important in the planning phase. Tool selection has a significant impact on this. Rake angles and cutter geometry are important. Tools are designed according to rough, semi-finish, and finish requirements. Tandem, multi-cutter designs will improve productivity but bring on specific challenges to the process engineer. Surface finish requirements are also very important. Milling methods can vary from climb cutting to conventional milling. Both methods have their place and impact surface finish and tool life. Radial infeed and reduced or increased feed rate on entry are other factors. Wet-versus-dry machining and oil-versus-water-soluble coolants impact tool life, part quality, and environmental concerns. Proper chip thickness and calculations for feed rate compensation must be considered. This paper takes a comprehensive view of all of the above mentioned topics to assist the manufacturing engineer or process planner in successfully choosing the design of gear milling cutters to make cost-effective cylindrical gears to the appropriate quality desired.

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15FTM10		1-55589-021-6	10

Influence of Hobbing Tool Generating Scallops on Root Fillet Stress Concentrations

Benjamin S. Sheen, Matthew Glass

In the design of gear and spline teeth, the root fillet area and its maximum tensile stress are of primary concern for the gear designer. In general terms, the tensile stress in the root fillet is based on specific geometries of the design: minor diameter, fillet radius, etc. However, additional concerns regarding the manufacturing method, cutting tool geometry, and process parameters can greatly influence the impact of stress concentration factors in the root fillet area. For a hobbed tooth manufacturing process, the root fillet geometry is controlled by the rack design of the cutter, but also by the number of generating scallops produced by the tool. For a shaping process, the generating scallops are close together and can produce a surface with almost no visible signs of root fillet generating scallops. However, for a hobbing process, the number of threads, number of gashes, and tip radius can create multiple variations of generated scallops. These can create stress concentrations, which can increase the tensile bending stress and potentially impact the service life of the component. For this discussion, stress concentrations caused by root fillet generating scallops will be reviewed.This paper will discuss a specific example regarding parallel-sided splines manufactured with a finish hobbing process and their effects on generating root fillet stress concentrations. To estimate the value of the stress concentrations, Finite Element Analysis was performed on the components for two unique hobbing tool designs. The FE results are compared to actual component field service histories.

Document		ISBN	Pages
15FTM08		1-55589-019-3	19

Proposed Pre-Finish Cylindrical Gear Quality Standard

Peter E. Chapin

It is quite common to specify a gear class for in-process quality requirements, usually calling for a lower quality class than is required for the finished gear quality. Although it is appropriate to have lower expectations for a pre-finish gear condition, it is not appropriate to subject the pre-finish gear to the same level of scrutiny as a finished gear. Gears in a pre-finish condition may have large feed scallops or generating flats, which are desirable for productivity and may be conducive to the finishing process. However, such features will be evaluated as errors when subjected to the full analysis as required by the finished gear class inspection. Therefore, the use of a finished gear quality specification is not recommended or even appropriate for pre-finish gear quality evaluation, even if the quality class has been adjusted to pre-finish expectations. Additionally, in-process requirements often require non-zero target helix and profile slopes, which necessitate a new method of analysis to determine the achieved quality class. Therefore, a pre-finish evaluation method and standard is proposed. This proposed standard would not make any recommendations regarding the required quality for any application. The intent is to establish standard pre-finish quality classes for typical finishing operations, which only include the inspection elements that are important to properly evaluate pre-finish gear quality as it applies to the finishing operation.

15FTM07		1-55589-018-6	24

Industry 4.0 and its Implication to Gear Manufacturing

Hermann J. Stadtfeld

The Industry 4.0 is an initiative of leading German industrial corporations and scientific institutions, supported with funding from the German government, which promotes the computerization of traditional industries such as manufacturing. This paper reviews the four industrial periods from the viewpoint of gear manufacturing and points out the special character of the fourth industrial period, which has just begun. The main part of the paper reports about the techniques and elements of the so-called cyber physical production systems and how they will change the way of industrial manufacturing. In the proceeding sections, the paper relates the features of Industry 4.0 to the Gleason achievements regarding machining process design, machine networking, expert systems, machine self-diagnosis, and cycle optimization, as well as remote diagnosis. The conclusion points out that the new movement will enhance manufacturing capabilities, improve product quality, and will create very flexible manufacturing. Gleason products today already show a significant content of smart features and modern data processing, which together with a leading strategy for future developments, is represented with the name Gleason 4.0.A concern of manufacturing personnel is the missing transparency and traceability of the action that a smart manufacturing control is executing. The concern, that chaotic situations can occur if the smart manufacturing system has to react to unexpected input information, is justified; the concern about missing traceability is, in most cases, not justified. For example, in the early days of G-AGE corrections, gear engineers liked to understand why the combination of five or more delta settings would correct a certain flank form error. However, the mathematics behind those corrections are rather complex and would require many hours—or even days—to verify a single set of correction data. After the first years of practice with G-AGE, gear engineers learned to trust the results and applied them without questioning. In the few cases when the theory failed and the corrections made the gear worse, the gear engineer used common sense and either applied simple manually calculated corrections or eliminated a critical input or output variable in order to unarm the unstable part of the originally computed results.This example shows that it is efficient to have the thousands of decisions or actions which are constantly reoccurring done by the smart manufacturing system. Its strength is to execute reoccurring operating tasks very fast. The human skill is to concentrate on all out-of-the-ordinary situations, in which the computerized intelligence is not very strong. The artificial neurons don’t take anyone’s workplace. Quite the contrary—future manufacturing will only exist if it follows the smart movement. Workplaces in factories will be sophisticated and interesting, and humans will be in control...probably in more control than they have been in the past.

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Powder Metal Gear Technology: A Review of the State of the Art

Anders Flodin

During the past 10 years, the PM industry has put a lot of focus on how to make Powder Metal gears for automotive transmissions a reality. To reach this goal, several hurdles had to be overcome, such as fatigue data generation on gears, verification of calculation methods, production technology, materials development, heat treatment recipes, design development, and cost studies.All of these advancements will be discussed, and a number of vehicles with powder metal gears in their transmissions will be presented. How the transmissions have been redesigned in order to achieve the required stress levels while minimizing weight and inertia, thus increasing efficiency, will also be discussed.

15FTM05		1-55589-016-2	12

Innovative Steel Design and Gear Machining of Advanced Engineering Steel

Lily Kamjou, Patrik Ölund, Erik Claesson, Joakim Fagerlund, Garry Wicks, Mats Wennmo, Hans Hansson

The basis for high fatigue performance in high hardness steel originates in precise inclusion engineering. In addition, recent research shows that by changing the alloying strategy, an increase in the bending fatigue limit can be achieved similar to an additional shot-peening process. Therefore, the near surface structure will exhibit excellent mechanical properties and compressive residual stresses in the as-carburized condition. The current paper describes the potential of clean steel for new approaches in transmission gear box manufacturing and possibilities to meet the future demands of being smaller, lighter and managing higher torque. One important factor is the bending fatigue performance of the gear teeth where an increasing fatigue strength is required. The paper discusses how shot peening might be eliminated in high-cleanliness, as-carburized steel components using an alternative composition. The fatigue performance of such a solution is compared to conventional grades used today, both with and without shot peening.The full benefit of this new steel design can be obtained by using a high-quality steel with a decreased number of critically-sized inclusions in the loaded volume. Results from extensive testing support how this type of steel compares to commonly used carburizing steels. The effect of material cleanliness on contact fatigue is also examined through FZG pitting testing.To address potential machining issues of clean steels, the paper also deals with the production process, including quantitative machining trials and the importance of tooling selection. The study is focused on the production of gears, dealing mainly with turning and hobbing. Initial results show how these clean steels can be machined in full scale production in standard conditions with equal or better efficiency and cost.

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Single-Piece, High-Volume, Low-Distortion Case Hardening of Gears

Maciej Korecki, Emilia Wolowiec-Korecka, Doug Glenn

Global output of gears in the automotive industry is estimated to be in excess of 1 billion units per year. While carburizing and quenching of steel gears for the automotive industry provides the surface-hardened teeth and flexible core necessary for a long-lasting gear, heat treating, and especially the quenching process, produces distortion. Distortion is most often corrected by the costly process of post-heat treat machining. The main goal of every high-volume gear heat treating process is the elimination of distortion. If distortion is not eliminated, the goal is significant reduction, predictability, and repeatability of distortion.This article looks at the major causes of deformation during heat treatment and methods for controlling, correcting, and eliminating distortion. A new concept—a single-piece flow case hardening system—will be presented. This system adjusts to the size and shape of the particular gear in order to minimize distortion and ensures ideal repeatability of results, gear after gear. It is a compact system designed for high-volume gear heat treating, is ideal for lean manufacturing configurations, and can easily be integrated into machining centers.

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Practical Approach to Determining Effective Case Depth of Gas Carburizing

March Li

Effective case depth is an important factor and goal in gas carburizing, involving complicated procedures in the furnace and requiring precise control of many thermal parameters. Based upon diffusion theory and years of carburizing experience, this paper calculates the effective case depth governed by carburizing temperature, time, carbon content of steel, and carbon potential of atmosphere. In light of this analysis, carburizing factors at various temperatures and carbon potentials for steels with different carbon content were calculated to determine the necessary carburizing cycle time. This methodology provides simple (without computer simulation) and practical guidance of optimized gas carburizing and has been applied to plant production. It shows that measured effective case depth of gear parts covering most of the industrial application range (0.020 inch to over 0.250 inch) was in good agreement with the calculation.

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Improved Materials and Enhanced Fatigue Resistance for Gear Components

Dr. Volker Heuer, Dr. Klaus Loeser, Gunther Schmitt

This paper shows the latest progress in steel grades and in case hardening technology for gear components.To answer the demand for fuel-efficient vehicles, modern gear boxes are built much lighter. Improving fatigue resistance is a key factor to allow for the design of thin components to be used in advanced vehicle transmissions. The choice of material and the applied heat treat process are of key importance to enhance the fatigue resistance of gear components. By applying the technology of Low Pressure Carburizing (LPC) and High Pressure Gas Quenching (HPGQ), the tooth root bending strength can be significantly enhanced, compared to traditional heat treatment with atmospheric carburizing and oil quenching.Besides heat treatment, significant progress has been made over the past years on the steels being used for gear components. The hardenability of case hardening steels such as 5130H, 5120H, 20MnCr5, 27MnCr5, 18CrNiMo7-6 etc. has been stepwise increased in recent years. An important factor for fatigue resistance is the grain size after heat treatment. Therefore, grain size control is a key goal when developing new modifications of steel grades. After enhancing grain size control, it was possible to increase the carburizing temperatures over the past years from 930°C to 980°C (1700°F to 1800°F) which resulted in shorter heat treatment cycles and thus in significant cost savings. With the introduction of new microalloyed steels for grain size stability, carburizing temperatures can now be even further increased to temperatures of up to 1050°C (1920°F), leading to even more economic process cycles. By adding microelements such as Niobium or Titanium in the ppm-range, nitride and carbonitride-precipitates are formed. These precipitates effectively limit the grain-growth during the heat treatment process.

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Influence of Surface Finishing on the Load Capacity of Coated and Uncoated Spur Gears

P. Konowalczyk, C. Brecher

In order to increase the power density of tribologically stressed drive train components, different approaches are being pursued in material and production technology. In addition to the development of efficient base materials, especially the optimization of surface finishing processes and the application of coating systems are promising. By combining mechanically highly stressable substrate materials and tribologically effective, extremely thin coatings, the components show modified wear and friction properties, which often lead to an increase of tooth flank load carrying capacity. A major advantage of this approach is that the highly accurate component geometry is only slightly changed by the coating.The influence of PVD/PECVD hard coatings on the load carrying capacity of cylindrical gears made of alloy steel is the subject of scientific research since the nineties. Several reports show that diamond-like carbon (DLC) coating systems reduce the occurrence of specific forms of gear damages, such as pitting or scuffing, and optimize the frictional behavior of gears. Despite the good results, PVD/PECVD coating technology could not be established in gear transmission technology yet. The use of a PVD/PECVD coating leads to higher component costs and longer manufacturing time. Furthermore, the surface finishing process before coating can influence the resulting tooth flank load capacity, and in some studies, a reduction of tooth root strength by the application of a coating can be observed. An extensive research concerning the influence of specific surface finishing processes on the tooth flank load capacity of uncoated and coated gears have not been focused in existing works. Furthermore, the existing works focus on the coating of both gears in contact and not on the coating of just one gear combined with optimized surface finishing processes.Therefore, the aim of this work is the investigation and determination of the influence of surface finishing processes on the impact of PVD/PECVD coatings concerning the pitting load capacity of gears. By means of running tests, the influence of different surface finishing processes on the pitting resistance is examined for the uncoated and coated tooth flank contact. The coated tooth flank contact will be further separated in the cases with just one or two coated gears in contact. By coating only one gear, a possible reduction of coating costs with simultaneous increase of the pitting resistance is targeted. As a DLC coating, a modified tungsten carbide coating (a-C:H:W (WC/C)) will be applied. Due to an optimized coating process, consistent coating adhesion without loss of hardness of the substrate material will be achieved. The result of this optimization will additionally be proven by the investigation of tooth root strength by means of pulsator testing.

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Applying AGMA Flexible Coupling Standards to the World of Gearing

Todd Schatzka

Applying AGMA Flexible Coupling Standards to the World of Gearing

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An Analytical Model for Real-Time Design Evaluations of Spline Couplings

Yi Guo, Jon Keller, Robert Errichello, and Chris Halse

An Analytical Model for Real-Time Design Evaluations of Spline Couplings
“Gear SCouP”

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14SP2		20

Evaluation of Risk of Micropitting. Activity in ISO and AGMA

Robin Olson

Evaluation of Risk of Micropitting. Activity in ISO and AGMA

Document	ISBN	Pages
14SP1		34

ISO 1328-1:2013, ANSI/AGMA ISO 1328-1-B14, A brief introduction

John M. Rinaldo

ISO 1328-1:2013, ANSI/AGMA ISO 1328-1-B14, A brief introduction

Document	ISBN	Pages
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On the Correlation of Specific Film Thickness and Gear Pitting Life

T. Krantz

The effect of the lubrication regime on gear performance has been recognized, qualitatively, for decades. Often the lubrication regime is characterized by the specific film thickness defined as the ratio of lubricant film thickness to the composite surface roughness. It can be difficult to combine results of studies to create a cohesive and comprehensive dataset. In this work gear surface fatigue lives for a wide range of specific film values were studied using tests done with common rigs, speeds, lubricant temperatures, and test procedures. This study includes previously reported data, results of an additional 50 tests, and detailed information from lab notes and tested gears. The dataset comprised 258 tests covering specific film values [0.47 to 5.2]. The experimentally determined surface fatigue lives, quantified as 10-percent life estimates, ranged from 8.7 to 86.8 million cycles. The trend is one of increasing life for increasing specific film. The trend is nonlinear. The observed trends were found to be in good agreement with data and recommended practice for gears and bearings. The results obtained will perhaps allow for the specific film parameter to be used with more confidence and precision to assess gear surface fatigue for purpose of design, rating, and technology development.

Document	ISBN	Pages
14FTM20	1-61481-112-1	12

Influence of Central Members Radial Support Stiffness on Load Sharing Characteristics of Compound Planetary Gear Sets

Z. Peng, S. Wu

In this study, a non-linear dynamics model of Ravigneaux compound planetary gear set which adopts the intermediate floating component is set up based on concentration parameter. By considering the position errors and eccentric errors, the dynamic load sharing factors of the gear set are calculated. The relationship between central members radial support stiffness and the dynamic load sharing factors is obtained and the influence of central members radial support stiffness on load sharing characteristic is analyzed. The research results show that central members radial support stiffness effect obvious to the gear pairs which are directly contacted to the central members, while the effect is rather small to the gear pairs which are not directly connected. Reducing the radial support stiffness of the central members helps improve the load sharing performance of the system.

Document		ISBN	Pages
14FTM19		1-61481-111-4	10

Application of ICME to Optimize Metallurgy and Improve Performance of Carburizable Steels

J. Grabowski, J. Sebastian, A. Asphahani, C. Houser, K. Taskin, D. Snyder

QuesTek Innovations LLC has applied its Materials by Design® computational design technology and its Integrated Computational Materials Engineering (ICME)-based methods to successfully design, develop and implement two new high-performance gear steels (Ferrium® C61™ and Ferrium C64® steels) that are being used in demanding gear and bearing applications in ground and aerospace military, commercial aerospace, high-performance racing, oil & gas and other industries. Additionally, QuesTek has successfully designed and developed two new high-performance structural steels (Ferrium S53® and Ferrium M54® steels). All four Ferrium alloys are commercially available from Carpenter Technology and have been awarded SAE AMS numbers for procurement. QuesTek has also designed several other high performance alloys using ICME technologies, including a stainless nitridable bearing and gear steel and alloys for additive manufacturing applications.

14FTM18		1-61481-110-7	12

Precision Bevel Gears with Low Tooth Count

S.P. Radzevich, V.V. Irigireddy

The paper deals with the geometry and kinematics of right-angle bevel gears that feature low tooth count. Right-angle bevel gears are a particular case of intersected-axis gearing (further Ia - gearing) with an arbitrary value of shaft angle. In this paper, gears that have 12 teeth and fewer are referred to as the low-tooth-count-gears (or LTC - gears, for simplicity).When operating, right-angle bevel gears often generate vibration and produce an excessive noise. Dynamic loading of the gear teeth can result in the tooth failure. These problems become more severe in bevel gearings with low tooth count. The performed analysis shows that inequality of base pitches of the gear and mating pinion is the root cause for insufficient performance of LTC - gears.In most applications, the main purpose of Ia - gearing is to smoothly transmit a rotation and torque between two intersected axes. Gear pairs that are capable of transmitting a uniform rotation from the driving shaft to the driven shaft are referred to as the geometrically accurate intersected-axis gear pairs (or, in other words, the ideal intersected-axis gear pairs).

Document	ISBN	Pages
14FTM17	1-61481-109-1	9

The Impact of Surface Condition and Lubricant on Gear Tooth Friction

S. Rao, A. Isaacson, G. Sroka, L. Winkelmann

Frictional losses in gear boxes are of significant interest to gear box designers as these losses transform into heat. The direct result is a reduction in the fuel efficiency of the vehicle involved. Further, in many instances, this heat has to be absorbed and dissipated so that lubricant properties and gear box performance are not significantly compromised. This effort is to measure and document the comparative friction losses in a gear mesh due to gear tooth surface condition and lubricant. Three distinct surface conditions are considered. They are ground, Isotropic Superfinished (REM ISF®) and tungsten-incorporated diamond-like carbon coating (W-DLC). Two lubricants, MIL-PRF-23699 and Mobil SHC 626 lubricants are considered.The experimental effort is conducted on a high speed, power re-circulating (PC), gear test rig, which had been specially instrumented with a precision torque transducer to measure input torque to the 4-square loop. The torque required to drive the loop is measured under various speeds and tooth loads within the torque loop, with test gears with different surface conditions and with different lubricants. Two operating torque levels within the 4-square loop at speeds ranging from 4,000 rpm (pitch-line velocity of 19 m/sec) to 10,000 rpm (pitch-line velocity of 47 m/sec) are evaluated. Based on the collected data a qualitative analysis of the effect of gear tooth surface condition on frictional losses is presented. Further, the surface characteristics of the tooth flanks of the ground, superfinished and coated gears are also described.

Document	ISBN	Pages
14FTM16	1-61481-108-4	16

The Modified Life Rating of Rolling Bearings – A Criterion for Gearbox Design and Reliability Optimization

A. Doyer, A. Gabelli, G. Morales-Espejel

This The concepts of rolling bearing rating life and basic load rating (load carrying capacity) were introduced by Arvid Palmgren in 1937 [1]. At that time, until the 1950s, most bearing manufacturers listed in their catalogues the load admissible on the bearing for thousands hours of operation at five different speeds. In those days the selection of a bearing size for a given application was a rather simple and approximate matter.The concept of a single rating factor to characterize the dynamic capacity of the bearing was new and initially used only within the bearing company that developed this new technology. This rating method was backed by the theory of Lundberg & Palmgren (L-P) [2] and by the Weibull statistics [3]. It was found that it could provide a correct interpretation of the many series of endurance tests available at the time, [2], [4], [5]. This calculation method prevailed on all the others methods used at the time and was adopted by ISO in 1962.

Document		ISBN	Pages
14FTM15		1-61481-107-7	13

Application of a Unique Anti-Wear Technology – Ion-Sulfurized Lubricating Gradient Material

G. Wang, Y. Zhang, X. Zhang, H. Liu

This Ion-sulfurization, also called plasma sulfurization, is a state-of-the-art technology conferring excellent anti-friction and wear-resistant characteristics on metallic parts including gears, splines, and bearings. It is characterized by a sulfur-proliferated zone composed of sulfides and sulfur-metal solid solution case with smooth sulfur compositional gradient towards the underlying substrate. Varity of metals and alloys, including steels, cast irons, super-hard alloys, and bronze, are suitable for ion-sulfurization. This treatment is carried out at low temperature, so that geometric integrity, microstructure and mechanical characteristics of the substrate are not impaired. Ion-sulfurized gears and bearings shorten the run-in time span of the machinery/automotive units. Even more, the contact fatigue in gears and splines can be noticeably reduced. Another distinguished engineering advantage is, the tribological property of the sulfide layer on steel can survive a temperature as high as 2000°F, which is rarely surpassed by other lubricants.In this article, the engineering characteristics of ion-sulfurization are introduced. Exemplary application is provided as reference for those interested in this technology.

Document		ISBN	Pages
14FTM14		1-61481-106-0	12

Theoretical and Experimental Study of the Frictional Losses of Radial Shaft Seals for Industrial Gearbox

M. Organisciak, P. Baart, S. Barbera, A. Paykin M. Schweig

In this paper SKF presents an engineering model for the prediction of radial lip seal friction based on a physical approach. The friction model includes the generation of friction due to rubber dynamic deformation and lubricant viscous shear between the surfaces of a seal and a shaft. The friction model is coupled with a heat generation and seal thermal model. Indeed, seal friction and seal temperature are closely related: the heat generated in the sealing lip is conducted through the seal and shaft and dissipated into the environment. This changes for instance the lubricant viscosity.The model is verified step by step in an extensive experimental study. Measurements of seal friction, seal temperature and lubricant film thickness have been performed for various dynamic lip seals. The analyzed parameters are: surface speed, oil viscosity, seal material, seal size, seal lip style and duty cycles. The correlation between model predictions and experimental friction measurements can therefore be verified.

Document	ISBN	Pages
14FTM13	1-61481-105-3	17

A Practical Approach for Modeling a Bevel Gear

B. Bijonowski

The modern bevel gear design engineer is often faced with knowing the basic appearance of the bevel gear tooth that he is designing. The geometry of the bevel gear is quite complicated to describe mathematically, and much of the overall surface topology of the tooth flank is dependent on machine settings and the cutting method employed. AGMA 929-A06, Calculation of Bevel Gear Top Land and Guidance on Cutter Edge Radius, lays out a practical approach for predicting the approximate top land thicknesses at certain points of interest regardless of the exact machine settings that will generate the tooth form. The points of interest that AGMA 929-A06 is concerned with consists of toe, mean, heel, and the point of involute lengthwise curvature.The following method expands upon the concepts described in AGMA 929-A06 to allow the user to calculate not only the top land thickness, but the more general case, the normal tooth thickness anywhere along the face and profile of the bevel gear tooth. This method does not rely on any additional machine settings; only basic geometry of the cutter, blank, and teeth are required to calculate fairly accurate tooth thicknesses. The tooth thicknesses are then transformed into a point cloud describing both the convex and concave flanks in a global Cartesian coordinate system. These points can be utilized in any modern computer aided design software package to assist in the generation of a 3D solid model. All pertinent macro tooth geometry can be closely simulated using this technique. Furthermore, a case study will be presented evaluating the accuracy of the point cloud data to a physical part.

Document	ISBN	Pages
14FTM12	1-61481-104-6	13

Optimization of Gear Tooth Contact by Helix Angle Modification

S. Hipsley, R.J. Davey, R.T. Wheway

This paper reports the results of a study of the effects of helix angle modification on the load distribution and stresses within teeth of helical gears, and the calculation of appropriate compensation for torsional effects.Load distribution and peak stress for helical gears under normal torsional forces inherent in helical gear drives are significantly influenced by the flexibility of the gear body, tooth structure and elastic deformation of the contact surfaces. Uncompensated, these factors reduce the gear face contact area and accordingly increase maximum stress and decrease pitting resistance and bending strength power ratings.This paper transforms the calculation of the compensation required by translating the underlying analysis into a MATLAB based program that can be run on a modest, standard PC computer. Informed practicing engineers – as opposed to esoteric experts in whose domain these calculations currently reside – now have a tool to do the necessary calculations with ease.The results from the program are confirmed by FEA analysis of compensated and uncompensated examples, together with a practical example with an operating, 3,000 kW gearbox. The results show that the program produces the appropriate adjustment, such that the contact areas are full width across the gear faces. The authors’ recommendation is, now that a user-friendly analysis tool is available, that helix angle compensation should be included in rating standards.

Document		ISBN	Pages
14FTM11		1-61481-103-9	16

Mathematical Modeling for the Design of Spiroid®, Helical, Spiral Bevel and Worm Gears

G. Kazkaz

This paper will present a novel work for spiroid and worm gears that mathematically calculates the gear tooth profile in terms of the geometry of the machining tool (hob) and the machining setup. Because of similarity, the work was also expanded to spiral bevel gear. We have developed software to plot the gear tooth when the parameters of the geometry of the tool and machining setup are entered. The gear tooth shape can then be altered and optimized by manipulating the input parameters until a desired tooth profile is produced. In effect, the result will be designing the hob and machining setup for best gear tooth profile on the computer. Afterward, the generated gear tooth data are entered into CAD software to generate a true 3D model of the gear. The tool path will also be generated from the data for CNC machining instead of hobbing.

14FTM10		1-61481-102-2	9

Involute Spiral Face Couplings and Gears: Design Approach and Manufacturing Technique

A.L. Kapelevich, S.D. Korosec

Face gears typically have a straight or skewed tooth line and varying tooth profile in normal cross section at different radii from major to minor diameter. These face gears are engaged with spur or helical involute pinions at intersecting or crossed axes.This paper presents spiral face gears with involute tooth line and identical tooth profile in the normal section at any radius. There are two main applications for such face gears. One of them is an alternative solution with certain advantages in performance and fabrication technology to the straight tooth, Hirth, or Curvic flange couplings. Another application is when a face gear is engaged with an involute helical pinion or worm at intersecting or crossed axes. Such engagement is also used in Helicon® type gears.The paper describes gear geometry analysis, and design technique of spiral face involute gears with symmetric and asymmetric tooth profiles. It also explains a highly productive hobbing method of these gears and tool design specifics, and illustrates gear and tool design with numerical examples.

14FTM08		1-61481-100-8	18

The Efficiency of a Simple Spur Gearbox – A Thermally Coupled Lubrication Model

A.I. Christodoulias, A.V. Olver, A. Kadiric, A.E. Sworski, F.E. Lockwood

A thermally coupled efficiency model for a simple dip-lubricated gearbox is presented. The model includes elastohydrodynamic friction losses in gear teeth contacts as well as bearing, seal and churning losses. An iterative numerical scheme is used to fully account for the effects of contact temperature, pressure and shear rates on EHL friction. The model is used to predict gearbox efficiency with selected transmission oils whose properties were first obtained experimentally through rolling-sliding tribometer tests under representative contact conditions.Although the gearbox was designed using standard methods against a fixed rating, the model was used to study efficiency over a much wider range of conditions. Results are presented to illustrate the relative contribution of different sources of energy loss and the effect of lubricant properties on the overall gearbox efficiency under varying operating conditions.

Document	ISBN	Pages
14FTM07	1-61481-099-5	11

A Case Study in a Practical Application of Smart Gearbox Technology

A.J. Soder

The purpose of the paper is to discuss the development of smart gearbox technology using real-world application testing and data analysis, while keeping in mind the needs of the end-user in order to assist them in developing their monitoring system. It will describe the previous maintenance methodologies used and how the ever-changing needs of the industry require them to introduce a proactive maintenance system rather than a typically reactive approach.It will explain the testing performed at the user's facility which helps gather the data that cannot be duplicated on a test system. It will then explain how after all the data is reviewed and analyzed, it is then relayed back to the user so it can be implemented by their maintenance departments. It will discuss reviewing the data of a failed gearbox during testing and how looking at the data can give a glimpse of how to understand what the data is telling us in regards to the end goal of the project.

Document	ISBN	Pages
14FTM06	1-61481-098-8	13

High Contact Ratio Gearing: A Technology Ready for Implementation?

C.D. Schultz

Today's competitive industrial gear marketplace demands products with excellent reliability, high capacity, and low noise. Surface hardened ground tooth gearing predominates but the legacy tooth forms handicap further improvements in capacity and noise generation. Vehicle and aircraft equipment use tooth forms not found in the standard charts to achieve better performance at little or no increase in cost. This paper will propose adopting these high contact ratio forms to industrial use.

Document	ISBN	Pages
14FTM05	1-61481-097-1	7

A Different Way to Look at Profile and Helix Inspection Results

J.M. Rinaldo

The traditional inspection of involute gear profile and helix deviations results in plots of deviations from a perfect involute and from a perfect helix. While this is appropriate for gears with an unmodified profile or helix, it is not ideal for gears that have intentional modifications. This paper explores the advantages of looking directly at deviations from the design shape. This type of analysis is implied but not explicitly stated nor is it pictured in the new edition of ISO 1328-1. Also presented is a modification to zone based tolerance evaluation as presented in ISO 1328-1:2013, with limits on the total deviation from design given graphically.

Document		ISBN	Pages
14FTM04		1-61481-096-4	10

Reliable Measurements of Large Gears

M. Stein, K. Kniel, F. Härtig

Large gears have become an indispensable part of modern technical applications. The expanding industrial sectors of power generation and transmission, like shipbuilding industry, wind turbine generators and petroleum conveying systems, have led to an increasing demand for large scale gear boxes. Thus, the qualified measurement of large gears has become more and more important as well. Their conformance with specifications according to ISO 14253-1 [1] has to be proved, which is not possible without a qualified statement of the task-specific measurement uncertainty. As a consequence, the manufacturing processes cannot be controlled quantitatively and at a reasonable process capability level, especially if tolerances are small compared to the achievable measurement uncertainty. This specifically applies to large gears.In this report three current projects are outlined and presented with a comparison for large involute gears. The measurement results are presented. As a second step towards traceable measurements of large gears, a special calibration laboratory shall be established. This is part of a joint research project, within which also a new measurement standard of 2 m in diameter has been developed. Lastly, information about a Joint Research Project within the European Metrology Research Program which will start in September 2014 is provided.

Document		ISBN	Pages
14FTM03		1-61481-095-7	13

Surface Roughness Measurements of Cylindrical Gears and Bevel Gears on Gear Inspection Machines

G. Mikoleizig

Alongside the macro test parameters on tooth flanks for profile and tooth traces, surface properties (roughness) play a decisive role in ensuring proper toothed gear function.The generally increased load stresses on gear teeth can only be implemented by maintaining precisely defined roughness parameters.Roughness measurements are therefore conducted on the gearing flanks in all highly developed drives, in the automotive industry, aircraft industry, or the area of wind energy drives, for example.This article addresses roughness measurement systems on tooth flanks. In addition to universal test equipment, modified test equipment based on the profile method for use on gears is addressed in particular. The equipment application here refers to cylindrical gear flanks and bevel gear flanks.

Document		ISBN	Pages
14FTM02		1-61481-094-0	15

Prediction of Surface Zone Changes in Generating Gear Grinding

F. Klocke, M. Brumm, J. Reimann, M. Ophey

One possible process for hard finishing gears is generating gear grinding. Due to high process efficiency generating gear grinding has replaced other grinding processes like profile grinding in batch production of small and middle sized gears.Despite the wide industrial application of generating gear grinding, the process design is based on experience and time and cost intensive trials. The science-based analysis of generating gear grinding needs a high amount of time and effort and only a few published scientific analyses exist. In addition, the transfer of existing knowledge from other grinding processes onto generating gear grinding is complicated due to the contact conditions between tool and gear flank, which change continuously during the grinding process.One research objective for generating gear grinding is to increase economic efficiency and productivity of the process. At the same time gear quality must be equal or higher and the external zone must not be damaged. But especially the influence of the grinding process on the external zone in generating gear grinding is unknown. In case of an inappropriate process design in combination with stock deviations an unrequested process result or even a thermal damage of the external zone can occur. In this report a thermo-mechanical process model, which describes influences on the surface zone in generating gear grinding, is introduced.

Document		ISBN	Pages
14FTM01		1-61481-093-3	11

Molecular Decomposition Process = Electrochemical Assisted Precision Form Grinding

J.A. DeAngelo

Molecular decomposition process (MDP) is an anodic dissolution process (electrochemical) whereby the work piece is the anode and the grinding wheel is the cathode. Specific controls of electrical, mechanical and chemical actions are applied to enable the MDP system to remove stock without mechanical or thermal deformation. This process enables stock removal rates in sample materials such as nickel and titanium alloys to occur at rates more aggressively than conventional creep-feed grinding. Migrating the system to employ super-abrasives greatly increases the rate of stock removal. The anodic process implemented permits the perishable wheel geometry to be preserved which equates to longer perishable life and dimensional stability, which enables longer production runs with consistent dimensional results.MDP has proven to produce gear involute geometries from “as supplied” blanks with minimal stock for finishing. Roughing and finishing of forms in full hardened 4140 tool steel yielding an MDP produced product with surfaces to less than 1 Ra μin while maintaining dimensional stability to achieve a 1.67 CPK. The MDP system removes large or small amounts of stock while providing a safe work environment for operators and the environment.

Document	ISBN	Pages
13FTM26	978-1-61481-083-4	7

Vacuum Carburizing Large Gears

N. Plough

Vacuum carburizing of gears has typically been limited to parts with relatively small cross-sections. Most alloys currently in use require oil quenching to achieve adequate surface hardness and core properties in large gear applications. Pit or large batch IQ furnaces with endothermic atmospheres are often used to process this type of gear. The majority of vacuum carburizing equipment is designed for processing smaller parts with a high pressure gas quench. Recent equipment and process developments allow vacuum carburizing and oil quenching of very large gears and pinions – up to 70" diameter and 7,000 lbs. Fixture design and careful process control help minimize distortion, while providing the case uniformity and surface integrity that is unique to vacuum carburizing. This paper will discuss specific case studies involving large gears and pinions. Distortion, case hardness profiles and microstructures from conventional gas carburizing and vacuum carburizing will be examined and compared.

Document	ISBN	Pages
13FTM25	978-1-61481-082-7	9

Press Quenching and the Effects of Prior Thermal History on Distortion during Heat Treatment

A.C. Reardon

Precision components such as industrial bearing races and automotive gears often distort unpredictably during heat treatment due to the deleterious effects of free or unconstrained oil quenching. Press quenching is a method that can be utilized to minimize the distortion of these complex components during heat treatment. This is accomplished in a quenching machine by utilizing specialized tooling for generating concentrated forces to constrain the movement of the component during oil quenching. When performed correctly, this method of quenching can often achieve the relatively stringent geometrical requirements stipulated by industrial manufacturing specifications. It can be performed on a wide variety of steel alloys. These include high carbon through-hardening grades such as AISI 52100 and A2 tool steel, as well as low carbon carburizing grades such as AISI 3310, 8620, and 9310. The relevant aspects of this specialized quenching technique will be presented together with a case study of the effects of prior thermal history on the distortion that is generated during press quenching.

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Innovative Induction Hardening Process with Preheating for Improved Fatigue Performance of Gear Component

Z. Li

Contact fatigue and bending fatigue are two main failure modes of steel gears. Surface pitting and spalling are two common contact fatigue failures, which are due to the alternating subsurface shear stresses from the contact load between two gear mates. When a gear is in service under cyclic load, concentrated bending stresses exist at the root fillet, which is the main driver of bending fatigue failures. Heat treatment is required to increase the hardness and strength of gears to meet the required contact and bending fatigue performance. Induction hardening is becoming more popular due to its process consistency, reduced energy consumption, clean environment, and improved product quality. It is well known that an induction hardening process of steel gears can generate compressive residual stresses in the hardened case. Compressive residual stresses in the hardened case of tooth flank benefit the contact fatigue performance, and residual compression in the root fillet benefits the bending fatigue. Due to the complex gear geometry, the residual stress distribution in the hardened case is not uniform, and different induction hardening process can lead to different residual stress pattern and significant variation of fatigue performance. In this paper, an innovative approach is proposed to flexibly control the magnitude of residual stress in the regions of root fillet and tooth flank by using the concept of preheating prior to induction hardening. Using an external spur gear made of AISI 4340 as an example, this concept of innovative process is demonstrated with finite element modeling, using commercial software DANTE.

13FTM23	978-1-61481-080-3	20

Ductile Iron for Open Gearing – A Current Perspective

F. Wavelet and M. Pasquier

For over three decades, open gearing for many applications has been successfully designed and manufactured from ductile iron. Examples spanning a full range of size and transmitted power are in service in various process industries throughout the world, proving the soundness of this material selection in technical as well as economical terms.The latest metallurgical and manufacturing developments have re-established the practical limits for this material, well beyond what was considered possible as recently as a few short years ago. A ductile iron gear of 16 m diameter, 340 BHN (min.) hardness, module 42, with a face width of 1200 mm and having AGMA Q10 teeth quality, capable of transmitting 2x10 000+ kW was previously a concept. Today, such a gear can be manufactured. Despite its long and successful service history, ductile iron remains a somewhat lesser known commodity as an open gearing material.The goal of this paper is to present the current “state-of-the-art" with respect to ductile iron as a gear material, including its mechanical properties as applicable to gear design, structural characteristics, typical manufacturing and inspection plans, and in-service behavior. For each of these aspects, ductile iron will be compared to other available materials for open gearing design and manufacture, such as cast.

13FTM22	978-1-61481-079-7	21

Heat Treatment of Large Components

G.L. Reese

Large gear components can be offered in many applications such as in marine, wind power, steel rolling mills, power plants, transportation, railroad, aircraft, cement crushers, mining and oil industry applications. There are three important surface hardening methods used to improve and expand the technical use of gear components. Design and material engineers must decide which hardening method to use. Case hardening is normally the first choice because of the highest load capacity. But, case hardening also poses challenges that must be acknowledged. Therefore, it is good to know that there are three options for very large components.

Document	ISBN	Pages
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How to Spec a Mill Gear

F.C. Uherek

For optimal torque delivery as a function of cost, there are critical parameters that need to be communicated to the gear designer from the mill builder when designing gear drive systems for ore grinding applications. Apart from loads and speeds, interface dimensions and site specific conditions are also needed. Deciding up front which gear rating practice to select can affect the torque capacity of the drive train by ~15%. How to deliver the torque to the mill pinion, either by a gear reducer or low speed motor, influences the distribution of cost between the prime mover and the gear train. This paper will outline the design considerations that go into construction of the drive system in order to explain why specific data is required and where design freedom is necessary. A clear specification up front that allows for matching interface dimensions while allowing for the most cost efficient up front design achieves this goal.

Document	ISBN	Pages
13FTM20	978-1-61481-077-3	14

Influence of Gear Loads on Spline Couplings

C.H. Wink and M. Nakandakari

Involute splines are commonly used in gearboxes to connect gears and shafts, especially when high torque is transmitted through the coupling. The load is shared among multiple teeth around the coupling circumference resulting in higher load capacity than a conventional single key. However, the total load is not equally shared among all spline teeth, mainly because of pitch deviations resulting from the manufacturing process. The load distribution along the spline engagement length is also non-uniform because of tooth misalignments and shaft torsional effects. A typical modeling assumption is that pure torsion load is applied to the spline coupling. In gearbox applications, when splines are used to connect a gear to a shaft, the torque is transmitted from the gear teeth in mesh to the shaft, or vice-versa, through the coupling. The gear loads, such as tangential and radial loads, can affect the load distribution of spline teeth. This paper presents an investigation on the influence of spur gear loads on load distribution of spline teeth. A generalized analytical model was developed to include external gear loads on spline couplings. The method divides the spline teeth into stations in the tooth axial direction, and calculates the load applied to each station based on separation between the mating points. A constant for tooth stiffness was used to calculate tooth deflections. The load distribution problem was solved using a simple approach from industry gear standards. The method was implemented into a spreadsheet for numerical example analyses. The results showed significant effect of side clearance, which is the difference between the space width of internal spline grooves and external spline tooth thickness, on the maximum load applied to the spline teeth. The greater the side clearance, the greater is the maximum load applied to the spline teeth. The proposed method may be helpful to quickly assess load distribution of spline teeth in gear applications, to determine tooth stresses, and to define lead modifications as needed.

Document		ISBN	Pages
13FTM19		978-1-61481-076-6	11

Gear Resonance Analysis and Experimental Verification Using Rapid Prototyped Gears

S.R. Davidson and J.D. Hayes

Determination of gear resonance frequencies is necessary in the design of light weight aerospace gears. Resonant frequencies and mode shapes calculated are then identified as damaging or non-damaging and compared to the gear's mesh frequencies to determine if gear tooth bending stresses will be amplified in a particular operating speed range. Finite Element Analysis (FEA) is well suited to determining gear resonant frequencies and modes. In order to verify the analysis quickly, rough gear geometry is fabricated and tested using accelerometers and a calibrated hammer in a modal excitation test. In past efforts, rough geometry fabricated was a simplified version of the final part minus gear teeth or other features. To reduce the time of fabrication and to increase the accuracy of the prototype part, modern rapid prototyping manufacturing techniques may hold promise in approaching the realism of the actual part with material properties that are similar to material properties of gear steels.This paper studies gear resonance modal excitation testing of two stage idler spur gear rapid prototyped parts, using two different rapid prototyping techniques and compares results to the final production part and FEA model. Damaging and non-damaging modes and nomenclature will be reviewed as well as the testing method.

13FTM18		978-1-61481-075-9	17

Gear Lubrication – Long Term Protection for Wind Turbines

S. Mazzola, M. Hochmann and J. Wald

The chemical and physical properties of gear oils in use may change more or less depending on its formulation and the operating conditions. For this reason, a gear oil was investigated after three years of use in a wind turbine to find out if changes are evident and if the protection of the gears and rolling bearings still meet the requirements as with fresh oil. Beside chemical and physical analyses, the used gear oil was examined on a FZG back-to-back gear test rig and on a FE8 test rig. The test results could show that the used gear oil as well as its ability to protect the gears and rolling bearings has changed very little compared to fresh oil.

Document		ISBN	Pages
13FTM17		978-1-61481-074-2	10

Dynamic Simulations of Radial Lip Seals Followability in an Industrial Gearbox

M. Organisciak, R. Iervolino, M. Sansalone, S. Barbera, A. Paykin and M. Schweig

Industrial gear units are widely used in power transmission systems. They are composed of shafts, gears, rolling elements bearings and dynamic lip seals. The seals performance is critical for a proper functioning of the system. Water or contamination ingress into a mechanical system may lead to a premature failure. Leakage of oil may have the same effect and be harmful for the environment. Depending on the application, seals may need to operate under various dynamic conditions, such as wide range of rotational speed (RPM) and temperatures, shaft–to–bore–misalignment (STBM), shaft dynamic run-out (DRO) or global structure deformations.The prediction of dynamic seal performance is a complex task. The rotating lip seals are usually made in elastomeric materials which display a hyper-elastic and viscoelastic behavior. Combined with the dynamic operating conditions, the simulation of the seal performance requires time dependent approaches which are very often time consuming. Innovative modeling methods need to be developed in order to be usable by the development engineering community.This paper presents a novel approach to predict seal dynamic performance under dynamic conditions. A formulation of viscoelastic super-elements is developed to predict the deformations of the seal lips. It is combined with a contact solver to assess contact force and its distribution around the shaft and other lip contersurfaces (such as other radial or axial locations). In order to demonstrate functionalities and advantages of the developed method, please consider an example of radial lip shaft seal. The problem addresses prediction of seal performance at cold temperature, large shaft-to-bore misalignment and dynamic run-out conditions. Different material and spring options are assessed in order to improve the performance.This unique modeling capability will allow selecting or developing the shaft seals which would meet and exceed modern gearbox demanding application. It will also enable gearbox manufacturers to bring to the market more performing and reliable gearboxes.

13FTM16		978-1-61481-073-5	30

The Anatomy of a Lubrication Erosion Failure – Causation, Initiation, Progression and Prevention

R.J. Drago, R.J. Cunningham, W. Flynn

Visual examination of a compressor box revealed that the Low Speed (LS) Pinion exhibited pitting type defects on each of its forty-seven (47) helical teeth. Review of the failed component revealed a somewhat repetitive type of damage at one end of the teeth only. Each tooth showed what appeared to be one defect at a similar location 3600 around the Pinion. Each defect was located within ~0.5 inch of the end of the helical tooth. It was noted that each tooth defect was observed on the coast side of the teeth only.Visual examination of the mating gear revealed no evidence of similar damage. While of and by itself, this pitting may not be cause for alarm, debris from the pitting can adversely affect other components in the gearbox, especially the bearings, and the stress concentration effect of the pitting, even though it is on the coast flank, could lead to partial tooth fracture in the region of the distress. This paper presents a discussion of the causation, diagnosis and metallurgical failure investigation of this lubrication erosion failure. Our effort was aimed at identifying the nature of the pitting and providing recommendations to avoid repeat instances of this failure in this specific application and in other future designs for similar applications.The subject is presented by way of the discussion of detailed destructive metallurgical evaluations of this specific lubrication erosion failure which the authors have conducted in order to analyze and characterize the failures. Lubrication erosion is generally limited to helical gears but the authors have also found this type of distress when evaluating damage to carburized, hardened and hard finished spiral bevel gears as well when operated under the “right" circumstances. Lubrication erosion observed on helical gears only, however, will be addressed in this presentation. Although a specific failure “case" is used as the vehicle for presentation, information has been extracted and condensed from several individual actual failure investigations conducted by the authors so that a better understanding of the specific conditions that lead to micropitting and the actual progression from micropitting to fracture can be presented.

Document		ISBN	Pages
13FTM15		978-1-61481-072-8	13

White Structure Flaking in Rolling Bearings for Wind Turbine Gearboxes

H. Uyama and H. Yamada

Bearing failures in wind turbine gearboxes were investigated and rolling contact fatigue tests to reproduce them using a hydrogen-charge method were conducted. Two main failure modes in wind turbine gearbox bearings were white structure flaking and axial cracking, which were involving a microstructural change. Both failure modes can be reproduced by using specimens charged with hydrogen. Operating conditions, which can induce hydrogen generation from lubricant and penetration of the bearing steel were discussed. Effects of bearing material on white structure flaking life were suggested as one of the countermeasures.

13FTM14		978-1-61481-071-1	7

Metallurgical Investigation of “Tiger Stripes" on a Carburized High Speed Pinion

M. Li, P. Terry, and R. Eckert

“Tiger stripes" on a high speed pinion made of carburized SAE 9310 steel were investigated. The stripes were on lines of action on the load side of the teeth coinciding with different angular positions of the gear mesh. Scanning Electron Microscopy (SEM) of the affected areas showed fused metal particles, with a diameter of 1–3 microns, and gas pockets. The morphology of the damage was typical of electric discharge damage shown in ANSI/AGMA 1010-E95. This indicates that the stripes were in fact electric discharge damage. Microhardness surveys on a metallurgical transverse section of a tooth showed a hardness loss due to the discharge, with load side surface hardness even lower than 58 HRC. The cause of the “tiger stripes" and potential damage to the gear tooth were analyzed.

13FTM13		978-1-61481-070-4	15

Gear Failure Analysis and Lessons Learned in Aircraft High-Lift Actuation

A. Wang, S. Gitnes, L. El-Bayoumy and J. Davies

Several gear failure cases and lessons learned in the development phase of aircraft high lift actuation systems are presented, including leading edge geared rotary actuators, and trailing edge geared rotary actuators, sector gears and pinions, and offset gearboxes. The high lift system of an aircraft, which contains trailing edge flaps and/or leading edge slats, increases lift for takeoff, controls flight during cruise, and reduces speed while increasing lift for shorter landing distance.Many of these components contain highly loaded gears to increase the power to weight ratio. Because of requirements on weight or envelope and consideration of cost, the gears are always designed to the limit with reasonable margins of safety in a high lift system. The structure which supports the gears is limited in size and simplified, and the gear material and heat treatment are selected for easy manufacturing. Therefore, when misalignment and/or deflection of the gears are large enough to cause reduction in tooth contact area, the stress on gears becomes large enough to cause damage. The failure modes can be classified as spalling or pitting at the location of concentrated loads. Most of the problems can be resolved by providing correct lead modification to alleviate the concentrated loading, while some need increase of the gear diameters, design modifications, or introduction of materials with higher allowable.

Document	ISBN	Pages
13FTM12	978-1-61481-069-8	32

Practical Considerations for the Use of Double Flank Testing for the Manufacturing Control of Gearing

E. Reiter and F. Eberle

The gearing industry has developed many unique measuring techniques for the production control of their products. Each technique has inherent advantages and limitations which should be considered by designers and manufacturers when selecting their use. Double flank composite inspection, (DFCI) is one such technique that can functionally provide quality control results of test gears quickly and easily during manufacturing. The successful use of DFCI requires careful planning from product design, through master gear design and gage control methods in order to achieve the desired result in an application.This document explains the practical considerations in the use of double flank testing for the manufacturing control of spur, helical, and crossed axis helical gearing including:-a general description of double flank inspection equipment including an explanation of what can be measured;-recommendations on practical master gear design;-the calculation of tight mesh center distance and test radius limits;-the resulting backlash that can be anticipated in gear meshes based on applying double flank tolerances in a design;-initial and ongoing statistical techniques in double flank testing and how they can be practically used to improve gear quality;-double flank gage measurement system analysis including case studies of gage repeatability and reproducibility (R&R) and uncertainty analysis.

Document	ISBN	Pages
13FTM11	978-1-61481-068-1	14

Striving for High Load Capacity and Low Noise Excitation in Gear Design

K. Stahl, M. Otto and M. Zimmer

In the design process of gearboxes, common requirements are high load capacity and low noise excitation. Reaching both goals is laborious and normally requires a trade-off. Detailed analyses of contact conditions and deformations are necessary. These should take place in an early design stage to realize a mostly straightforward design approach and prevent late design changes. Focused on cylindrical gears, the paper covers an approach starting at the first draft of a gearbox.Defining the macrogeometry of the teeth regarding load capacity calculation according to standards leads to a reasonable gear design. On that basis, the micro geometry of the teeth is specified and load distribution as well as noise excitation is calculated. The design parameters are interdependent so provisions have to be made to adjust each step on the remaining ones. Effects resulting from changing profile contact ratio under load and contact patterns not covering the whole flank have to be regarded. The beneficial effect of a modified microgeometry is dependent on the ability to precisely account for contact conditions and meshing clearances.To find an optimal solution for the competing goals of capacity and excitation, detailed calculation methods are required. To be able to apply latest research results, these are implemented in highly specialized software. The task described above is handled by using the software that was developed at the Gear Research Center (FZG) with funding by the German Research Association for Gears and Transmissions (FVA). The underlying calculation methods and analyzed phenomena are covered.

Document		ISBN	Pages
13FTM10		978-1-61481-067-4	19

Calculation of the Tooth Root Load Carrying Capacity of Beveloid Gears

C. Brecher, M. Brumm and J. Henser

In this paper, two developed methods of tooth root load carrying capacity calculations for beveloid gears with parallel axes are presented. The first method calculates the tooth root load carrying capacity in an FE-based approach. The initial step of the method is the manufacturing simulation in the WZL software GearGenerator. The manufacturing simulation calculates the 3D geometry of the beveloid gears by simulating the generating grinding process. The next step is an FE-based (finite element) tooth contact analysis with the WZL software ZaKo3D which is able to calculate the tooth root stresses of several gear types during the meshing. From these stresses and further parameters (e.g., local material properties) the tooth root load carrying capacity is calculated in an approach which is based on the weakest link model of Weibull.The second method uses analytic formulas to calculate the tooth root load carrying capacity of beveloid gears. In this method the tooth root load carrying capacity of beveloid gears is compared to the tooth root load carrying capacity of cylindrical gears. The effects which are observed during this comparison are described and formulas are derived to take these effects into account. Finally, both methods are applied to a test gear. The methods are compared to each other and to tests on beveloids gears with parallel axes in test bench trials.

13FTM09		978-1-61481-066-7	16

Investigations on Tooth Root Bending Strength of Case Hardened Gears in the Range of High Cycle Fatigue

N. Bretl, S. Schurer, T. Tobie, K. Stahl and B.-R. Höhn

Tooth root load-carrying capacity is one of the determining factors in gear design. In addition to the strength of the material itself, the existing state of stress significantly influences tooth root load-carrying capacity. Based on extensive experimental investigations of gears, the beginning of the fatigue strength range is generally set 3×106 load cycles, which common calculation methods, like ISO 6336, also take into account. According to this, standard test methods for tooth root bending endurance strength usually assume a load cycle limit of 3-6 106.However, current as well as completed studies on tooth root load carrying capacity show tooth root fractures with relatively high numbers of load cycles in a range of general fatigue strength and above. Analysis of these fracture surfaces shows that these late breakages are often initiated by small inclusions or microstructural defects in the material. These tooth fractures that initiate with cracks under the surface have a negative effect on the tooth root load-carrying capacity in the range of high cycle fatigue. Therefore, experimental investigations regarding high cycle fatigue have been carried out in a pulsator test rig on gears of various sizes, materials and residual stress conditions. As a result, depending on the existing residual stress condition, there are different levels of tooth root load carrying capacity, different failure behaviors in high cycle fatigue and different types of damage. Especially for test variants with high residual stresses, the size of the gear and the cleanness of the material have an impact on the tooth root load-carrying capacity and the damage pattern.This paper discusses the different fracture modes by means of examples. Furthermore, it presents the influence of residual stresses, size and material cleanness on the tooth root load-carrying capacity and on the type of tooth root fractures with crack initiation on and under the surface. These influences will be additionally confirmed by examples of experimental test results.

Document		ISBN	Pages
13FTM08		978-1-61481-065-0	19

Application and Improvement of Face Load Factor Determination Based on AGMA 927 (Accurate and Fast Algorithm for Load Distribution Calculation, for

U. Kissling

The face load factor KHβ, which in rating equations represents the load distribution over the common face width in meshing gears, is one of the most important items for a gear strength calculation. In the international standard for cylindrical gear rating, the ISO 6336-1, using method C, some formulas are proposed to get a value for this factor. But as the formulas are simplified, the result is often not very realistic. Also AGMA 2001 (or AGMA 2101) proposes a formula for KHβ, different from ISO 6336, but again not always appropriate. Therefore, a note in AGMA stipulates, that “it may be desirable to use an analytical approach to determine the load distribution factor".In the last edition of ISO 6336 (2006), a new annex E was added: “Analytical determination of load distribution". This annex is entirely based on AGMA 927-A01. It is a well-documented procedure to get a direct and precise number for the face load factor. Today an increasing number of gear designers are using tooth contact analysis (TCA) methods to get precise information over the load distribution on the full gear flank. Contact analysis is very time consuming and does not permit to get a value for KHβ, as defined by the ISO or AGMA standard. A contact analysis result combines different factors of ISO 6336 as KHβ, KHα, Zε, Zβ, ZB, ZD and buttressing effects, etc., thus to ` extract' KHβ from a TCA is not possible. The use of the algorithm, as proposed by AGMA 927, is a good solution to get proper values for KHβ; it is simpler and therefore much quicker than a contact analysis calculation. The paper explains how this algorithm can be applied for classic gear pair rating procedure, for ratings with complex duty cycles and even for planetary systems with interdependent meshings between sun, all planets and ring.

13FTM07		978-1-61481-064-3	11

Finite Element Analysis of a Floating Planetary Ring Gear with External Splines

V. Kirov and Y. Wang

This study investigates the stresses and deflections of a floating ring gear with external splines working in a large planetary wheel motor of a mining truck. Such calculations carried out with conventional engineering approaches described in popular standards and textbooks are not comprehensive because of the complexity of the problem. These approaches can give us good stress numbers for non-floating gears and some guidance about the rim thickness factor but they lack the capabilities to effectively calculate the deflections and their influences on the stresses, especially for floating gears. Moreover, they cannot calculate an entire gearing system and the interdependent influences of the different components. The model studied consists of a floating ring gear driving a torque tube. The ring gear is driven through internal gear meshing by three planets and it transmits the torque to the torque tube through its external splines. The torque tube transmits the motion to the hub and the truck tires. A nonlinear static analysis of the ring gear and torque tube was conducted in ABAQUS. Linear 8-node hex elements and linear tetra elements were used to model the ring gear and torque tube. External torque was resolved into corresponding tangential force, which was then applied directly onto three of the ring gear's internal teeth. Contact pairs were used to capture the load transfer between the ring gear and torque tube through the splines.The results show that the deflections in the ring gear were so excessive that about one-tenth of the spline teeth were actually transmitting torque against the common engineering understanding that only half of the spline teeth are typically engaged. The crowning of the spline teeth had also effect on the stresses though quite small compared to the deflections. Conclusions and recommendations were made about the effectiveness of the design.

Document		ISBN	Pages
13FTM06		978-1-61481-063-6	12

High Gear Ratio Epicyclic Drives Analysis

A. Kapelevich

Epicyclic gear stages provide high load capacity and compactness to gear drives. There is a wide variety of different combinations of planetary gear arrangements [1, 2]. For simple epicyclic planetary stages when the ring gear is stationary, the practical gear ratio range varies from 3:1 to 9:1. For similar epicyclic planetary stages with compound planet gears, the practical gear ratio range varies from 8:1 to 30:1. This paper presents analysis and design of epicyclic gear arrangements that provide extremely high gear ratios. Using differential-planetary gear arrangements it is possible to achieve gear ratios of several hundred to one in one-stage drive with common planet gears and several thousand to one in one-stage drive with compound planet gears. A special two-stage planetary arrangement may utilize a gear ratio of over one hundred thousand to one.This paper shows an analysis of such uncommon gear drive arrangements, defines their major parameters, limitations, and gear ratio maximization approaches. It also demonstrates numerical examples, existing designs, and potential applications.

13FTM05		978-1-61481-062-9	10

Cubitron™ II: Precision Shaped Grains (PSG) Turn the Concept of Gear Grinding Upside Down

W. Graf

To date, grinding, according to the German DIN Standard 8580, is “machining with geometrically undefined cutting edges" while other machining processes such as turning and milling are classified as processes with “geometrically defined cutting edges". New abrasive grains, called PSG and developed by 3M, stand this definition on its head. For the first time, grinding wheels made with PSG, called Cubitron™ II, can claim to be made up of “geometrically defined cutting edges" as each and every grain is exactly the same engineered shape. Hence, it might be more appropriate to talk about “micro-milling" rather than grinding. This is borne out by looking at the resulting “flowing" chips which are akin to chips seen in milling operations, just finer.These free-flowing chips no longer clog up the grinding wheel and, therefore, the grinding wheel remains free-cutting and dressing becomes only necessary due to loss of from rather than loss of cutting ability. In repeated tests, this has shown to drastically reduce the risk of burning and to give consistent and predictable results. Furthermore, tests and subsequent long term trials under production conditions have shown that grinding time can be cut in most cases by at least 50% in comparison to grinding wheels made of standard ceramic abrasives.Based on more than 100 carefully monitored and documented gear grinding trials, this paper will demonstrate how Cubitron™ II grinding wheels work both in continuous generating grinding of car and truck gears, and in form grinding of large diameter gears for wind generators, for example. Furthermore, the paper will discuss chip formation, filmed with high resolution slow motion; and the benefits of the free-flowing chips in terms of resulting consistent surface finish, superior form holding and extended dressing cycles.

Document		ISBN	Pages
13FTM04		978-1-61481-061-2	11

Best Practices for Gearbox Assembly and Disassembly

J. Bello

When industry is looking at the best ways to increase efficiency, reduce downtime and increase profitability, gearbox performance and reliability are key factors. In most applications gearbox reliability is critical to the productivity of the overall plant operation. Repair is often required with a swift turn around, as down time is very expensive. Designing for repair, and writing effective repair procedures, can speed the service time, and provide a quality refurbishment. Minimizing down time and extending service life will contribute significantly to achieving the lowest overall operation costs.The best practices listed below are proven, effective methods used to install and remove bearings, seals, gears, couplings and shafts within a gearbox. These techniques are not new, and are usually obtained by hard won experience. Collecting them in one location is an attempt to document the best practices and provide a reference for design engineers. Engineers write the procedures for assembly and disassembly, they also dictate to the rest of the design team the design intent. Including features to facilitate disassembly, minimizes repair cycle time and helps to prevent damage to components that could radically compromise their design life or performance.

13FTM03		978-1-61481-060-5	9

Analysis of Gear Root Forms: A Review of Designs, Standards and Manufacturing Methods for Root Forms in Cylindrical Gears

N. Chaphalkar, G. Hyatt, and N. Bylund

Gear root is an important but often neglected element of the gear. The stress concentration point typically lies in the tooth to root transition area and it is this point that determines the life or the fatigue life of a gear in many applications. Specific standards are in place on design of the involute part of a gear tooth, the root area however is less standardized. New manufacturing methods enable the designer of gears greater latitude in the design of strong alternative root forms. The standards on design and specification for the root geometry are lax so these root forms fit into current standards.This paper reviews the designs of various root forms for the gears. It compares the various root forms on basis of their strength, fatigue resistance and other parameters. This analysis will be based on compilation of various research previously conducted on gear root forms. The paper also discusses current manufacturing methods to produce the roots, and recently introduced alternatives. It will compare the traditional methods with new methods of gear manufacturing it terms of types of roots produced and overall control over the root profile.

13FTM02		978-1-61481-059-9	12

Performance and Technological Potential of Gears Ground by Dressable cBN Tools

J. Reimann, F. Klocke, M. Brumm, A. Mehr and K. Finkenwirth

Dressable vitrified bond cBN grinding tools combine the advantages of other common tool systems in generating gear grinding. The cBN grains are a highly productive cutting material due to their high specific stock removal rate. Vitrified bonds are dressable and thereby very flexible: By dressing different profile modifications can be set up and constant gear quality can be guaranteed during the tool life time. Despite those technological advantages there is only a small market distribution of these grinding tools due to high tool costs. Furthermore, only a few published scientific analysis of generating gear grinding with dressable cBN exist. Especially, the influence of the grinding tool system on manufacturing related component properties has not been analyzed yet. The research objective of this report is to determine the advantages of dressable cBN tools in generating gear grinding.

Document		ISBN	Pages
13FTM01		978-1-61481-058-2	18

Power Skiving of Cylindrical Gears on Different Machine Platforms

H.J. Stadtfeld

Skiving is a cutting process which was first patented in 1910 as an efficient process to manufacture internal ring gears. Like honing, Power Skiving uses the relative sliding motion between two “cylindrical gears" whose axes are inclined. The skiving cutter looks like a shaping cutter with a helix angle for example, 20� different than the helix angle of the cylindrical gear to be machined.The skiving process is multiple times faster than shaping and more flexible than broaching, due to the continuous chip removal in skiving, but it presents a challenge to machines and tools. While the roll motion between the cutting edge and the gear slots occurs with the spindle RPM, the relative axial cutting motion is only about one third of the circumferential speed of the cutter. The cutting components of rolling and cutting which result in a “spiral peeling" are represented with the process designation skiving. Because of the relatively low dynamic stiffness in the gear trains of mechanical machines as well as the fast wear of uncoated cutters, skiving of cylindrical gears never achieved a breakthrough against shaping or hobbing until recently. The latest machine tools with direct drive train and stiff electronic gear boxes present an optimal basis for the skiving process. Complex tool geometry and the latest coating technology were required to give the soft skiving of cylindrical gears a breakthrough. Gleason has developed a line of dedicated power skiving machines, which apply solid HSS cutters for small to medium modules.

12FTM24		1-978-61481-055-1	9

Recent Inventions and Innovations in Induction Hardening of Gears and Gear-like Components

V. Rudnev

Presentation focuses on recent inventions and innovations (last 4–6 years) in induction hardening of gears and gear-like components, including but not limited to:-�Know-how" in controlling distortion of induction hardened gears.-�Simultaneous dual-frequency induction hardening.-�Advanced induction hardening process recipes when hardening small and medium size gears.-�Novel inductor designs to minimize a distortion when induction hardening of hypoid and spiral bevel gears.-�IFP technology for induction gear hardening.-�Induction tempering and stress relieving of gear-like components with improved temperature uniformity.Presentation also provides a review of basic principles and applications devoted to induction hardening small, medium and large size gears using tooth-by-tooth techniques and encircling method.

Document	ISBN	Pages
12FTM23	1-978-61481-054-4	14

Enhancing Control of Distortion Through “One-Piece Flow – Heat Treatment”

V. Heuer, D. Bolton, K. Löser, T. Leist

Proper control of distortion has become even more important on new powertrain designs. To answer the demand for fuel-efficient vehicles, modern transmissions are built much lighter, therefore the components of the transmission exhibit less wall thickness which makes them more sensitive to distortion. Distorted gear components can create noise in the transmission, require post heat treat machining processes and may even create problems during transmission assembly. By applying the technology of Low Pressure Carburizing (LPC) and High Pressure Gas Quenching (HPGQ), the distortion caused by heat treatment can be significantly reduced. This technology has been successfully established in serial production for many different gear applications. With the introduction of One Piece Flow – Heat Treatment, the distortion control can be further enhanced. This 'One-piece Flow – heat treatment' allows for a rapid case hardening where the components are low pressure carburized at high temperatures (1050°C) followed by gas quenching. The components are not treated in conventional big batches with multiple layers, but they are treated in small batches consisting of one layer only. The quench intensity is controlled more precisely to allow for processes which are customized individually for each gear-component. The single-layer treatment provides -�omogenous and rapid heating of the components;-�omogenous and rapid carburizing of the components;-�omogenous and precisely controlled gas quenching. All the variations from layer to layer are eliminated, which leads to reductions in distortion-variation within the load.

In addition, this new technology allows strong costs-savings for logistics. The manufacturing-line can be completely automated since the parts are 1st taken one by one from the soft machining unit, then 2nd heat treated in time with the cycle-time of soft machining (“Synchronized heat treatment”) and then 3rd passed down one by one to the hard machining unit. The paper presents applications for enhanced distortion control when using One Piece Flow – Heat Treatment.”

Document		ISBN	Pages
12FTM22		1-978-61481-053-7	9

Crack Testing and Heat Treat Verification of Gears Using Eddy Current Technology

D. DeVries

While eddy current technology has long been used in the testing of bar, tube, and wire stock, advances in electronics, automation, and coil design have paved the way for a new generation of testers specifically designed for component testing applications. This includes the testing of gears and bearings which go into automotive and industrial applications. These testing systems easily integrate into production processes allowing for in-line testing at production line speeds. In addition to enabling 100% of production components to be inspected, it can help monitor upstream processes notifying operators that something is not functioning correctly. This greatly reduces scrap and warranty costs for gear and bearing manufacturers.Eddy current crack testing is performed by passing a small pair of coil windings over a section of the component to be tested. These coil windings are small enough to test between gear teeth, and with multi-coil probes can test very complex shapes. Most crack test applications require only one test frequency since most tests require the detection of only surface flaws. Simultaneous testing with multiple frequencies allows for testing of both surface and sub-surface defects when inspecting nonferromagnetic parts.While not an absolute hardness test like a Rockwell test, eddy current heat treat verification can achieve sorting results on par with Rockwell testing. This has been demonstrated with both forged and powder metal gears. Eddy current heat treat inspection coils come in both standard encircling coil configurations and multi-coil custom configurations. The custom configurations allow for precise location testing verifying that induction heating parameters were correctly applied. Defects to be tested include misplaced case, shallow case, short quench, delayed quench, air cooled, non-heat-treat, and ground out conditions. When performing heat-treat inspection, multiple test frequencies are used to reliably detect these various heat-treat anomalies.Eddy current testing offers fast, repeatable testing of gears and bearings. Testing data on each component can be stored electronically and re-analyzed off-line at a later date. Eddy current test instruments are designed to integrate with PLC's in material handling stations to set up real-time rejection capabilities. These are all features that complement modern QC requirements.

12FTM21		1-978-61481-052-0	14

Typical Heat Treatment Defects of Gears and Solutions Using FEA Modeling

Z. Li, B.L. Ferguson

Steel gears are heat treated to obtain enhanced properties and improved service performance. Quench hardening is one of the most important heat treatment processes used to increase the strength and hardness of steel parts. Defects seen in quenched parts are often due to high thermal and phase transformation stresses. Typical defects include excessive distortion, surface decarburization, quench cracks, large grain growth, and unfavorable residual stresses. Gear geometries with large section differences may suffer high stress concentrations and crack during quenching. Surface decarburization before quenching may lead to high surface residual tension and possible post heat treatment cracking. In this paper, the commercial heat treatment software DANTE is used to investigate three examples of heat treatment defects. Improved processes are suggested with the help of modeling. The first example is an oil quench process for a large gear. Peeling cracks were observed on the gear surface during grinding of the quench hardened gears. Computer modeling showed that surface decarburization was the cause. The second example is a press quench of a large face gear. Unexpected large axial bow distortion was observed in quenched gears, and computer modeling indicated that an incorrect press load and die setup were the reasons. The third example is an in-process quenching crack caused by high concentrated tensile stress from unbalanced temperature and phase transformations in a spiral bevel pinion gear. The quenching process was modified to solve the problem. This example also emphasizes the need for heat treatment modeling in gear design to reduce the possibility of heat treatment defects. The three examples illustrate how to effectively use heat treatment modeling to improve the quality of the gear products.

Document	ISBN	Pages
12FTM20	1-978-61481-051-3	15

The Effect of the Surface Profile on Micropitting

M. Bell, G. Sroka, R. Benson

A wide choice of surface roughness parameters is available to characterize components, such as gears or bearings, with the goal of predicting the performance of such metal-to-metal contacting parts. Commonly in industry, the Roughness Average (Ra) or the Mean Peak-to Valley Height (Rz (DIN)) is chosen to calculate the Specific Film Thickness Ratio for both superfinished and honed surfaces. However, these two surface roughness parameters fail to adequately predict the performance properties of surfaces that are superfinished or surfaces that are honed. In this paper, a superfinished surface is defined as a planarized surface having a ≤0.25 μm Ra. A honed surface is not considered to be planarized, even with a finish of ≤0.25 μm Ra. Thus, one is falsely led to predict that a planarized surface or a honed surface, having an equivalent Ra or Rz, will perform similarly. Nothing is further from the truth. Experimentally, an isotropic planarized surface delivers superior performance. The following discussion utilizes another roughness parameter, 3s50, to further explain this phenomenon.

Document	ISBN	Pages
12FTM19	1-978-61481-050-6	13

A Field Case Study of “Whining" Gear Noise in Diesel Engines

Y. Kotlyar, G.A. Acosta, S. Mleczko, M. Guerra

The proposed paper is a field case study of diesel engine whining gear noise. The paper will describe the development work performed to reduce the gear whining noise. It will include the problem definition, inspection of BOB & WOW engines, design of experiment, development and review of gear geometry modifications, inspection charts, sample size for a statistically significant analysis, and correlation of noise measurement results and tooth profiles.

Document	ISBN	Pages
12FTM18	1-978-61481-049-0	11

Analysis of Ripple on Noisy Gears

G. Gravel

A low noise level is an important quality feature in modern gearboxes for passenger cars. But a troublesome noise can have many causes. The noise origination and transmission is amongst others affected by the design layout, by the actual deviations of the components, by the assembly of the components and also by the mounting situation of the complete gearbox.Damages, form errors and displacement errors or ripples are often present on the flanks of a gear, if it is found to be the cause of problems in a noise check. Especially ripples or 'ghost frequencies' of a gear are problematic, because up to now they rarely can be detected on a gear measuring device but only in a relative complex single-flank roll checking procedure. A new evaluation method now allows to identify and to describe ripples on the flanks of gears based on the results of a normal gear measurement. The deviation curves were approximated by sine functions, the results are displayed graphical and by characteristic values. A combination of the deviation of each measured point with its rotation angle allows an evaluation equal to a rolling with the mating gear. The results show a very good correlation to a noise check and to a single-flank roll check. The application of the software is demonstrated by practical examples of the manufacturing methods generating grinding, honing, broaching and shaving. Vibrations of machine tool and ripple generating influences in the manufacturing process can be verified down to a level of a few tenth micrometers. At the same time this method is well suited to describe long-wave form deviations like an ovality or a 3- or 4-fold ripple caused by the clamping or by a square blank. With this new evaluation method gears can be tested in an early state of production for known, critical ripples and conclusions can be drawn on the state of machine tool, cutting tool and clamping device.

Document		ISBN	Pages
12FTM17		1-978-61481-048-3	13

Dynamic Analysis of a Cycloidal Gearbox Using Finite Element Method

S. Thube, T. Bobak

Speed reducers incorporating cycloidal technology as their primary reduction mechanism have always been active topics of research given their unique trochoidal tooth profile. A cycloidal reducer is recognized for its strength and mainly studied for rotational performance improvement. Nowadays, this study can be performed by digital prototyping, which has become a valuable tool for simulating exact scenarios without experimenting on actual model. This paper discusses the stress distribution, modeled in a dynamic simulation environment, on the rotating parts of Cycloidal reducer. A three dimensional finite element model is developed using Algor FEA commercial code to simulate the combined effect of external loading and dynamic as well as inertial forces on one-cycloid disc system. This model utilizes surface-to-surface contact to define interaction between rotating parts of the reducer assembly. The results are analyzed for the variation in stress and deformation with respect to time for a certain simulation period. This study gives an insight of internal load sharing of rotating parts and their capability of carrying shock loads.

Document		ISBN	Pages
12FTM16		1-978-61481-047-6	9

Gear Design Optimization for Low Contact Temperature of a High-Speed, Non-Lubricated Spur Gear Pair

C.H. Wink, N.S. Mantri

This paper presents a gear design optimization approach that was applied to reduce both tooth contact temperature and noise excitation of a high-speed spur gear pair running without lubricant. The optimum gear design search was done using the RMC (Run Many Cases) program from The Ohio State University. Over 480 thousand possible gear designs were considered, which were narrowed down to the 31 best candidates based on low contact temperature and low transmission error. The best gear design was selected considering, also, its manufacturability. The selected optimum gear design was compared to an existing gear set using LDP (Load Distribution Program) from The Ohio State University. Tooth contact temperature was calculated for both designs using dry a steel-on-steel coefficient of friction. Predicted contact temperature correlated well with results observed on dynamometer tests with the existing gear set. Predictions with the optimized design showed a 48% contact temperature reduction and a 79% noise excitation reduction. The low contact temperature of the optimized design will significantly contribute to preventing tooth surface damage under no lubricant operating conditions.

Document	ISBN	Pages
12FTM15	1-978-61481-046-9	21

New Methods for the Calculation of the Load Capacity of Bevel and Hypoid Gears

C. Wirth, B.-R. Höhn, C. Braykoff

A failure mode called "flank breakage" is increasingly observed in different applications of cylindrical and bevel gears. These breakages typically start from the active flank approximately in the middle of the active tooth height and propagate to the tooth root of the unloaded flank side. Crack initiation can be localized below the surface in the region between case and core of surface hardened gears. This failure mode can neither be explained by the known mechanism of tooth root breakage nor by the mechanism of pitting. Even bevel gears in truck and bus applications are at the risk to suffer from subsurface fatigue, if the optimum utilization of the material should be achieved. In this case a balance between the flank breakage and pitting risk has to be found. The purpose of this paper is to describe a new material physically based calculation method to evaluate the risk of flank breakage versus the risk of pitting. The verification of this new method by experimental tests is exemplarily shown. In cooperation with "ZG-Zahnräer und Getriebe GmbH" (ZG) "MAN truck and bus AG" (MTB) developed a new method for the calculation of the risks of flank failure by flank breakage and pitting. The calculation method has been adjusted and approved by experimental tests on powertrain test rigs of MAN. The ten different test gear variants had an outer diameter of de2 = 390 mm to 465 mm, a ratio i = 4,5 to 5,7 and a normal module of mmn = 6 mm to 8 mm. Also variants with the same main geometry but different Ease-Off designs were examined. All gear sets were tested under a defined load spectrum. Based on the research work at the FZG (Gear Research Center at the Technical University of Munich in Germany) of Oster, Hertter and Wirth a calculation method for bevel gears was established. The principle of the calculation model is the local comparison of the occurring stresses and the available strength values over the whole tooth volume. Therefore, it is possible to evaluate the risk of initial cracks beyond the surface of the flank. Close to the surface cracks may grow and cause pitting— especially in the flank area with negative specific sliding. Cracks in the transient area between case and core lead to a high flank breakage risk.First the local stresses and forces on the flank are determined by a loaded tooth contact analysis followed by the calculation of the maximum exposure (regarding yielding) and dynamic exposure (regarding fatigue) of the material inside the tooth. Thereby the stress components from the Hertzian contact, bending, thermal effects (flash temperature) and friction are considered. Furthermore, the positive effect of residual compressive stresses and accordingly the disadvantageous effect of the residual tensile stresses can be implicated. Finite elements method investigations have been carried out in order to achieve a sufficient approximation of the residual stress distribution in the transverse tooth section. The strength values are locally considered, depending on the material depth and the position on the flank.The recalculation of the test gears showed a good correlation between the occurred type of damage and the determined material exposure inside the tooth. The variants failed with flank breakage could be reliably distinguished from the variants failed by pitting by the new material-physical method. With this knowledge it is now possible to optimize the main geometry parameters of the gear set (e.g. number of teeth, spiral angle, pressure angle) as well as the micro geometry (Ease-Off) that influences the load distribution on the flank. Altogether this new method leads to an insured increase of the permissible material utilization and hence to smaller gear sizes while keeping the load capacity on a constant level.

Document		ISBN	Pages
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Large Pinions for Open Gears: The Increase of Single Mesh Load – A New Challenge for Manufacturing and Quality Inspection

M. Pasquier, and F. Wavelet

Most of the large open gear sets for mining industry are designed according to AGMA 6014-A06 and AGMA 2001-D04. and rating according to AGMA standard (service factor) involve the final design of the pinion such as: material and heat treatment (through hardening or case carburized pinion), and the finishing process of the teeth (to achieve the design geometry).Basically, customer specification and rating according to AGMA standard (service factor) involve the final design of the pinion such as: material and heat treatment (through hardening or case carburized pinion), and the finishing process of the teeth (to achieve the design geometry).Moreover, the increase of applied load for a single meshing becomes a new challenge.In addition to the mechanical properties for the material used and its associated heat treatment requirements given in standards, elastic and thermal behavior and resulting accuracy, as well, have to be taken into account at design stage, even for large open gears.Beside design consideration, such increase of single meshing load cannot be achieved by using conventional manufacturing and quality control methods.Therefore, improvements in manufacturing process and in quality inspections for such heavily loaded single large parts, as already performed for smaller parts in batch are now mandatory to achieve these new design requirements.Based on examples, in this paper, it is presented such manufacturing and the associated quality controls improvements from steel fabrication to final machining for heavy parts, to ensure the customer that the result meets the specification requirements.

12FTM13		1-978-61481-044-5	14

Gear Material Selection and Construction for Large Gears

F.C. Uherek

For gears larger than 3 m (10 feet), construction of gear blanks tend to divide into cast steel, ductile iron, and forged rim welded web structures for use in cylindrical grinding mills and kilns. This paper will review the application, various options for material selection, and the impact of selection on tooth geometry. A group of sample gears are developed to compare each of the materials and method of blank construction. Each sample is discussed in light of structural stress, deflection, expected life, handling weight, material origin, fabrication method, inspection requirements during construction, and impact of selection on field performance. Based on the above, a roadmap is developed listing critical considerations and optimal use of each material and method of construction in this application.

Document		ISBN	Pages
12FTM12		1-978-61481-043-8	15

Manufacturing Method of Pinion Member of Large-Sized Skew Bevel Gears Using Multi-Axis Control and Multi-Tasking Machine Tool

I. Tsuji, K. Kawasaki, H. Gunbara, H. Houjyou, S. Matsumura

In this paper, a manufacturing method of the pinion member of large-sized skew bevel gears using multi-axis control and multi-tasking machine tool considering that the gear member is provided is proposed. First, the tooth surface forms of skew bevel gears are modeled. Next, the real tooth surfaces of the gear member are measured using a coordinate measuring machine and the deviations between the real and theoretical tooth surface forms are formalized using the measured coordinates. It is possible to analyze the tooth contact pattern of the skew bevel gears with consideration of the deviations of the real and theoretical tooth surface forms expressing the deviations as polynomial equations. Moreover, the deviations of the tooth surface form of the gear member are fed back to the analysis of the tooth contact pattern and transmission errors, and the tooth surface form of the pinion member that has a good performance mating with the gear member. Finally, the pinion member is manufactured by swarf cutting using multi-axis control and multi-tasking machine tool. Afterward, the real tooth surfaces of the manufactured pinion member were measured using a coordinate measuring machine and the tooth surface form errors were detected. As a result, although the tooth surface form errors were large relatively on the heel side, those were small on the other side. In addition, the tooth contact pattern of the manufactured pinion member and provided gear member was compared with those of tooth contact analysis. As a result, there was good agreement.

12FTM11		1-978-61481-042-1	10

Contemporary Gear Pre-Machining Solutions

C. Kobialka

Depending on production volumes, batch sizes and work piece geometry, several gear manufacturing technologies are used for industrial gear production. Most frequently applied is the hobbing process, followed by broaching, shaping, sintering and rolling processes. Upcoming gear manufacturing processes are power skiving, forging, precision blanking and cold forging. Due to improvements to the numerical control of direct drive technology, the power skiving process has become a competitive gear manufacturing process in comparison to shaping, blanking and broaching. The potential of the reinvented power skiving process will be explained by production volume analyses, achievable gear quality and gear geometry modifications. Also the economical and environmentally friendly aspect of the power skiving process will be explained.

Document		ISBN	Pages
12FTM10		1-978-61481-041-4	13

Development of Novel CBN Grade for Electroplated Finish Grinding of Hardened Steel Gears

U. Sridharan, S. Kompella, S. Ji, J. Fiecoat

The unique requirements of an electroplatable superabrasive CBN grit used in profile grinding of hardened steel gears as well as the attributes and grinding behavior of a new CBN developed specifically for this application are discussed. Profile gear grinding parameters were simulated in through-hardened AISI 4140 steel (56 HRC) and the grinding performance of the new CBN was compared against a competitive CBN grade widely used in the application. Consistent with field criteria, grinding performance was characterized based on occurrence of 'burn' or 'form' failure. The 'burn' or metallurgical phase transformation failure was detected by Barkhausen Noise Analysis (BNA) and corroborated by microstructural and microhardness evaluations. The 'form' failure was simulated by tracking average radial wheel wear to a threshold value where form loss was expected to occur. Grinding tests indicate that the new CBN grit can grind 35% more parts compared to the competitive CBN grade before burn failure. In addition, the new CBN displayed a lower wear rate. The new CBN grade also exhibited a unique ability to grind with lower grinding power, resulting in a near constant BNA response on the ground surface throughout the test. This implied minimal microstructural change on the ground part from start to end of the test compared to the progressive softening of ground surface noticed with the competitive CBN.

Document	ISBN	Pages
12FTM09	1-978-61481-040-7	22

Systematic Approach for the Psychoacoustic Analysis of Dynamic Gear Noise Excitation

C. Brecher, M. Brumm, C. Carl

The sound quality of technical products is an increasingly important quality criterion and has a significant influence on the product acceptance. But sound quality does not only depend on the physical attributes of the sound signal. It is defined to a large extent by human sound and noise perception. This perception is based on a physiological and psychological signal processing. These aspects depend on complex properties of the physical signal like the spectral distribution and a relative comparison. However, today the sound design of gearboxes is mainly based on the physical reduction of the noise level that is detected by absolute and objectivized parameters. The noise oriented gear design is based on a fundament of physical key parameters like the reduction of transmission error in compliance with achievable manufacturing tolerances. Nevertheless, these design rules may lead to a minimal sound pressure level but cannot solely be applied for an optimal sound quality in every case. Under economic and technical aspects there is no excitation free gear set. Furthermore, modern tendencies such as lightweight design and masking noise reduction (engine downsizing and electrification) lead more and more to scenarios where the sound of a gear set, which is only designated to have low transmission error, can be perceived as annoying. This requires design guidelines which take also the human related aspects of gear noise into account. Nowadays the gear design does not yet consider human noise perception sufficiently. Thus, a research project at the WZL has been established that investigates the correlation between gear mesh excitation and the evaluation of gear noise. The objective of this project is to deduce a method for the consideration of perception-based noise evaluation already in the stage of gear design. Therefore, psychoacoustics metrics are used to analyze the gear noise of different gear sets in the dimensions of airborne noise, structural vibration and the excitation due to meshing. The aim of this paper is to discuss the correlation between the signal properties of the excitation and the radiated noise in order to investigate the possibilities to transfer the perception related evaluation from sound pressure to the gear mesh excitation. The paper firstly shows central psychoacoustic parameters that are most relevant for the properties of gear noise. Furthermore, a new test fixture will be introduced that allows a dynamic measurement of gear mesh excitation directly adjacent to the meshing. Regarding these aspects two different gear sets are discussed concerning the calculated transmission error and the experimentally determined excitation, surface vibration and noise radiation. These aspects are accordingly examined with respect to human noise perception, which is described by psychoacoustics. It is shown that operating conditions, order distributions as well as the gear geometry are the main influences on the signal evaluation. The influence of dynamic aspects and especially the influence of resonance effects on the noise characteristics are additionally considered.

12FTM08	1-978-61481-039-1	20

Combined Marine Propulsion Systems: Optimization and Validation by Simulation

B. Pinnekamp and F. Hoppe

Modern Navy and Coast Guard Vessels usually have combined propulsion systems using gas turbines, diesel engines and electric motors as main propulsors. Desired operating profiles demand for individual optimization of the gear propulsion system with respect to efficiency, noise, operational flexibility and capital cost. Combined systems are complex and therefore sensitive to dynamic excitation and resonance. To avoid unfavorable dynamic effects, it is necessary to validate candidate arrangements using modern tools like multi body simulation.The paper describes the evaluation process for optimized combined marine propulsion systems and system validation by dynamic simulation.

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Validation of a Model of the NREL Gearbox Reliability Collaborative Wind Turbine Gearbox

C.K. Halse, Z.H. Wright, A.R. Crowther

Gearboxes in the wind industry have been suffering from a poor reputation due to major issues with reliability. There has been a long list of issues; e.g. grind temper, material inclusions, axial cracking in bearings, poor load sharing on shaft-bearing arrangements, significant gear misalignment, bearing ring creep, gear scuffing, gear and bearing micropitting; all of which are common and often serial problems. There has been improvement in the last few years for some of the products, yet it is not uncommon for wind sites built as recently as 2008 to have 20–40% of gearboxes requiring a component replacement (such as a high speed pinion or intermediate shaft bearing) already (by 2012) and 5–10% complete gearbox failures. An important program for the industry, “The Gearbox Reliability Collaborative" (GRC), has been funded by the US Department of Energy and run by the National Renewable Energy Laboratory for several years to aid the industry in improving the reliability of this key component. The collaborative has brought together manufacturers, academia, national laboratories, engineering consultants and gear and bearing software providers as part of a program to model, build, simulate and test gearboxes with a goal to improve reliability and reduce the cost of energy.The team at NREL have instrumented two gearboxes with over 125 channels, for measurements such as planetary tooth load distributions, annulus gear hoop strains, planet bearing load distribution, sun orbit and carrier deflection. They were then subjected to a rigorous testing regime, both up-tower and on the NREL 2.5MW dynamometer. Romax Technology have been a collaborator in the GRC Analysis Group and have developed detailed computer simulation models of the gearbox including gear macro and micro-geometry, bearing macro and micro-geometry, structural stiffness of gearbox housing, carrier and annulus gear, system clearances and preloads, and surrounding boundary conditions (such as main shaft, rotor hub and bedplate). The model is used for accurate simulation of the whole system deflections and the prediction of the resulting gear and bearing contact conditions under various loading conditions.The focus of this paper is a comparison between measurement and simulation for key parameters including gear load distributions, annulus deflection and sun motion. The simulation results that are robust and those that are sensitive to hard-to-predict parameters that include significant effects from manufacturing and assembly variations will be outlined. Lessons learned in how best to apply computer-aided-engineering tools to improve wind turbine gearbox reliability will be described.

12FTM06	1-978-61481-037-7	16

Virtual Optimization of Epicyclic Gearbox Planet Bearings in Wind Turbines

S. Vasconi, D. Raju

Demand for higher reliability, robustness and performance in epicyclical gearboxes have led SKF to develop Design for Six Sigma (DfSS) based simulation tools and methods. This paper will illustrate the advantages of using simulation driven design in the development of planetary gearboxes for multi megawatt wind turbines. The simulation example will show the influence of the housing flexibility and of the non-linear bearing and gear stiffness on the gearbox performance under transient load. In particular, the load distribution and deformation of the planetary gears and bearings will be analyzed.The flexibility and accurate stiffness description led to non-intuitive results. The gear deformation and load distribution led to significantly different results compared to results obtained by using traditional calculation tools and methods. A comparison between advanced and standard calculation methods is given as evidence that advanced analyses should be used to design reliable, robust and high performing gearboxes.A virtual design of experiments was used to determine the most influential parameters affecting the gearbox performance. This paper will highlight the results of this DfSS study.

Document		ISBN	Pages
12FTM05		1-978-61481-036-0	16

Combined Effects of Gravity, Bending Moment, Bearing Clearance, and Input Torque on Wind Turbine Planetary Gear Load Sharing

Y. Guo, J. Keller, W. LaCava

This computational work investigates planetary gear load sharing of three-mount suspension wind turbine gearboxes. A three dimensional multi-body dynamic model is established, including gravity, bending moments, fluctuating mesh stiffness, nonlinear tooth contact, and bearing clearance. A flexible main shaft, planetary carrier, housing, and gear shafts are modeled using reduced degrees-of-freedom through modal compensation. This drive train model is validated against the experimental data of Gearbox Reliability Collaborative for gearbox internal loads. Planet load sharing is a combined effect of gravity, bending moment, bearing clearance, and input torque. Influences of each of these parameters and their combined effects on the resulting planet load sharing are investigated. Bending moments and gravity induce fundamental excitations in the rotating carrier frame, which can increase gearbox internal loads and disturb load sharing. Clearance in carrier bearings reduces the bearing load carrying capacity and thus the bending moment from the rotor can be transmitted into gear meshes. With bearing clearance, the bending moment can cause tooth micropitting and can induce planet bearing fatigue, leading to reduced gearbox life. Planet bearings are susceptible to skidding at low input torque.

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Energy Efficient Industrial Gear Lubricants

D. Blain, A. Galiano-Roth, R. Russo, K. Harrington

Global energy demand is predicted to be about 30 percent higher in 2040 compared to 2010. Energy demand growth will slow as economies mature, population growth moderates and efficiency gains accelerate. This paper will focus on the third factor: energy efficiency. The industrial sector consumes almost 48% of global energy, with the remainder being used for residential/commercial and transportation. Clearly, improvements in energy efficiency in the industrial setting can have a major impact on overall global energy use and resultant CO2 emissions.There are multiple sources of lubricant-related energy loss in industrial equipment in general, and gearboxes in particular. These include frictional losses due to metal-to-metal contact, frictional traction losses under elasto-hydrodynamic lubrication conditions and windage/churning loses in the bulk oil. All three of these factors can be improved by using a properly formulated lubricant, with carefully selected base oils and additives to improve efficiency.ExxonMobil has developed a series of industrial lubricants that can reduce energy usage by up to 4% relative to conventional lubricants. These savings have been documented in both carefully controlled laboratory testing and in extensive evaluations in actual industrial equipment in the field. Experiments to measure lubricant-related energy efficiency benefits are inherently challenging. Valid determinations of these benefits require precise measurements and controls, meticulous attention to detail and appropriate statistical analysis. In addition to the energy efficiency benefits, these oils can reduce equipment operating temperatures, resulting in increased component and lubricant life. This leads to longer oil drain intervals, and less used oil disposal.ExxonMobil defines sustainability as having three components: social development, economic growth and environmental protection. In addition to discussing all of the points above, this paper will also describe how the new energy efficient lubricants contribute to each of these sustainability attributes.

Document		ISBN	Pages
12FTM03		1-978-61481-034-6	15

Gear Lubrication – Gear Protection also at Low Oil Temperatures

M. Hochmann

To find out if the high-performance gear oils of today are able to reliably protect gears and rolling bearings in gearboxes against damage also at a reduced oil temperature of 40°C, different high-performance gear oils were examined on an FZG back-to-back gear test rig as well as on an FE8 bearing test rig by modifying the standardized test methods. It has been shown that the advanced additive technologies used in today's high-performance gear oils are capable of inducing the required reactions on the surfaces of gears and bearings also at 40°C, thus providing reliable damage protection even under these operating conditions.

12FTM02		1-978-61481-033-9	11

Power Loss and Axial Load Carrying Capacity of Radial Cylindrical Roller Bearings

S. Söndgen, W. Predki

The application of cylindrical roller bearings (CRB) is widely spread in mechanical engineering. CRB can carry comparatively high loads and are usable in high speed ranges. These bearings have been proven to be variously applicable and economic. With lipped inner and outer rings CRB permit the transmission of axial loads in addition to radial loads. The axial load is induced on the lip of the inner or the outer ring and transferred by the roller end face contacts to the opposing lip. In comparison to an only radially loaded bearing there are additional friction losses in the contact between the lip and the roller ends as a result of sliding. The limiting factors for the permissible axial load are high temperatures which can cause smearing and seizing, lip fracture, fatigue failure and wear. In consequence of the axial loading the stresses in the contact between the roller and the raceway rise and the fatigue durability of the bearing is reduced. At high speeds the permissible thrust load is dominantly limited by high temperatures. At low speeds the limiting factors are lip fracture and wear. Within the examination an extensive test program with different bearing geometries is carried out. Thereby the decisive measure is the friction torque of the bearings.The friction torque of a thrust loaded radial cylindrical roller bearing is mainly dependent on the parameters speed, load, size and design of the bearing.An analytical simulation model which has been developed at the institute allows calculating the lubrication conditions, the stresses within the lip-roller contact and the axial load dependent friction torque.The intention of the study is to enlarge the application range of radial cylindrical roller bearings by means of a more precise determination of the thrust load capacity and to allow more economic designs.

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12FTM01	1-978-61481-032-2	10

Balancing – No Longer Smoke and Mirrors

R. Mifsud Hines

In the late 1970's a balancing machine salesman visited a customer's plant who had just received a new balancer from the salesman's competitor. The plant manager said they were very happy with their automatic balancing machine and offered to show it to the salesman. The manager walked the salesman out on the floor and the two of them watched the operator and balancer in action. The operator placed a part on the balancer and closed the door. The balancer spun up the part, welded on a weight, spun up again, and displayed “good part.” The operator removed the balanced part, put in a new part, and closed the door. The balancer spun up the part, welded on a weight, spun up again, and displayed “good part.” This scenario was repeated several more times as the salesman and the manager watched. The manager commented, “We just love our new machine. All day long it balances parts by welding on weights and puts out good parts.” The salesman suggested having the operator place a “balanced part” back in the balancer again just to see what would happen. So the operator placed the previously balanced part back in the balancer again and closed the door. The balancer spun up the part, welded on a second weight, spun up again, and displayed “good part.” The manager had the operator take another balanced part and put it into the balancer again. Again, the balancer spun up the part, welded on another weight, spun up again, and displayed “good part.” Suddenly the manager was not so happy with his balancing machine. It seems this machine was not balancing the parts at all. They had purchased an expensive welding machine to weld weights on their parts.

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11FTM28	1-978-61481-021-6	12

Simulation of Wear for High Contact Ratio Gear – A Mixed FE and Analytical Approach

G. Venkatesan, M. Rameshkumar and P. Sivakumar

High contact ratio gears offer high load carrying capacity and increased life with less volume and weight. Gear tooth wear of high contact ratio gears is of great importance as excessive wear is characterized by loss of tooth profile and thickness, which might result in higher dynamic gear mesh and tooth forces. Surface wear changes not only the contact pattern and load distribution, but also the vibration and noise characteristics of the gear system. This paper deals with the simulation of wear for high contact ratio (HCR) and normal contact ratio (NCR) gears using a Mixed Finite Element (FE) and analytical approach. A numerical model for wear prediction of gear pair is developed. The methodology employs single point, observation-based gear contact mechanics in conjunction with the Archard's wear formulation to predict the tooth wear in spur gears. The contact pressure and loads are determined using a FE approach in which a two dimensional deformable body contact model of HCR and NCR gears is analyzed in ANSYS software, and ANSYS Parametric Design language (APDL) is used for capturing the load sharing ratio and contact stress variation on the complete mesh cycle of the gear pair. A MATLAB code program is developed to determine the sliding velocities, equivalent contact radius and contact width along the path of contact for both HCR and NCR gears. The contact loads and pressures obtained using FEM are used for predicting the wear depth for NCR and HCR gear pair.

Document	ISBN	Pages
11FTM27	1-978-61481-027-8	14

Manufacturing and Processing of a New Class of Vacuum-Carburized Gear Steels with Very High Hardenability

C.P. Kern, J.A. Wright, J.T. Sebastian, J.L. Grabowski, D.F. Jordan and T.M. Jones

Ferrium C61 and C64 are new secondary-hardening steels that provide superior mechanical properties versus 9310, 8620, Pyrowear Alloy 53 and other steels typically used for power transmission, such as significantly higher core tensile strength, fracture toughness, fatigue strength and thermal stability (i.e. tempering temperature). One recent example of their application is the application of C61 to the forward rotor shaft of CH-47 Chinook helicopter, in order to reduce the weight of the shaft by 15–25% and provide other benefits. This paper reviews the significant manufacturing and processing benefits that arise from this new class of secondary-hardening steels, and analyze the potential implications and opportunities. C61 and C64 were computationally designed to take advantage of high-temperature, low-pressure (i.e. vacuum) carburization technology, in part by combining carburizing and austenizing steps as well as being designed to have very high hardenability. The very high hardenability of these steels permits a mild gas quench subsequent to low-pressure vacuum carburizing and reduces part distortion, thus reducing grind stock removal, simplifying final machining and heat treat operations. A framework analysis is used to compare total manufacturing/production costs and impacts (including environmental) of these new steels versus traditional gear steels. Conclusions and recommendations are drawn regarding best manufacturing practices and appropriate use of these new steels for product applications.

Document	ISBN	Pages
11FTM26	1-978-61481-026-1	8

Atmosphere Furnace Heating Systems

J.W. Gottschalk

A detailed evaluation of furnace heating systems is presented. Topics of discussion include application guidelines for both gas fired and electrically heated furnaces. Heating system selection considers operating temperature, processing atmosphere and heating method (radiant or convective heating) along with heating system orientation within the furnace chamber.The evaluation consists of a comparison of operating costs, environmental considerations and lifetime maintenance costs of the various systems. Systems to be evaluated consist of alloy radiant tubes (single ended, U-tube, etc.), ceramic radiant tubes (single ended and U-tubes) and a variety of electrical element designs. Actual case studies of the various heating systems are presented with respect to maintenance and operating costs.

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11FTM25		1-978-61481-025-4	12

Controlling Gear Distortion and Residual Stresses During Induction Hardening

Z. Li and B.L. Ferguson

Induction hardening is widely used in both automotive and aerospace gear industries to reduce distortion and obtain favorable residual stresses. The heating process during induction hardening has a significant effect on the quality of the heat-treated parts, but the importance of the quench portion of the process often receives less attention. However, experiences have shown that the cooling rate, cooling fixture design and cooling duration can significantly affect the quality of the hardened parts in terms of distortion, residual stresses, as well as the possibility of cracking. DANTE is commercial heat treatment software based on finite element method. In this paper, DANTE is used to study an induction hardening process for a helical ring gear made of AISI 5130 steel. Prior to induction hardening, the helical gear is gas carburized and cooled at a controlled cooling rate. In this study, two induction frequencies in sequential order are used to heat the gear tooth. After induction heating, the gear is spray quenched using a polymer/water solution. By designing the spray nozzle configuration to quench the gear surfaces with different cooling rates, the distortion and residual stresses of the gear can be controlled. The crown and unwind distortions of the gear tooth are predicted and compared for different quenching process designs. The study also demonstrates the importance of the spray duration on the distortion and residual stresses of the quenched gear.

11FTM24		1-978-61481-024-7	8

Induction Hardening of Gears with Superior Quality and Flexibility Using Simultaneous Dual Frequency (SDF®)

C. Krause, F. Biasutti, and M. Davis

Induction hardening of gear teeth is well known for its challenges, but also for its potential for improved quality and process control. For complex geometric parts like gears, the power density and induction frequency need to be adjusted very precisely to achieve the required hardening pattern. Since 1940s it is known that working with two simultaneous frequencies (1–15 kHz and 200–20 000 kHz) is the optimal way to heat a geared part to hardening temperature. The key point in this process is that the medium frequency (about 10 kHz) affects primarily the tooth root and the high frequency affects first of all the tip of the tooth and the flanks. The right combination of the power densities of medium- and high-frequency energy values and the heating time are the crucial factors to reach a contour true heating pattern and, thereby, a contour true hardening pattern. The authors will describe the state of the art of induction hardening of gears with simultaneous dual frequency using some examples of use and present the possibilities to manipulate the hardening pattern in a positive way for different gear geometries.

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11FTM23	1-978-61481-023-0	12

Integration of Case Hardening into the Manufacturing-Line: "One Piece Flow"

V. Heuer, K. Löser, G. Schmitt and K. Ritter

For decades the gear industry has addressed the challenge to produce high performance components in a cost-efficient manner. To meet quality specifications, the components need to be heat treated, which traditionally takes place in a central hardening shop. However, this separation between machining and heat treatment results in high costs for transportation and logistics within the production plant. Therefore, for many years it has been being discussed how to integrate heat treatment into the manufacturing line.For about 10 years it has been possible to integrate heat treatment into the machining facility by applying the technology of Low Pressure Carburizing (LPC) and High Pressure Gas Quenching (HPGQ). The components are collected after soft-machining into big batches and treated with LPC- and HPGQ-technology. This means however that the heat treatment is not synchronized with soft- and hard-machining since the components must be collected in buffers before heat treatment and must be singularized again after heat treatment.In order to totally integrate heat treatment into the manufacturing line and in order to synchronize heat-treatment with machining, a new heat treatment cell has been developed. Following the philosophy of "One Piece Flow" the parts are: taken one by one from the soft machining unit; then heat treated in time with the cycle-time of soft machining ("synchronized heat treatment") and then passed down one-by-one to the hard machining unit. To allow for rapid case hardening, the components are low pressure carburized at high temperatures (1050°C) followed by gas quenching.In addition to the cost-savings for logistics, the new concept in equipment offers the following advantages: individual processes customized for each gear-component; homogenous and quick heating of the components and therefore low spread of distortion; homogenous and controllable gas quenching and therefore low spread of distortion; environmentally friendly carburizing and quenching; and compact and space-saving heat treat unit.The paper shows first results achieved with the new process technology applied in the new heat treatment cell.

Document	ISBN	Pages
11FTM22	1-978-61481-022-3	12

Bearing Contribution to Gearbox Efficiency and Thermal Rating: How Bearing Design Can Improve the Performance of a Gearbox

A. Doyer

Gearbox efficiency is a topic of rising interest amongst both OEM and end-users due to an increased sensitivity to gearbox performance, reliability, total cost of ownership (energy cost), overall impact on the environment, and also anticipating future regulations. In a gearbox there are difference sources of losses: gear, lubrication, seal and bearing loss. The use of modern simulation tools makes easier the evaluation of losses in various load case conditions. It has been demonstrated that the contribution of bearing loss on the system efficiency is dependent on the load cases. Even if the bearing is by far not the primary source of losses, the optimization of the bearing set can significantly improve gearbox performance. Simulation of a single stage gearbox using tapered roller bearings shows that the running temperature of the gearbox can be reduced up to 10C, by using latest bearing generation. Such a saving could improve the thermal rating of the gearbox by up to 30%. Experiments also demonstrated that different design of tapered roller bearing shows significant variation in friction performance.Having proper bearing design can significantly improve the performance of a gear unit: by a lower running temperature, by improving lubricant life, potentially simplified lubrication system, and consequently reduced running cost.

Document		ISBN	Pages
11FTM21		1-978-61481-020-9	17

Gearbox Bearing Service Life – A Matter of Mastering Many Design Parameters

H. Wendeberg

The service life of a gearbox is determined by many factors. The bearings in the gearbox play a major role since they themselves deliver an important function, and in addition interact with the shafts, the casing and the oil. Without a doubt, the sizing of the bearings is of great importance for the gearbox reliability. Since more than 50 years the bearing dynamic carrying capacity has been used to determine a suitable size needed to deliver a sufficient fatigue life – but despite the advanced calculation methods developed, the methods do not fully predict service life. Producers of high quality bearings have introduced high performance class bearings and, lacking better ways to express the improved performance, this is only represented by increased dynamic carrying capacity. The availability of high-strength shaft materials in combination with bearings with high carrying capacity allows slimmer shafts to be used. The modulus of elasticity remains the same, so seat design for bearings and gears must be given close attention.This paper covers the following: sizing of bearings based on dynamic carrying capacity and how this relates to service life; how the design of the interface between bearing and shafts should be adapted to modern shaft materials; how the design of the interface between bearing and gearbox casing influences service life of the gearbox; and influence of modern electric motor speed controls in bearing type selection.

11FTM20		1-978-61481-019-3	18

Case Study Involving Surface Durability and Improved Surface Finish

G. Blake and J. Reynolds

Gear tooth wear and micro-pitting is a very difficult phenomenon to predict analytically. The failure mode of micro-pitting is closely correlated to the lambda ratio. Micropitting can be the limiting design parameter for long-term durability. Also, the failure mode of micropitting can progress to wear or macropitting, and then manifest into more severe failure modes such as bending. The results of a gearbox test and manufacturing process development program will be presented to evaluate super finishing and its impact on micropitting.Testing was designed using an existing aerospace two stage gearbox with a low lambda ratio. All gears were carburized, ground and shot peened. Two populations were then created and tested. One population was finish honed and the second was shot peened and isotropic super finished.A standard qualification test was conducted for 150hrs at maximum continuous load. The honed gears experienced micro and macro pitting during the test. The Isotropic Super Finishing (ISF) gears were also tested for 150hr under the same loading. The ISF gears were absent of any surface distress. The ISF gears were further subjected to a 2000hr endurance test. The ISF gears had less surface distress after 2000hr than the baseline honed gears after 150hrs.

Document		ISBN	Pages
11FTM19		1-978-61481-018-6	18

Convoloid® Gearing Technology – The Shape of the Future

B.E. Berlinger, Jr. and J. Colbourne

Since the invention of the involute curve and the application thereof to gearing, the world has embraced and developed this type of gear tooth form to a very high degree of engineering and manufacturing excellence. Improvements in recent years have been relatively modest, since this form has been so rigorously studied and applied. The long term adoption of the involute is rooted in large part to the simplicity of its tools and field operation. Straight sided tools and conjugacy, even with limited changes in center distance, were consistent with the industrial revolution of the 18th, 19th, and 20th centuries, and the mechanically based machine tools of these ages. The recent ubiquitous nature of computers and CNC machinery exacerbates the cost effective freedom to optimize many parameters affecting gear tooth forms.Convoloid is a new gear tooth form capable of increasing torques 20% to 35% over those of conventionally designed involute pairs. The form is computer optimized, is compatible with the world's existing capital asset infrastructure, and mirrors the manufacturing sequences, processes and basic production costs of involute gears. The result is a major enhancement in gear drive system power density and cost reduction for a given power requirement. Convoloid gearing is totally scalable and is used in parallel axis helical, planetary, and other configurations.The design, rating (surface durability and bending), flash temperature analysis and other important performance criteria for this technology along with the manufacturing and inspection protocols in keeping with AGMA and ISO specifications will be discussed. Test results confirming many of the superior load carrying characteristics of this tooth form will be presented. Side by side comparisons of involute versus Convoloid designs and test performance results will be presented confirming the validity of the theory.

11FTM18		1-978-61481-017-9	11

Longitudinal Tooth Contact Pattern Shift

J.B. Amendola, J.B. Amendola III, and D. Yatzook

After a period of operation turbo gears may exhibit a change in the tooth contact pattern, reducing full face width contact, and thereby increasing the risk of tooth distress due to the decreased loaded area of the teeth. The phenomena may or may not occur. In some units the shift is more severe than others and has been observed in cases where there is as little as 50,000 hours of operation. In other cases, there is no evidence of any change for units in operation for more than 100,000 hours. This condition has been observed primarily in single helical gears with low helix angles (10–13°). All recorded observations have been with case carburized hardened and ground gear sets. This paper describes the phenomena observed among some of many installed high speed gear units in field operation that have been inspected. The authors have not found any written material describing this behavior and upon further investigation suggest a possible cause. Left unchecked and without corrective action, this occurrence may result in tooth breakage.

11FTM17		1-978-61481-016-2	19

Morphology of Micropitting

R.L. Errichello

Micropitting occurs in gears and rolling-element bearings that operate in the mixed or micro EHL lubrication regime. It manifests in many different ways depending on the loads, speeds, rolling and sliding velocities, macrogeometry, surface topography, edge effects, metallurgy, and lubricant properties. The failure analyst must discern whether the micropitting is a primary failure mode or a secondary failure that occurs because of prior damage. Understanding the morphology of micropitting is the key to determining the primary failure mode and root cause of failure.Several examples of micropitting in gears and rolling-element bearings are presented to illustrate the morphological variation that can occur in practice.

Document	ISBN	Pages
11FTM16	1-978-61481-015-5	11

Gear Lubrication – Stopping Micropitting by Using the Right Lubricant

M. Hochmann and H. Siebert

Micropitting is a type of fatigue failure occurring on hardened tooth flanks of highly loaded gears. This failure consists of very small cracks and pores on the surface of tooth flanks. Micropitting looks greyish and causes material loss and a change in the profile form of the tooth flanks, which can lead to pitting and breakdown of the gears.The formation of micropitting depends on different influences. Besides material, surface roughness, and geometry of the tooth flanks, the lubricant and the operating conditions show a main influence on micropitting formation. The micropitting load-carrying capacity of gears can be calculated according to ISO/TR 15144-1, where the influence of lubricant, operating conditions, and surface roughness is considered with the specific lubricant film thickness. For this purpose, the specific lubricant film thickness of a practical gear is compared with a minimum required specific lubricant film thickness. The latter is the specific film thickness where no micropitting risk is given for a lubricant and can be determined by performing a micropitting test according to FVA 54/7. This test procedure consists of a load stage test and an endurance test. Lubricants with a high micropitting load-carrying capacity reach the failure criterion of a profile form deviation of 7.5 μm due to micropitting in load stage greater than or equal to LS 10 of the load stage test. In the endurance test, a stagnation of micropitting formation compared with the micropitting area at the end of the load stage test is preferred but not required.In field applications, micropitting formation is often reported even though industrial gear oils with a high micropitting load-carrying capacity are used. Such oils offer a good micropitting protection determined in the load stage test, but with a low micropitting performance in the endurance test. The aim of research is therefore the investigation whether a change from an oil with low micropitting performance in the endurance test to an oil with high micropitting performance in the endurance test can stop the micropitting formation.

Document	ISBN	Pages
11FTM15	1-978-61481-014-8	15

Micropitting – A Serious Damage? Testing, Standards and Practical Experience

B. Pinnekamp, T. Weiss and G. Steinberger

Micropitting is a surface fatigue phenomenon on highly loaded case hardened gear flanks. Main contributors are local stress, surface roughness, sliding speed and lube oil properties. To determine the lube oil performance with respect to micropitting, different test methods have been established in the past. Actual proposals are evaluated for adopting suitable calculation methods for micropitting resistance to the ISO 6336 gear rating standards. But is micropitting necessarily a damage in any case? Practical experience shows, that a certain level of micropitting is actually acceptable, leading to even more favorable load distribution and can end up in a stable flank condition performing without problems for the designed service live.The paper describes testing, calculation approaches and application to practical cases with respect to micropitting on wind turbine and high speed gears and perennial observations and experience.

Document	ISBN	Pages
11FTM14	1-978-61481-013-1	11

AGMA 925-A03 Predicted Scuffing Risk to Spur and Helical Gears in Commercial Vehicle Transmissions

C.H. Wink

The risk of gear tooth scuffing in commercial vehicle transmissions has gained more attention because of increasing demand for fuel-efficient powertrain systems in which diesel engines run at lower speeds, power density is higher, and lubricants are modified to improve efficiency and compatibility with components of new technologies, such as dual clutch transmissions. Thus, predicting scuffing risk during the design phase is vital for the development of commercial vehicle transmissions. AGMA 925-A03 is a comprehensive method to predict the probability of gear scuffing. Therefore, this paper presents the AGMA 925-A03 scuffing risk predictions for a series of spur and helical gear sets in transmissions that are used in commercial vehicles ranging from SAE class 3 through class 8. Limiting scuffing temperatures of mineral and synthetic lubricants were determined from FZG scuffing tests, dynamometer tests and field data. The agreement between prediction, test results and actual usage can provide confidence in the predictor of scuffing risk of gears in commercial vehicle transmissions.

Document	ISBN	Pages
11FTM13	1-978-61481-012-4	16

Investigations on the Flank Load Carrying Capacity in the Newly Developed FZG Back-to-Back Test Rig for Internal Gears

B.-R. Höhn, K. Stahl, J. Schudy, T. Tobie, and B. Zornek

Micropitting, pitting and wear are typical gear failure modes, which can occur on the flanks of slowly operated and highly stressed internal gears. However, the calculation methods for the flank load carrying capacity have mainly been established on the basis of experimental investigations on external gears.

The target of a research project was to verify the application of these calculation models to internal gears. Therefore, two identical back-to-back test rigs for internal gears have been designed, constructed and successfully used for gear running tests. These gear test rigs are especially designed for low and medium circumferential speeds and allow the testing of the flank load carrying capacity of spur and helical internal gears for different pairings of materials at realistic stresses. The three planet gears of the test rig are arranged uniformly around the circumference. Experimental and theoretical investigations regarding the load distribution across the face width, the contact pattern and the load sharing between the three planet gears have been carried out.Furthermore, substantial theoretical investigations on the characteristics of internal gears were performed. Internal and external spur gears were compared regarding their geometrical and kinematical differences as well as their impact on the flank load. Based on the results of these theoretical investigations an extensive test program of load stage tests and speed stage tests on internal gears of different material, different finishing of the flanks and different operating conditions has been carried out. The main focus of this test program was on the fatigue failures of micropitting and wear at low circumferential speeds.The paper describes the design and functionality of the new developed test rigs for internal gears and shows basic results of the theoretical studies. Furthermore, it presents basic examples of experimental test results.

Document	ISBN	Pages
11FTM12	1-978-61481-011-7	15

The Application of the First International Calculation Method for Micropitting

U. Kissling

The international calculation method for micropitting, ISO/TR 15144, was recently published. It is the first official international calculation method to check for the risk of micropitting ever published. Years ago AGMA published a method for the calculation of the specific oil film thickness containing some comments about micropitting, and the German FVA published a calculation method based on intensive research results. The FVA and the AGMA are close to the ISO/TR. New is the calculation of the micropitting safety factors. The technical report presents two calculation rules, method A and B. Method A needs as input the Hertzian pressure on every point of the tooth flank, based on an accurate calculation of the meshing of the gear pair, considering tooth and shaft deflections to get the load distribution over the flank line in every meshing position. Method B is much simpler; the load distribution is defined for different cases as spur or helical gears, with and without profile modifications.The risk of micropitting is highly influenced by profile and flank line modifications. A new software tool can evaluate the risk of micropitting for gears by automatically varying different combinations of tip reliefs, other profile modifications and flank line modifications, in combination with different torque levels, using method A. The user can define the number of steps for variation of the amount of modification. Then all possible combinations are checked combined with different (user defined) torque levels. Any modifications including flank twist, arc-like profile modifications, etc. can be combined. The result is presented in a table, showing the safety factor against micropitting for different subsets of profile/flank modifications, depending on the torque level.Some applications from wind turbine and industrial gearboxes, known to the author, will be discussed.

Document	ISBN	Pages
11FTM11	1-978-61481-010-0	18

Marine Reversing Main Gear Rating Factor Versus Number of Loading Reversals and Shrink Fit Stress

E.W. Jones, S. Ismonov and S.R. Daniewicz

The marine vessel reversing main gear tooth is subjected to three different loading cycles: ahead travel with load pulsing from zero to 100% of full power; astern travel with load pulsing from zero to about minus 66% of full power; and reversal of direction with load changing from 100% of full power to about minus 66% of full power. The number of repetitions of these three different loading cycles varies with the vessel duty cycle and life. The published values of allowable design stress for teeth are based on pulsing loads, which must be modified for this third loading cycle. The tooth may also be subjected to mean stress due to shrink fitting of the gear onto a hub.Publications which address these conditions include: -Guide values for mean stress influence factor, Ym, of ISO 6336-3 gives a factor, which de-rates the pulsing, i.e. unidirectional, allowable stress value for non-pulsing load. -The American Bureau of Shipping Rules, derate the allowable unidirectional bending strength by 10% for the reversing main gear tooth. (Idler gear teeth, which are under bidirectional loading at full power, are de-rated by 30%).-Det Norske Veritas DNV Classification Notes No. 41.2 addresses gears: with other working conditions than pure pulsations; with periodical changes of rotational direction; and with shrink fitting stresses. For gears with occasional full load in reversed direction such as the main wheel in a reversing gearbox, the derating factor of 10% is recommended.This paper evaluates the derating factor for marine reversing main gear tooth allowable bending stress using the Goodman fatigue line and Miners equation as a function of the average number of changes in vessel direction per hour, shrink fitting stress values, and different materials based on the AGMA values for allowable stress and life factor.

Document		ISBN	Pages
11FTM10		1-978-61481-009-4	20

New Methods for the Calculation of the Load Capacity of Bevel and Hypoid Gears

B.-R. Höhn, K. Stahl, and C. Wirth

Pitting and tooth root breakage are still the two most frequent failure types occurring in practical applications of bevel gears. There are several national and international standards for the calculation of the load carrying capacity of these gears such as DIN 3991, AGMA 2003 and ISO 10300. But up to now these standards do not cover bevel gears with offset (hypoid gears). For that reason, a research project was carried out at FZG (Gear Research Centre, Munich, Germany) to analyze the influence of the hypoid offset on the load capacity of bevel gears by systematic theoretical and experimental investigations.The results of the tooth root tests showed, as expected, an increasing load capacity with higher offsets. In contrast, the pitting tests showed an increasing, but after reaching a maximum, a decreasing load capacity with higher offsets. This can be explained by two interfering phenomena: On the one side higher offsets lead to decreasing pinion loads and thus decreasing contact stresses; on the other side the permissible stresses are decreasing due to the higher sliding velocities.Regarding these test results a new standard capable calculation method was developed on the basis of ISO 10300. First the bevel gear geometry is transformed into a virtual cylindrical gear. Systematic theoretical investigations and comparisons with tooth contact analysis methods have shown that the new virtual cylindrical gears have representative mesh conditions compared to the bevel gears. This includes the size and shape of the contact area as well as the load distribution between the mating teeth. Particularly with regard to hypoids it is necessary to consider the unbalanced mesh conditions between drive and coast side flank, what can be described by the limit pressure angle. Several influence factors were adjusted considering geometry, material properties and operating conditions of the gear set. For the tooth root safety factor, the influence factors were adapted to the specific conditions of hypoid gears. For the calculation of the pitting safety factor two new influence factors were introduced to consider the hypoid specific sliding conditions on the gear flanks. The recalculation of the pitting and tooth root tests showed a very good correlation of calculated with real load capacity of the test gears.Meanwhile the newly developed calculation method is widely-used in the gear manufacturing industry. For that reason, it is currently introduced into the revision of ISO 10300 as method B1 beside method B2 based on the AGMA calculation method for bevel and hypoid gears.

11FTM09		1-978-61481-008-7	18

Standardization of Load Distribution Evaluation: Uniform Definition of KHβ for Helical Gears

K. Nazifi

The load distribution measurement of gear teeth and the determination of the face load factor for contact stress KHβ are of fundamental importance to the gear manufacturing industry. The factor is a measure for the uniformity of the load along the face width. The closer this factor is to one the more uniform is the load distributed along the face width. In the design phase this factor is determined with the help of approximation equations and finite element analysis and is used to dimension the flank modifications. In addition, KHβ is used in the lifetime calculations according to DIN 3990 and ISO 6336 required by the certification societies. In the testing phase this factor is experimentally determined by strain measurements of the tooth fillets in order to verify the load distribution calculations and the suitability of the used modifications.For spur gears with no helix angle the interpretation of the measurements to a face load factor is intuitively easy. For helical gears, used more frequently in large gearboxes, the determination of the factor gets more difficult. The line of contact of these gears runs inclined over the face width of the teeth flank. In this context the question arises whether the face load factor is evaluated along the face width or along the path of contact.Evaluation of the measured values and the interpretation to a face load factor is a complex challenge and is not standardized. The standardization of load distribution evaluation and a uniform definition of KHβ especially for helical gears enable a safer design for the manufacturers and an easier comparability of the results for the customers.The paper will compare the different suggestions to the KHβ definition and will derive a new definition suitable for the calculation methods in DIN 3990 and ISO 6336.

Document	ISBN	Pages
11FTM08	1-978-61481-007-0	18

A Comprehensive System for Predicting Assembly Variation with Potential Application to Transmission Design

K.W. Chase and C.D. Sorensen

Recent advances in tolerance analysis of assemblies allow designers to: predict tolerance stack-up due to process variations; examine variation in clearances and fits critical to performance; use actual production variation data or estimates from prior experience; and use engineering design limits to predict the percent rejects in production runs.A comprehensive system has been developed for modeling 1D, 2D, and 3D assemblies, which includes three sources of variation: dimensional (lengths and angles), geometric (GD&T), and kinematic (small internal adjustments due to dimensional variations).Once the assembly has been described, an algebraic model is created, in which each dimension is represented by a vector, with a nominal +/- tolerance. The vectors are linked into chains or loops, describing each critical clearance or assembly feature in terms of the contributing dimensions. The chains form vector loops describing the interaction and accumulation of the three sources of variation in the assembly. Small variations are applied to each source and analyzed statistically to predict the resulting variation in the critical assembly features. Solutions for the mean and standard deviations are obtained by matrix algebra. Only two assemblies are analyzed: one for the mean and another for the variance of the assembly features. The same modeling elements may be used to model complex assemblies. Benefits of tolerance analysis include reduced reject rates, fewer problems on the assembly floor, reduced costs, and shorter time to market. Critical requirements of shaft alignment, gear meshing and controls in transmissions and gear trains are ideally suited for this efficient, comprehensive system.

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11FTM07	1-61481-006-3	14

The Effects of Helix Angle on Root Stresses of Helical Gears

D.R. Houser and A.P. Thaler

The ISO and AGMA Gear Rating Committees have for several years been comparing the results of different rating methods for several sets of gear pairs that have similar normal sections but different helix angles. The analysis presented here uses a finite element code that was developed specifically for gear and bearing contacts to analyze the example gear sets. Analyses are also performed using a more conventional load distribution analysis program. The results for the original gear sets show that the narrow face width gear teeth twist significantly, thus moving the load to one edge of the face width and essentially showing that the example gear sets are highly unrealistic. Yet when analyzed by the ISO and AGMA rating methods, the results do not reflect this twisting action. In an effort to come up with a valid comparison of stresses for different helix angles, three adjustments using wider face widths were attempted. The first uses a narrow load patch in the middle of the tooth pair and results in the stresses increasing with helix angle. The second scheme again uses a wider face width, but with perfect involutes. Edge effects result in the peak stresses being near the ends of the face width. The third method, which uses the wide face width with teeth that have some lead crown and tip relief, gives the most reasonable results, with the root stresses being at a maximum in the center region of the tooth face widths. The paper compares each of the results to earlier analyses performed by others using both the AGMA and ISO calculations.

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11FTM06	1-61481-005-6	19

Reversed Gear Tooth Bending Stress and Life Evaluation

J. Chen

There is a wealth of literature and test results regarding the subject on single directional gear tooth bending stress and life relationships (S-N curves), they have been published on various journals and handbooks over the past decades, and several of them had been widely accepted and adapted as industry standards by different gear societies around the world. However, very limited information regarding the bi-directional tooth bending life has been revealed.

To fill in the above mentioned gap for practical usages, the authors first intended to apply the traditional fatigue theories such as modified Goodman, Gerber, Morrow or similar theories with minor modifications to derive a series of S-N equations for different loading conditions, but the correlation with the actual test results was not satisfied. Nevertheless, from the observation on these test results, the slopes and endurance limits on the fitted S-N curves from all the test points were reasonable closer to each other, as long as the test gears were produced by the same material and similar manufacturing process. Based on the above observation, the author proposes a new approach that uses the common (or averaged) slope and endurance limit, and a series of S-N curve equations on any loading conditions can be derived, once the single directional S-N curve has been obtained.

Document	ISBN	Pages
11FTM05	1-61481-004-9	25

Epicyclic Load Sharing Map – Application as a Design Tool

A. Singh

One of the main advantages of planetary transmissions is that the input torque is split into a number of parallel paths. However, equal load sharing between the planets is possible only in the ideal case due to the presence of positional type manufacturing errors, equal load sharing is not realized, and the degree of inequality in load sharing has major implications for gear system sizing, tolerancing schemes, and torque ratings.The sensitivity of load sharing to torque, tolerance level, directionality of error, system flexibility, number of planets, and amount of float in the system have all been studied. However, a physical understanding of the true mechanism that leads to the load sharing phenomenon was lacking. In a recent paper, the author has proposed a physical mechanism that explains all known load sharing behavior. The physical explanation leads to simple expressions that seem to completely describe the complex load sharing behavior. Comparisons to computational models and experimental results have shown excellent correlation.The proposed physical explanation leads to the concept of an epicyclic load sharing map (ELSM). The ELSM is a plot of the load ratio (or % of input torque) versus a non-dimensional parameter Xe. The non-dimensional parameter is a function of combined system stiffness, tolerance level, and operating torque. The ELSM contains curves for 3, 4, 5, 6 and 7 (and more) planet systems. Once a gear set is located on the ELSM, its behavior under any load and error condition can be quickly predicted. Also, the advantages of adding extra planets can be accurately estimated.The use of the ELSM as a design tool for the general case when there are errors on the position of every carrier pin-hole are illustrated. Statistical simulations are performed for a given manufacturing error distribution for 3 to 7 planet systems.

Document	ISBN	Pages
11FTM04	1-61481-003-2	11

First International Involute Gear Comparison

F. Härtig, W. Adeyemi, and K. Knielm

Seven national metrology institutes have carried out the first international intercomparison in the field of gear metrology organized from the EURAMET (European Association of National Metrology Institutes) with non-European involvement. As leader the Physikalisch-Technische Bundesanstalt (PTB) provided three of their involute gear artifacts and sent them to the participants from China, Japan, Thailand, United Kingdom, Ukraine and USA. Each of the institutes measured the profile, helix and the pitch artifact and evaluated the specified measurands. The results collected and evaluated by the PTB were compared and analyzed by evaluating the normalized error En. At the end of this comparison the large distribution of the results which lay in the range of today's required tolerances in industry pose a lot of questions. The presentation explains details of the measurement setup and evaluation parameter, damages of some artifacts due to unqualified handling, and finally the interesting results.

Document	ISBN	Pages
11FTM03	1-61481-002-5	14

Towards an Improved AGMA Accuracy Classification System on Double Flank Composite Measurements

E. Reiter

AGMA introduced ANSI/AGMA 2015-2-A06 – Accuracy Classification System – Radial System for Cylindrical Gears – in 2006 as the first major rewrite of the double flank accuracy standard in over twelve years. Although this document is not yet in wide use, many practical problems exist in the standard which affects its intended benefit.This document explains the issues related to the use of ANSI/AGMA 2015-2-A06 as an Accuracy Classification System and recommends a revised system which can be of more service to the gearing industry.

Document	ISBN	Pages
11FTM02	1-61481-001-8	15

Generating Gear Grinding – New Possibilities in Process Design and Analysis

J. Reimann, F. Klocke, and C. Gorgels

To improve load carrying capacity and noise behavior, case hardened gears usually are hard finished. One possible process for the hard finishing of gears is the continuous generating gear grinding, which has replaced other grinding processes in batch production of small to medium sized gears due to its high process efficiency. Despite the wide industrial application of this process only a few published scientific analyses exist. The science-based analysis of generating gear grinding needs a high amount of time and effort. This is due to the complex contact conditions between tool and gear flank, which change continuously during the grinding process. These complicate the application of the existing knowledge of other grinding processes onto the generating gear grinding.The complex contact conditions lead to high process dynamics which pose challenges in the design of machine tools, the control engineering and the process design. Furthermore, unfavorable contact conditions can lead to process related profile form deviation. So the knowledge of the cutting forces and their time dependent behavior is necessary to describe and optimize the process dynamics and results.The aim of this report is to determine the existing cutting forces for a sample gear in trials for the first time and to analyze their connection to the process parameters and the appearance of profile form deviations. Simultaneously for the sample gear the same process design will be analyzed using a manufacturing simulation. The results of the trials and the simulation will be compared. The report will present new possibilities in process analysis and will give the process user ideas for future process improvements.

Document	ISBN	Pages
11FTM01	1-61481-000-1	14

A New Way of Face Gear Manufacturing

H.J. Stadtfeld

There are two major intentions to apply face gears in power transmissions: the advantage to be able to use a cylindrical gear as a pinion member; and particular design solutions which require a plurality of cylindrical driving members as in a propulsion system.While the automotive and truck industry conducted substantial research in the application of face gear systems in their drive trains, the results did not favor face gears versus bevel and hypoid gears. In many cases, the face gear system was found to be the less economical solution, as the manufacturing of the face gear itself was expensive. Machine tools require a special design, are not readily available, and the cutting tools have to be designed specifically for the particular face gear design.The obstacles which prevented manufacturers in the past to apply face gears were removed entirely, when a new way of forming the profile of face gear teeth, using standard bevel gear cutting and grinding machines as well as standard cutter heads was designed. The idea is based on the tools used in straight bevel gear cutting and grinding according to the CONIFLEX method, however, using a generating gear which is not flat like it is for straight bevel gears but cylindrical, resembling the mating cylindrical pinion for the particular face gear design.The complexity of modified cylindrical hobbing and shaping machines and job dependent custom tooling disappears completely with the new CONIFACE cutting and grinding process.

Document	ISBN	Pages
10FTM17	1-55589-992-9	8

Self-Locking Gears: Design and Potential Applications

A.L. Kapelevich and E. Taye

In most of the gear drives, when the driving torque is suddenly reduced as a result of power off, torsional vibration, power outage or any mechanical failure at the transmission input side, then gears will be rotating either in the same direction driven by the system inertia, or in the opposite direction driven by the resistant output load due to gravity, spring load, etc. The latter condition is known as backdriving. During inertial motion or backdriving, the driven output shaft (load) becomes the driving one and the driving input shaft (load) becomes the driven one. There are many gear drive applications where the output shaft driving is less desirable. In order to prevent it, different types of brake or clutch devices are used. However, there are also solutions in gear transmission that prevent inertial motion or backdriving using self-locking gears without any additional devices. The most common one is a worm gear with a low lead angle. In self-locking worm gears, torque applied from the load side (worm gear) is blocked, i.e. cannot drive the worm. However, their application comes with some limitations: the crossed axis shafts' arrangement, relatively high gear ratio, low speed, low gear mesh efficiency, increased heat generation, etc.The paper describes the design approach as well as potential applications of the parallel axis self-locking gears. These gears, unlike the worm gears don't have such application limitations. They can utilize any gear ratio from 1:1 and higher. They can be external, internal, or incorporated into the planetary gear stage or multistage gear system. Their gear mesh efficiency is significantly higher than the worm gears and closer to conventional gears. As a result, they generate less heat. The self-locking can be designed to prevent either the inertia driving, or backdriving, or both. The paper explains the principle of the self-locking process for gears with symmetric and asymmetric teeth profile, and shows their suitability for different applications. It defines the main parameters of gear geometry and operating conditions. It also describes potential self-locking gear applications and references to related publications.

Document	ISBN	Pages
10FTM16	1-55589-991-2	11

Analysis of Load Distribution in Planet-Gear Bearings

L. Mignot, L. Bonnard and V. Abousleiman

In epicyclic gear sets aimed at aeronautical applications, planet-gears are generally supported by spherical roller bearings with bearing outer race being integral to the gear hub. This paper presents a new method to compute roller load distribution in such bearings where the outer ring can't be considered rigid. Based on well-known Harris method, a modified formulation enables to account for centrifugal effects due to planet-carrier rotation and to assess roller loads at any position throughout the rotation cycle. New model load distribution predictions show discrepancies with results presented by Harris, but are well correlated with 1D and 3D Finite Element Models. Several results validate the use of simplified analytical models to assess the roller load distribution instead of more time consuming Finite Element Models. The effects of centrifugal effects due to planet-carrier rotation on roller loads are also analyzed. Finally, the impact of the positions of rollers relative to the gear mesh forces on the load distribution is shown.

Document	ISBN	Pages
10FTM15	1-55589-990-5	14

Drive Line Analysis for Tooth Contact Optimization of High Power Spiral Bevel Gears

J. Rontu, G. Szanti and E. Mäsä

It is a common practice in high power gear design to apply relieves to tooth flanks. They are meant to prevent stress concentration near the tooth edges. Gears with crownings have point contact without load. When load is applied, instantaneous contact turns from point into a Hertzian contact ellipse. The contact area grows and changes location as load increases. To prevent edge contact, gear designer has to choose suitable relieves considering contact indentations as well as relative displacements of gear members. In the majority of spiral bevel gears spherical crownings are used. The contact pattern is set to the center of active tooth flank and the extent of crownings is determined by experience. Feedback from service, as well as from full torque bench tests of complete gear drives have shown that this conventional design practice leads to loaded contact patterns, which are rarely optimal in location and extent. Too large relieves lead to small contact area and increased stresses and noise; whereas too small relieves result in a too sensitive tooth contact.Today it is possible to use calculative methods to predict the relative displacements of gears under operating load and conditions. Displacements and deformations originating from shafts, bearings and housing are considered. Shafts are modeled based on beam theory. Bearings are modeled as 5-DOF supports with non-linear stiffness in all directions. Housing deformations are determined by FEM-analysis and taken into account as translations and rotations of bearing outer rings. The effect of temperature differences, bearing preload and clearances are also incorporated. With the help of loaded tooth contact analysis (LTCA), it is possible to compensate for these displacements and determine a special initial contact position that will lead to well centered full torque contact utilizing a reasonably large portion of the available tooth flank area. At the same time, crownings can be scaled to the minimum necessary amount. This systematic approach leads to minimum tooth stressing, lower noise excitation as well as increased reliability and/or power density as compared to conventional contact design method.During recent years ATA Gears Ltd. has gained comprehensive know-how and experience in such analyses and advanced contact pattern optimization. The methodology and calculation models have been verified in numerous customer projects and case studies.

Document		ISBN	Pages
10FTM14		1-55589-989-9	15

Analysis and Testing of Gears with Asymmetric Involute Tooth Form and Optimized Fillet Form for Potential Application in Helicopter Main Drives

F.W. Brown, S.R. Davidson, D.B. Hanes, D.J. Weires and A. Kapelevich

Gears with an asymmetric involute gear tooth form were analyzed to determine their bending and contact stresses relative to symmetric involute gear tooth designs which are representative of helicopter main drive gears. Asymmetric and baseline (symmetric) toothed gear test specimens were designed, fabricated and tested to experimentally determine their single-tooth bending fatigue strength and scuffing resistance. Also, gears with an analytically optimized root fillet form were tested to determine their single-tooth bending fatigue characteristics relative to baseline specimens with a circular root fillet form. Test results demonstrated higher bending fatigue strength for both the asymmetric tooth form and optimized fillet form compared to baseline designs. Scuffing resistance was significantly increased for the asymmetric tooth form compared to a conventional symmetric involute tooth design.

10FTM13		1-55589-988-2	19

Gear Design for Wind Turbine Gearboxes to Avoid Tonal Noise According to ISO/IEC 61400-11

J. Litzba

Present wind turbine gearbox design usually includes one or two planetary gear stages and at least one high speed helical gear stage, which play an important role regarding noise and vibration behavior. Next to the overall noise of the gearbox and the structure-born noise on the gearbox housing also tonal noise is becoming a much more important issue in recent years. Since tonal noise is problematic due to the human perception as “uncomfortable", avoidance is important. Conventional theories regarding low noise gear design are not developed in view of tonal noise. This leads to the question: How to deal with tonal noise in the design stage and which gear parameters can be used for an optimization regarding good tonal noise behavior?Within a research project measurements have been performed on different gearboxes using different gear designs. These measurements have been evaluated according to ISO/IEC 61400-11 and the results have been analyzed in view of the influence of different gear parameters. It was also investigated if it is possible to rank gearboxes in wind turbines according to their tonal noise behavior as observed on the test rig. The paper will give an introduction into the definition of tonal noise according to ISO/IEC 61400-11 and give insight in measurement results from test rigs and from gearboxes in the field, where noise behavior is also evaluated according to ISO/IEC 61400-11. Furthermore, the paper will show and discuss the link between measurement results and different gear parameters, which are affecting tonal noise behavior. In addition, simulation results will be presented, showing how tonal noise can be estimated within the design stage using state-of-the–art calculation software.The paper will give recommendations regarding a gear design process that is considering tonal noise in the design stage and will compare an, regarding tonal noise, improved gear set with an older one.

Document	ISBN	Pages
10FTM12	1-55589-987-5	15

Flank Load Carrying Capacity and Power Loss Reduction by Minimized Lubrication

B.-R. Höhn, K. Michaelis and H.-P. Otto

The lubrication of gears has two major functions: Reducing friction and wear as well as dissipating heat. The power losses, especially the no-load losses, decrease with decreasing immersion depth using dip lubrication. The load-dependent gear power losses are nearly unaffected by minimized lubrication. However, the gear bulk temperatures rise dramatically by using minimized lubrication due to a lack of heat dissipation. With minimized lubrication the scuffing load carrying capacity decreased by up to more than60%compared to rich lubrication conditions. The dominating influence of the bulk temperature is therefore very clear. Starved lubrication leads to more frequent metal-to-metal contact and the generation of high local flash temperatures must be considered. An additional factor for the scuffing load carrying capacity calculation in case of minimized lubrication conditions is proposed.Concerning pitting damage test runs showed that by lowering the oil level the load cycles without pitting damage decreased by approximately 50% up to 75% for minimized lubrication compared to the results with rich lubrication conditions. The allowable contact stress is clearly reduced (up to 30%) by minimized lubrication. A reduced oil film thickness as a consequence of increased bulk temperatures results in more frequent metal-to-metal contacts causing a higher surface shear stress. In combination with a decreased material strength due to a possible tempering effect at high bulk temperatures the failure risk of pitting damage is clearly increased. The common pitting load carrying capacity calculation algorithms according to DIN/ISO are only valid for moderate oil temperatures and rich lubrication conditions. For increased thermal conditions, the reduction of the pitting endurance level at increased gear bulk temperatures can be approximated with the method of Knauer (FZG TU München, 1988). An advanced calculation algorithm for pitting load carrying capacity calculation at high gear bulk temperatures (valid for high oil temperatures as well as for minimized lubrication) is proposed.The micropitting risk was increased by low oil levels, especially at high loads and during the endurance test. The micropitting damage is caused by poor lubrication conditions which are characterized by a too low relative oil film thickness due to high bulk temperatures. Again, the actual bulk temperatures are of major significance for calculation of the micropitting load carrying capacity.The wear rate of the gears is almost unaffected by the oil level. Only a slight increase of wear could be observed with minimized lubrication. This increase can be explained by the higher bulk temperature of the gears running under minimized lubrication conditions. The investigations showed that there exists a natural limitation for lowering the oil quantity in transmissions without detrimental influence on the load carrying capacity. Knowing these limitations enables the user to determine the possible potential benefits of reduced oil lubrication. The correct prediction of the actual gear bulk temperatures is of major importance in this context. A method for the estimation of the gear bulk temperature at reduced immersion depth respectively poor lubrication conditions is proposed.

10FTM11	1-55589-986-8	11

Point-Surface-Origin, PSO, Macropitting Caused by Geometric Stress Concentration, GSC

R.L. Errichello, C. Hewette, and R. Eckert

Point-Surface-Origin, PSO, macropitting occurs at sites of Geometric Stress Concentration, GSC, such as discontinuities in the gear tooth profile caused by micropitting, cusps at the intersection of the involute profile and the trochoidal root fillet, and at edges of prior tooth damage such as tip-to-root interference. When the profile modifications in the form of tip relief, root relief, or both are inadequate to compensate for deflection of the gear mesh, tip-to-root interference occurs. The interference can occur at either end of the path of contact, but the damage is usually more severe near the start-of-active-profile, SAP, of the driving gear.An FZG-C gearset (with no profile modifications) was tested at load stage 9 and three pinion teeth failed by PSO macropitting. It is shown that the root cause of the PSO macropitting was GSC created by tip-to-root interference.

Document		ISBN	Pages
10FTM10		1-55589-985-1	15

Evaluation of Methods for Calculating Effects of Tip Relief on Transmission Error, Noise and Stress in Loaded Spur Gears

D. Palmer and M. Fish

The connection between transmission error and noise and vibration during operation has long been established. Calculation methods have developed to describe the influence such that it is possible to evaluate the relative effect of applying a specific modification at the design stage. The calculations can allow the designer to minimize the excitation from the gear pair engagement at a specific load. This paper explains the theory behind transmission error and the reasoning behind the method of applying the modifications through mapping the surface profiles and deducing the load sharing. It can be used to explain the results of later experimental validation on various types of tip relief in low contact ratio (LCR) gears, from very long to very short. The paper will also demonstrate that though the effects of modification in any specific case can be modeled with some certainty, the same modifying strategy cannot be applied universally but must consider the required operating conditions. It illustrates that the effect of tip relief on transmission error and load sharing is not a black art but can be fully explained by applying existing theory.A study of high contact ratio (HCR) gears will be presented to demonstrate why it is often necessary to apply different amounts and extents of tip relief in such designs, and how these modifications affect load sharing and highest point of tooth loading. Specific attention will be paid to the phenomenon of extended contact, where if no modification or insufficient tip relief is applied, contact does not stop at the end of active profile but continues beyond this point as the gear rotates resulting in contact on the tip. This effectively increases contact ratio and has implications for the tooth load and in particular how this may affect the loading position, highest point of single tooth contact (HPSTC), which is relevant to both ISO and AGMA standard rating. The paper will consider 3 methods commonly employed in the industry; a simple 2D mapping procedure carried out on graph paper, a 3D linear tooth stiffness computation method, and a 3D finite element analysis (FEA) calculation. The paper will demonstrate that though in some cases these methods can produce similar results, albeit with varying degrees of accuracy, further examples will be presented which demonstrate behavior which can only be detected using some of the more complex analysis methods. The commercial viability of implementing a better quality models against the time constraints in the development process will be discussed and conclusions drawn.

10FTM09		1-55589-984-4	9

Reverse Engineering

C.D. Schultz

As America's manufacturing base has contracted the need for reverse engineering has grown. Well established suppliers have disappeared, often leaving customers with no source of spare parts or technical support. Over time certain pieces of equipment require changes to output speeds or power levels and new parts have to be designed, built, and installed. And unfortunately, some pieces of equipment don't measure up to the demands they are subjected to and need redesign or improvement. In many ways, reverse engineering is just as demanding a discipline as original product development with many of the same challenges but plus the additional restrictions of fitting inside of an existing envelope.The typical reverse engineering project begins with very limited information on the existing piece of equipment. This paper will describe a methodology for the reliable measurement, evaluation, re-design, and manufacture of replacement parts for gearboxes and industrial machinery. A step-by-step example will be provided.

Document	ISBN	Pages
10FTM08	1-55589-983-7	11

Calculation of Load Distribution in Planetary Gears for an Effective Gear Design Process

T. Schulze, C. Hartmann-Gerlach, B. Schlecht

The design of gears—especially planetary gears—can just be carried out by the consideration of influences of the whole drive train and the analysis of all relevant machine elements. In this case the gear is more than the sum of its machine elements. Relevant interactions need to be considered under real conditions. The standardized calculations are decisive for the safe dimensioning of the machine elements with the consideration of realistic load assumptions. But they need to be completed by extended analysis of load distribution, flank pressure, root stress, transmission error and contact temperature.

Document	ISBN	Pages
10FTM07	1-55589-982-0	17

A New Statistical Model for Predicting Tooth Engagement and Load Sharing in Involute Splines

J. Silvers, C.D. Sorensen and K.W. Chase

Load-sharing among the teeth of involute splines is little understood. Designers typically assume only a fraction of the teeth are engaged and distribute the load uniformly over the assumed number of engaged teeth. This procedure can widely over- or underestimate tooth loads.A new statistical model for involute spline tooth engagement has been developed and presented earlier, which takes into account the random variation of gear manufacturing processes. It predicts the number of teeth engaged and percent of load carried by each tooth pair. Tooth-to-tooth variations cause the clearance between each pair of mating teeth to vary randomly, resulting in a sequential, rather than simultaneous tooth engagement. The sequence begins with the tooth pair with the smallest clearance and proceeds to pick up additional teeth as the load is increased to the maximum applied load. The new model can predict the number of teeth in contact and the load share for each at any load increment.This report presents an extension of the new sequential engagement model, which more completely predicts the variations in the engagement sequence for a set of spline assemblies. A statistical distribution is derived for each tooth in the sequence, along with its mean, standard deviation and skewness. Innovative techniques for determining the resulting statistical distributions are described. The results of an in-depth study are also presented, which verify the new statistical model. Monte Carlo Simulation of spline assemblies with random errors was performed and the results compared to the closed-form solution. Extremely close agreement was found. The new approach shows promise for providing keener insights into the performance of spline couplings and will serve as an effective tool in the design of power transmission systems.

Document	ISBN	Pages
10FTM06	1-55589-981-3	12

Finite Element Analysis of High Contact Ratio Gear

M. Rameshkumar, G. Venkatesan and P. Sivakumar

Modern day vehicles demand higher load carrying capacity with less installed volume and weight. The gears used in the vehicles should also have lesser noise and vibration. Even though helical gears will meet the requirement, they are prone for additional axial thrust problem. High contact ratio (HCR) is one such gearing concept used for achieving high load carrying capacity with less volume and weight. Contact ratio greater than 2.0 in HCR gearing results in lower bending and contact stresses. Previously published literature deal with studies on various parameters affecting performance of HCR gears but a comparison of HCR and normal contact ratio (NCR) gears with same module and center distance has not been carried out so for. This paper deals with finite element analysis of HCR, NCR gears with same module, center distance and the comparison of bending, contact stress for both HCR, NCR gears. A two dimensional deformable body contact model of HCR and NCR gears is analyzed in ANSYS software. ANSYS Parametric Design language (APDL) is used for studying the bending and contact stress variation on complete mesh cycle of the gear pair for identical load conditions. The study involves design, modeling, meshing and post processing of HCR and NCR gears using single window modeling concept to avoid contact convergence and related numerical problems.

10FTM05	1-55589-980-6	9

Comparison of the AGMA and FEA Calculations of Gears and Gearbox Components Applied in the Environment of Small Gear Company

V. Kirov

The current AGMA standards provide a lot of information about the calculations of loose gears and gearbox components – shafts, splines, keys, etc. These recommendations are based mostly on the “traditional" methods of mechanical engineering, found in many classical textbooks and research papers. Their accuracy and reliability have been proven in many years of gearbox design and field tests. They are clear, concise, in most cases easy to program and apply even by a small gear company with limited resources. However new methods for calculations of mechanical engineering components like FEA (finite element analysis) are becoming wide spread. Once these techniques were used only by big companies because of their complexity and price but with the development of the computer technology they become more and more accessible to small gear companies which are the majority of participants in the market.Nowadays, in the gear business, even a small gear company is usually in possession of a modern CAD system which always includes a basic or advanced FEA package. Such CAD systems are most often run by one gear engineer who makes 3D models, engineering calculations and production drawings. The level of the FEA packages is such that it allows the gear engineer to be able to do components calculations without deep knowledge in the FEA itself.So the question about the effectiveness of the traditional AGMA calculations and the new FEA methods becomes of vital importance particularly for small firms.

Document		ISBN	Pages
10FTM04		1-55589-979-0	16

Low Distortion Heat Treatment of Transmission Components

V. Heuer, K. Löser, D.R. Faron and D. Bolton

In many applications the high demands regarding service life of transmission components can be reached only by the application of a customized case hardening. This case hardening process results in a wear resistant surface-layer in combination with a tough core of the component. However, as a side-effect the components get distorted during heat treatment. This distortion has a significant cost-impact, because distorted components often need to be hard-machined after heat treatment. Therefore, the proper control of distortion is an important measure to minimize production costs.By applying the technology of low pressure carburizing (LPC) and high pressure gas quenching (HPGQ) heat treat distortion can be significantly reduced. HPGQ provides a very uniform heat transfer coefficient. The predictability of movement during quenching is more certain and uniform throughout the load. Further improvements can be achieved by “Dynamic Quenching" processes where the quenching severity is varied during the quench sequence by step control of the gas velocity. Proper fixturing is another factor for distortion control. Modern CFC-materials (carbon reinforced carbon) are well suited as fixture-material for gas quenching.The paper presents how LPC and HPGQ processes are successfully applied on internal ring gears for a 6 speed automatic transmission. The specific challenge in the heat treat process was to reduce distortion in such a way that subsequent machining operations are entirely eliminated. As a result of extensive development in the quenching process and the use of specialized CFC-fixtures it was possible to meet the design metrological requirements.The Internal ring gears addressed in this report have been in continuous production since 2006. Subsequent testing and monitoring over a two-year period progressively demonstrated that consistent metrology was achieved and quality inspection was reduced accordingly.

10FTM03		1-55589-978-3	10

A Novel Approach to the Refurbishment of Wind Turbine Gears

M. Michaud, G.J. Sroka and R.E. Benson

Multi-megawatt wind turbine gearboxes operate under demanding environmental conditions including considerable variation in temperature, wind speed, and air quality. It is not uncommon for gearboxes rated for a maintenance free 20-year lifespan to fail after only a few years. These gearboxes experience several types of repairable damage including micropitting or “gray staining", abrasive wear, foreign object debris (FOD) damage, surface corrosion and fretting corrosion. Wear is greatest on the input stage, especially on the sun pinion gear. Historically, grinding is utilized to refurbish these damaged gears. However, there are numerous drawbacks including but not limited to high capital investment and the extraordinary amount of time and skill involved in the grinding process. Moreover, nitrided gears cannot be ground and must be scrapped. However, chemically accelerated vibratory finishing, or isotropic superfinishing (ISF), represents a value adding, low-cost option for refurbishing both case carburized and nitrided gears. Isotropic superfinishing removes light to moderate gear flank surface damage. The result is a surface with a non-directional pattern with a roughness of approximately 0.08 mm or less. Moreover, evidence suggests that isotropic superfinishing imparts a finish that increases gear durability and service life in the field. A case study on a sun pinion gear is presented.

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10FTM02	1-55589-977-6	19

Improving Heat Treating Flexibility for Wind Turbine Gear Systems through Carburizing, Quenching and Material Handling Alternatives

W. Titus

Part handling and processes for heat treating large gears have created challenges for decades. Growth in wind energy technology has focused more attention on this issue in recent years. The vast majority of installations processing such large parts utilize conventional methods via pit furnace systems. Such equipment has inherent limitations with respect to quench flow and part handling, making true improvements in areas such as distortion control difficult due to physical limitations of this processing approach. This presentation will explain alternative methods for heat treating large components that allow part distortion to be minimized. Benefits will be quantified regarding cost savings to produce such gearing and quality.

Document	ISBN	Pages
10FTM01	1-55589-976-9	8

Complete Machining of Gear Blank and Gear Teeth

C. Kobialka

Demands for increased throughput, with smaller lot sizes at lower cost have led to the development of an innovative approach to machining both: the gear bland and gear teeth on a single machine.This paper will concentrate on the potentials and risks of combined process machines what are capable of turning, hobbing, drilling, milling, chamfering and deburring of cylindrical gears. The same machine concept can be used for singular operations of each manufacturing technology on the same design concept. This leads to reduced amounts of different spare parts, increases achievable work piece quality and harmonizes on common user friendliness. In the end the economic potential of combined process technology and a vision for integrated heat treatment is shown.

Document	ISBN	Pages
09FTM19	1-55589-972-1	19

The Effect of Gearbox Architecture on Wind Turbine Enclosure Size

C.D. Schultz

Gearbox architecture—the type of gearing used, the overall gear ratio, the number of increaser stages, the number of meshes, the ratio combinations, and the gear proportions—can have a profound effect on the “package” size of a wind turbine. In this paper the author applies a common set of requirements to a variety of potential gearbox designs for a 2.0 MW wind turbine and compares the resulting “geared component” weights, gearbox envelope sizes, generator sizes, and generator weights. Each design option is also evaluated for manufacturing difficulty via a relative cost estimate.

Document		ISBN	Pages
09FTM18		1-55589-971-4	30

Does the Type of Gear Action Affect the Appearance of Micro-Pitting and Gear Life?

A. Williston

Early results from testing conducted have raised questions concerning the role of gear action with the appearance of micropitting as well as surface fatigue (macropitting). Comparisons between similar gear sets with the same loads, speeds, and lubrication but operated either as speed increasers or as speed reducers have yielded strikingly different propensities for wear. Further, these observations are not limited to lubrication based failures such as micropitting, but, so far, have applied to traditional surface fatigue failures (macropitting) as well. Findings point to an increase in the presence of micropitting on gearing operated as speed reducers. All components are operating at the same speed and load, yet wear is greatly reduced for the driven components. Perhaps more intriguing is that to date all macropitting failures have occurred to the driving pinions of gear sets operated as speed reducers. While the number of samples is decidedly small, the length of life for these components is much less than would be anticipated under smooth load circumstances. The other gear sets (operated as speed increasers) do not show any fatigue wear.In addition to how gear action affects micropitting in gearing is the question of how the gear action affects fatigue life. Current gear rating standards are based upon statistical analysis of real-world experience and mathematical stress-versus-cycle calculations. If gear action affects how gearing fails in fatigue, there may be significant ramifications in the industry. However, before any such conclusion may be made, additional testing is necessary.

09FTM17		1-55589-970-7	14

Variation Analysis of Tooth Engagement and Load-Sharing in Involute Splines

K. Chase, C. Sorenson and B. DeCaires

Involute spline couplings are used to transmit torque from a shaft to a gear hub or other rotating component. External gear teeth on the shaft engage an equal number of internal teeth in the hub. Because multiple teeth engage simultaneously, they can transmit much larger torques than a simple key and keyway assembly. However, due to manufacturing variations, the clearance between each pair of mating teeth varies, resulting in only partial engagement.A new model for tooth engagement, based on statistics, predicts that the teeth engage in a sequence, determined by the individual clearances. As the shaft load is applied, the tooth pair with the smallest clearance engages first then deflects as the load increases, until the second pair engages. Thus, only a subset of teeth carry the load. In addition, the load is non-uniformly distributed, with the first tooth carrying the biggest share. As a consequence, the load capacity of spline couplings is greatly reduced, though still greater than a single keyway.This paper discusses the results of a statistical model which predicts the average number of teeth which will engage for a specified load, plus or minus the expected variation. The model quantitatively predicts the load and stress in each engaged pair. Critical factors in the model are the stiffness and deflection of a single tooth pair and the characterization of the clearance. Detailed finite element analyses were conducted to verify the tooth deflections and engagement sequence. The closed form statistical results were verified with intensive Monte Carlo simulations.

Document	ISBN	Pages
09FTM16	1-55589-969-1	8

Allowable Contact Stresses of Jacking Gear Units Used in the Offshore Industry

A. Montestruc

An offshore jack-up drilling rig is a barge upon which a drilling platform is placed. The barge has legs which can be lowered to the sea floor to support the rig. Then the barge can be "jacked-up" out of the water providing a stable work platform from which to drill for oil and gas. The rack and pinion systems used to raise and lower the rig are enormous in terms of gear pitch or module by gear industry standards. Quarter pitch (101.6 module) pinions are common. Lifetime number of cycles for these units are—again, by gear industry standards—small, as rack teeth typically have 25-year lifetime cycles measured in the low hundreds. That is off the charts for AGMA (and ISO or DIN) design rules which draw a straight line to zero cycles for contact stress cycles less than 10,000. Use of any standards was abandoned from the start in the offshore industry for jacking applications. The author presents methods, and experience of that industry and suggested allowable contact stresses in such applications.

Document	ISBN	Pages
09FTM15	1-55589-968-4	16

High Performance Industrial Gear Lubricants for Optimal Reliability

K.G. McKenna, J. Carey, N.Y. Leon, and A.S. Galiano-Roth

In recent years, gearbox technology has advanced and Original Equipment Manufacturers have required gear oils to meet the lubrication requirements of these new designs. Modern gearboxes operate under severe conditions and maintain their reliability to ensure end-user productivity. The latest generation of industrial gear lubricants can provide enhanced performance even under extreme operating conditions for optimal reliability and reduced cost of operation. This paper describes how gear lubricants function in gearboxes and discusses the facts vs. myths of industrial gear lubricants. The paper will show how advanced gear lubricant technology can optimize the life of the gears, bearings and seals, resulting in reduced cost of operation. Opportunities to use advanced synthetic gear lubricants to achieve operational benefits in the areas of improved energy efficiency, wider operating temperature ranges, extended oil drain intervals and equipment life will be discussed.

Document	ISBN	Pages
09FTM14	1-55589-967-7	14

Design Development and Application of New High-Performance Gear Steels

J.A. Wright, J.T. Sebastian, C.P. Kern, and R.J. Kooy,

A new class of high strength, secondary hardening gear steels that are optimized for high-temperature, low-pressure (i.e., vacuum) carburization is being developed. These alloys were computationally designed as secondary-hardening steels at three different levels of case hardness. The exceptional case hardness, in combination with high core-strength and toughness properties, offer the potential to reduce drive train weight or increase power density relative to incumbent alloys such as AISI 9310 or Pyrowear® X53. This new class of alloys utilizes an efficient nano-scale M2C carbide strengthening dispersion, and their key benefits include: high fatigue resistance (contact, bending, scoring); high hardenability achieved via low-pressure carburization (thus reducing quench distortion and associated manufacturing steps); a tempering temperature of >900°F to provide up to a 500°F increase in thermal stability relative to incumbent alloys; and core tensile strengths in excess of 200 ksi. Ferrium C69™ is one alloy in this family that can achieve a carburized surface hardness of HRC 67 (with a microstructure substantially free of primary carbides), has exceptionally high contact fatigue resistance which make it an excellent candidate for applications such as camshafts and bearings as well as gear sets.

Document	ISBN	Pages
09FTM13	1-55589-966-0	14

Bending Fatigue, Impact Strength and Pitting Resistance of Ausformed Powder Metal Gears

N. Sonti, S. Rao and G. Anderson

Powder metal (P/M) process is making inroads in automotive transmission applications because of substantially lower cost of P/M steel components for high volume production as compared to wrought or forged steel parts. Although P/M gears are increasingly used in powered hand tools, gear pumps, and as accessory components in automotive transmissions, P/M steel gears are currently in limited use in vehicle transmission applications. The primary objective of this project was to develop high strength P/M steel gears with bending fatigue, impact, and pitting fatigue performance equivalent to current wrought steel gears. Ausform finishing tools and process were developed and applied to powder forged (P/F) steel gears in order to enhance the strength and durability characteristics of P/M gears, while maintaining the substantive cost advantage for vehicle transmission applications. This paper presents the processing techniques used to produce Ausform finished P/F steel gears, and comparative bending fatigue, impact and surface durability performance characteristics of Ausform finished P/F steel gears, as well as conventional wrought steel gears.

Document	ISBN	Pages
09FTM12	1-55589-965-3	12

The Anatomy of a Micropitting Induced Tooth Fracture Failure – Causation, Initiation, Progression and Prevention

R.J. Drago, R.J. Cunningham, and S. Cymbala

Micropitting has become a major concern in certain classes of industrial gear applications, especially wind power and other relatively highly loaded somewhat slow speed applications, where carburized gears are used to facilitate maximum load capacity in a compact package. While by itself the appearance of micropitting does not generally cause much perturbation in the overall operation of a gear system, the ultimate consequences of a micropitting failure can, and frequently are, much more catastrophic. Micropitting is most often associated with parallel axis gears (spur and helical) however, the authors have also found this type of distress when evaluating damage to carburized, hardened and hard finished spiral bevel gears. This paper presents a discussion of the initiation, propagation and ultimate tooth fracture failure mechanism associated with a micropitting failure. The subject is presented by way of the discussion of detailed destructive metallurgical evaluations of several example micropitting failures that the authors have analyzed on both parallel axis and bevel gears.

Document	ISBN	Pages
09FTM11	1-55589-964-6	7

Unique Design Constraints for Molded Plastic Transmissions

R. Kleiss and E. Wiita

Molded plastic gears and transmissions must work effectively in extremely variable conditions just as their counterparts in steel. Plastics have the added variables of large thermal expansion and contraction, moisture absorption, greater tolerance variation, lower strength, and form deviations due to the molding process. The design of a molded transmission must consider these effects and characteristics. This paper will offer an example of the development of a molded plastic gear pump intended for the very steady delivery of 50 psi water pressure for a medical application. It will present our approach in design, tolerancing, material selection, molding procedure, and testing to achieve and verify an effective as-molded transmission.

Document		ISBN	Pages
09FTM10		1-55589-963-9	13

The Effect of Flexible Components on the Durability, Whine, Rattle and Efficiency of a Transmission Geartrain System

A. Korde and B.K. Wilson

Gear Engineers have long recognized the importance of considering system factors when analyzing a single pair of gears in mesh. These factors include: load sharing in multi-mesh gear trains, bearing clearances, and effects of flexible components such as housings, gear blanks, shafts, and carriers for planetary gears. Quality requirements and expectations in terms of durability, lower operating noise and vibration, and efficiency have increased. With increased complexity and quality requirements, a gear engineer must use advanced system design tools to ensure a robust gear train is delivered on time, meeting all quality, cost, and weight requirements. As a standard practice, finite element models have traditionally been used for analyzing transmission system deflections, but this modeling environment does not always include provisions for analysis of vibration, efficiency, or any considerations for attribute variation. And that often requires many runs of the test to ensure all variations have been included and tested.An advanced software tool is available for the analysis of transmission system durability, noise, vibration, and efficiency, all within a single programming environment, including the effects of flexible components such as housings, gear blanks, and shafting, while also allowing manufacturing variation studies to be performed. This paper includes the results of a case study of this program.

Document		ISBN	Pages
09FTM09		1-55589-962-2	9

Designing for Static and Dynamic Loading of a Gear Reducer Housing with FEA

M. Davis, Y. S. Mohammed, A.A. Elmustafa, P.F. Martin and C. Ritinski

A recent trend has been toward more user friendly products in the mechanical power transmission industry. One of these products is a high horsepower, right angle, shaft mounted drive designed to minimize installation efforts. Commonly referred to as “alignment-free” type, this drive assembly offers quick installation with minimum level of expertise required. It is also more cost effective. These characteristics make this type of drive ideal for use in applications such as underground mining where there is little room to maneuver parts. An alignment free drive is direct coupled to the driven shaft only; it is not firmly attached to a foundation or rigid structure. A connecting link or torque arm connects the drive to a fixed structure, which limits the drive's rotational movement about the driven shaft. The electric motor is supported by the reducer housing through a fabricated steel motor adapter; the coupling connecting the motor shaft and reducer shaft is enclosed by this motor adapter. FEA was used to test the cast iron housing to determine any potential problem areas before production began. Once analyses were completed, the motor adaptor was redesigned to lower stresses using the information from the FEA and comparing it to the infield test data.

Document	ISBN	Pages
09FTM08	1-55589-961-5	12

Load Sharing Analysis of High Contact Ratio Spur Gears in Military Tracked Vehicle Application

M. Rameshkumar, P. Sivakumar, K. Gopinath and S. Sundaresh

Military tracked vehicles demand a very compact transmission to meet mobility requirements. Some of the desirable characteristics of these transmissions include: increased rating, improved power to weight ratio, low operating noise and vibration, and reduced weight. To achieve all or some of these characteristics, it is has been decided to apply a High Contact Ratio (HCR) spur gearing concept which will improve load carrying capacity, lower vibration, and reduce noise. Similar to helical gears, the load in HCR gearing is shared by minimum two pair of teeth. Therefore, load sharing analysis was conducted on Normal Contact Ratio (NCR) gearing used in sun-planet gears of an existing drive.This paper deals with analysis of load sharing of individual teeth in mesh for different load conditions throughout the profile for both sun and planet gears of NCR/HCR gearing using Finite Element Analysis. Also, the paper reveals the variation of bending stress and deflection along the profile of both gearing designs.

Document	ISBN	Pages
09FTM07	1-55589-960-8	20

Optimizing Gear Geometry for Minimum Transmission Error, Mesh Friction Losses and Scuffing Risk

R.C. Frazer, B.A. Shaw, D. Palmer and M. Fish

Minimizing gear mesh friction losses is important if plant operating costs and environmental impact are to be minimized. This paper describes how a validated 3D FEA and TCA can be used to optimize cylindrical gears for low friction losses without compromising noise and power density. Some case studies are presented and generic procedures for minimizing losses are proposed. Future development and further validation work is discussed.

Document	ISBN	Pages
09FTM06	1-55589-959-2	19

Dependency of the Peak-to-Peak Transmission Error on the Type of Profile Correction and Transverse Contact Ratio of the Gear Pair

U. Kissling

Profile corrections on gears are a commonly used method to reduce transmission error, contact shock, and scoring risk. There are different types of profile corrections. It is a known fact, that the type of profile correction used will have a strong influence on the resulting transmission error. The degree of this influence may be determined by calculating tooth loading during mesh. The current method for this calculation is very complicated and time consuming; however, a new approach has been developed which could reduce the calculation time.This approach uses an algorithm which includes the conventional method for calculating tooth stiffness in regards to bending and shearing deformation, flattening due to Hertzian pressure, and tilting of the tooth in the gear body. The new method was tested by comparing its results with FEM and LVR. This paper illustrates and discusses the results of this study. Furthermore, the maximum local power losses are compared with the scoring safety calculated following the flash temperature criteria of AGMA 925 and DIN 3990.

Document	ISBN	Pages
09FTM05	1-55589-958-5	15

HYPOLOID™ Gears with Small Shaft Angles and Zero to Large Offsets

H. Stadtfeld

Beveloid gears are used to accommodate a small shaft angle. The manufacturing technology used for beveloid gearing is a special set up of cylindrical gear cutting and grinding machines.A new development, called Hypoloid gearing, addresses the desire of gear manufacturers for more freedom in shaft angles. Hypoloid gear sets can realize shaft angles between zero and 20□ and at the same time allow a second shaft angle (or an offset) in space which provides the freedom to connect two points in space. In all wheel-driven vehicles that traditionally use a transfer case with a pinion/idler/gear arrangement or a chain, the exit of the transfer case needs to be connected with the front axle. This connection necessitates the use of two CV joints, because the front axle input point has a vertical offset and is shifted sideways with respect to the transfer case exit. Compared to a single CV joint, the two CV connections are more costly and less efficient.However, the newly developed Hypoloids can remedy the situation by offering more freedom in shaft angle and additional offset which eliminates the need for an additional CV joint. Moreover, the Hypoloid technology offers enhanced performance compared to beveloids with straight teeth. In addition to the automotive drive trains, Hypoloid technology can be applied to aircraft as well as general gearbox manufacturing.

Document	ISBN	Pages
09FTM04	1-55589-957-8	18

New Developments in Gear Hobbing

O. Winkel

Several innovations have been introduced to the gear manufacturing industry in the past few years. In the case of gear hobbing, dry cutting technology and the ability to do it with powder-metallurgical HSS-materials might be two of the most impressive ones. But the technology is still moving forward. The aim of this paper is to present recent developments in the field of gear hobbing, focusing on innovations regarding tool materials, process technology and process integration.

Document	ISBN	Pages
09FTM03	1-55589-956-1	16

Producing Profile and Lead Modifications in Threaded Wheel and Profile Grinding

A. Türich

Modern gear boxes are characterized by high torque load demands, low running noise, and compact design. In order to fulfill these demands, profile and lead modifications are being applied more and more. The main reason for the application of profile and or lead modification is to compensate for the deformation of the teeth due to load, thus ensuring proper meshing of the teeth which will result in optimized tooth contact pattern.This paper will focus on how to produce profile and lead modifications by using the two most common grinding processes, threaded wheel and profile grinding. In addition, more difficult modifications, such as defined flank twist or topological flank corrections, will also be described in this paper.

Document	ISBN	Pages
09FTM02	1-55589-955-2	15

Implementing ISO 18653, Evaluation of Instruments for the Measurement of Gears

R.C. Frazer and S.J. Wilson

A trial test of the calibration procedures outlined in ISO 18653, Gears – Evaluation of instruments for the measurement of individual gears, showed that the results are reasonable, but a minor change to the uncertainty formula is recommended.Gear measuring machine calibration methods are reviewed. The benefits from using work-piece like artifacts are discussed and a procedure for implementing the standard in the work place is presented. Problems with applying the standard to large gear measuring machines are considered and some recommendations are offered.

09FTM01	1-55589-954-7	11

Influence of the Residual Stresses Induced by Hard Finishing Processes on the Running Behavior of Gears

V. Vasiliou, C. Gorgels and F. Klocke

Low noise and high load carrying capacity are two important characteristics of competitive power transmissions. The challenge in the development, design and manufacturing of these power transmissions is to meet these requirements economically. One of the ways to meet both of these requirements is through a process known as hard finishing. There are various types of hard finishing and it is important to know which process produces which requirement. The aim of this research project is to induce residual stresses in the edge of the work pieces by different hard finishing processes and to analyze their influence on the durability of the gears. The tested gears are manufactured by profile grinding, gear honing and generating grinding. The gear deviations and the finish quality have to be comparable. Through this the influence of the residual stresses on the durability can be analyzed independent from the geometrical conditions. The presentation will show the results of the load carrying capacity tests depending on the values of the residual stresses.

08FTM19	1-55589-949-3	14

How Are You Dealing with the Bias Error in Your Helical Gears?

J. Lange

Using illustrations this paper explains that bias error (“the twisted tooth phoneme”) is a by-product of applying conventional radial crowning methods to produced crowned leads on helical gears. The methods considered are gears that are finished, shaped, shaved, form and generated ground. The paper explains why bias error occurs in these methods, and then addresses what techniques are used to limit/eliminate bias error. Profile and lead inspection charts will be used to detail bias error and the ability to eliminate it.The paper details the simultaneous interpolation of multiple axes in the gear manufacturing machine to achieve the elimination of bias error. It also explains that CNC machine software can be used to predict bias error, and equally important that it could be used to create an “engineered bias correction” to increase the load carrying capacity of an existing gear set.

Document	ISBN	Pages
08FTM18	1-55589-948-6	13

Gear Corrosion During the Manufacturing Process

G. Blake and G. Sroka

No matter how well gears are designed and manufactured, gear corrosion can occur that may easily result in catastrophic failure. Since corrosion is often difficult to observe in the root fillet region or in fine pitched gears with normal visual inspection, it may well go undetected. This paper presents the results of an incident that occurred in a gear manufacturing facility several years ago that resulted in pitting corrosion and intergranular attack (IGA). It shows that superfinishing can mitigate the damaging effects of IGA and pitting corrosion, and suggests that the superfinishing process is a superior repair method for corrosion pitting versus the current practice of glass beading.

Document	ISBN	Pages
08FTM17	1-55589-947-9	12

Innovative Concepts for Grinding Wind Power Energy Gears

C. Kobialka

Over the past years, wind power energy has gained greater importance to reduce CO_2 emissions and thus antagonize global warming. The development of wind power is driven by increased performance, which requires larger wind turbines and gear boxes. The quality demands of those gears are increasing while the production cost must decrease. This requires new production methods to grind the gears. Profile grinding is known as a process to achieve highest possible quality, even for complex flank modifications, while threaded wheel grinding is known for high productivity. New machine concepts make it now possible to use both advantages at the same time. This paper will show the newest developments for cycle time reduction and increased work piece quality using tool change systems to be able to use different grinding wheels for rough and finishing operation, work piece clamping systems, and concepts of process integration for one work piece flow.

Document	ISBN	Pages
08FTM16	1-55589-946-2	15

Hob Tool Life Technology Update

T. Maiuri

The method of cutting teeth on a cylindrical gear by the hobbing process has been in existence since the late 1800's. Advances have been made over the years in both the machines and the cutting tools used. This paper will examine hob tool life and the many variables that affect it. It will cover the state of the art cutting tool materials and coatings, hob tool design characteristics, process speeds and feeds, hob shifting strategies, wear characteristics, etc. The paper will also discuss the use of a common denominator method for evaluating hob tool life in terms of meters [or inches] per hob tooth as an alternative to tool life expressed in parts per sharpening.

Document		ISBN	Pages
08FTM15		1-55589-945-5	12

Extending the Benefits of Elemental Gear Inspection

I. Laskin

It may not be widely recognized that most of the inspection data supplied by inspection equipment following the practices of AGMA Standard 2015 and similar standards are not of elemental accuracy, deviations but of some form of composite deviations. This paper demonstrates the validity of this “composite” label by first defining the nature of a true elemental deviation, and then, by referring to earlier literature, demonstrating how the common inspection practices for involute, lead (on helical gears), pitch, and in some cases, total accumulated pitch, constitute composite measurements. The paper further explains how such measurements often obscure the true nature of the individual deviations. It also contains suggestions as to some likely source of the deviation in various gear manufacturing processes, and how that deviation may affect gear performance. It further raises the question of the likely inconsistencies of some of these inspection results and of inappropriate judgments of gear quality, even to the point of the rejection of otherwise satisfactory gears. Finally, there are proposals for modifications to inspection software, possibly to some inspection routines, all to extending the benefits of the basic elemental inspection process.

Document		ISBN	Pages
08FTM14		1-55589-944-8	11

Effects of Axle Deflection and Tooth Flank Modification on Hypoid Gear Stress Distribution and Contact Fatigue Life

H. Xu, J. Chakraborty, and J.C. Wang

Flank modifications are often made to overcome the influences of errors coming from manufacturing and assembly processes, as well as deflections of the system. This paper presents a semi-analytical approach on estimating the axle system deflections by combining computer simulations and actual loaded contact patterns obtained from lab tests. By using an example hypoid gear design, influences of axle deflections and typical flank modifications (lengthwise crowning, profile crowning and twist) on stress distribution of the hypoid gear drive are simulated. Finally, several experimental gear samples are made and tested. Tooth surface topography is examined by using a Coordinate Measuring Machine. Test results are reported to illustrate the effect of tooth flank modifications on contact fatigue life cycles.

Document		ISBN	Pages
08FTM13		1-55589-943-1	11

Hydrogen & Internal Residual Stress Gear Failures – Some Failure Analyses and Case Studies

R. Drago

Hydrogen and internal stress failures are relatively rare; however, when they occur they are often very costly and sometimes quite catastrophic. While hydrogen and internal stress issues are generally recognized as significant in the design and manufacture of larger gears, they are also important for smaller gears as well.This paper presents, via illustrated actual case studies, the mechanisms by which these failures occur, the manner in which they progress, and methods for testing finished gears for the possibility of internal problems. In addition, precautionary steps that can be taken during design, manufacture, heat treatment and quality control to minimize the possibility of these problems occurring in a finished part along with similar steps required to prevent any flawed gears from entering service are also presented and discussed.

Document	ISBN	Pages
08FTM12	1-55589-942-4	10

In-situ Measurement of Stresses in Carburized Gears via Neutron Diffraction

R. LeMaster, B. Boggs, J. Bunn, J. Kolwyck, C. Hubbard, and W. Bailey

The total stresses in a mating gear pair arise from two sources: 1) externally induced stresses associated with the transmission of power, and 2) residual stresses associated with the heat treatment and machining of the tooth profiles. The stresses due to power transmission are the result of complex normal and shearing forces that develop during the meshing sequence. The total stress from these two sources contributes to the life of a gear.This paper, funded by the AGMA Foundation, presents the results of research directed at measuring the total stress in a pair of statically loaded and carburized spur gears. Measurements were made using neutron diffraction methods to examine the change in total stress as a function of externally applied load and depth below the surface. The paper includes a summary of the various test methods that were used and a discussion of their applicability to carburized gears.

Document	ISBN	Pages
08FTM11	1-55589-941-7	12

Bending Fatigue Tests of Helicopter Case Carburized Gears: Influence of Material, Design and Manufacturing Parameters

G. Gasparini, U. Mariani, C. Gorla, M. Filippini, and F. Rosa

For helicopter gears many aspects of design and manufacturing must be analyzed, such as material cleanliness, case depth and hardness, tooth root shape and roughness, and compressive residual stresses. Moreover, these gears are designed to withstand loads in the gigacycle field, but are also subjected to short duration overloads. Therefore, a precise knowledge of the shape of the S-N curve is of great importance for assessing their in-service life.A single tooth bending (STB) test procedure has been developed to optimally map gear design parameters and a test program on case carburized, aerospace standard gears has been conceived and performed in order to appreciate the influence of various technological parameters on fatigue resistance, and to draw the curve shape up to the gigacycles region. The program has been completed by failure analysis on specimens and by static tests. Some accessory investigations, like roughness and micro-hardness measurements, have also been performed. Gigacycle tests confirm the estimations done on the basis of the shorter tests, both in term of fatigue limit and of curve shapes.

Document	ISBN	Pages
08FTM10	1-55589-940-0	10

The Effect of Superfinishing on FZG Gear Micropitting – Part II

L. Winkelmann and M. Bell

The most common failure mechanism of highly stressed case carburized gears is micropitting (grey staining). The standard FZG gear test (FVA Work Sheet 54) is generally used to determine the micropitting load capacity of gear lubricants. In recent years, FZG gear testing has also demonstrated its usefulness for evaluating the effect of superfinishing on increasing the micropitting load capacity of gears. Results from the Technical University of Munich were previously presented in Part 1 of this paper. Part II will present the results of Ruhr University Bochum. Both research groups concluded that superfinishing is one of the most powerful technologies for significantly increasing the load carrying capacity of gear flanks.

Document		ISBN	Pages
08FTM09		1-55589-939-4	11

Concept for a Multi Megawatt Wind Turbine Gear and Field Experience

T. Weiss and B. Pinnekamp

The increasing call for the use of renewable energy in all industrial countries demands for the extension of wind power generation capacity. In central Europe, as in parts of the Americas and Asia, such further expansion is only possible by re-powering— replacement of existing turbines by higher rated ones—or by developing locations in the open sea—offshore. To this end, the gear industry worldwide is challenged to develop and supply the required number of reliable 5 MW class wind turbine gears.This paper summarizes the concept evaluation and design of the 5 MW Multibrid® wind turbine transmission arrangement, test bed measurements with the prototype, as well as field experience over a test period of 3 years.

08FTM08		1-55589-938-7	9

PM Materials for Gear Applications

S. Dizdar, A. Flodin, U. Engström, I. Howe and D. Milligan

The latest material and process developments in powder metal (PM) gears have increased their load capacity. These new developments allow PM to fully compete with hardened machined wrought gears in a variety of power transmission applications. New grades of PM materials that can be case hardened using the same conditions as wrought materials improve their load capacity. Increased load capacity is also achieved by surface densifying gear teeth deeper than case hardened depth requirements. Since tooth Hertzian and bending stress gradients are within the fully dense layer, PM gears are virtually equivalent to wrought gears. The performance is demonstrated by gear tooth bending and RCF data on prototype gears.

08FTM07		1-55589-937-0	17

Planetary Gearset Lubrication Requirement Estimation Based on Heat Generation

H. Kim, S. McKenny, D. Zini, J. Chen and N. Anderson

A planetary gearset is composed of sun gear, planet gears, ring gear, carrier and bearings. As the gearset is in motion under torque, heat is generated at all sliding and rolling contacts for gear meshes and bearing surfaces as lubricant is supplied. Without lubrication the gearset cannot operate properly because all contact surfaces are influenced by heat and subsequent damages. On the other hand, excessive lubrication could cause a significant heat generation as churning or dragging losses increase. It is very important to predict a right amount of lubrication required for each component and to supply a necessary amount of lubricant in an effective way.Empirical data of temperature increase inside a planetary gearset at different inlet lubrication temperature, torque and speed are presented with physical explanation. It has been attempted to utilize heat generation data as an indicator for required lubrication measure and also for gearset efficiency measure. Heat generation sources are classified to examine largest and smallest contributors and then project a better way to effective lubrication for the planetary gearset. Some published gear efficiency equations are examined with power loss calculations based on gearset heat generations which are empirically measured in the present study.

Document	ISBN	Pages
08FTM06	1-55589-936-3	11

Tooth Fillet Profile Optimization for Gears with Symmetric and Asymmetric Teeth

A. Kapelevich and Y. Shekhtman

Involute flanks are nominally well described and classified by different standard accuracy grades, depending on gear application and defining their tolerance limits for such parameters as runout, profile, lead, pitch variation, and others. The gear tooth fillet is an area of maximum bending stress concentration. However, its profile is typically marginally described as a cutting tool tip trajectory. Its accuracy is defined by a usually generous root diameter tolerance. The most common way to reduce bending stress concentration is application of the basic (or generating) rack with full radius.This paper presents a fillet profile optimization technique based on the FEA and random search method, which allows for a substantial bending stress reduction, by 15 to 30% compared to traditionally designed gears. This reduction results in higher load capacity, longer lifetime, and lower cost. It includes numerical examples confirming the benefits of fillet optimization.

08FTM05	1-55589-935-6	10

Gear Failure Analysis Involving Grinding Burn

G. Blake, M. Margetts, and W. Silverthorne

Aerospace gears require post case-hardening grinding of the gear teeth to achieve their necessary accuracy. Tempering of the case hardened surface, commonly known as grinding burn, occurs in the manufacturing process when control of the heat generation at the surface is lost. A gearbox with minimal service time was removed in service from an aircraft, disassembled, and visual inspection performed. Linear cracks along the dedendum of the working gear tooth face were found in three adjacent teeth. A detailed inspection of the gearbox found no other components with distress.ANSI/AGMA 14104-A17 provides details of the temper etch process and exclusively uses a Nitric acid etch process, which is typically used in production quality inspections. The incident gear was processed for grinding burn using an Ammonium Persulfate etch solution. Quality records documented variation in chemical concentration levels during the time the failed gear was manufactured. A design of experiments was conducted to understand the effects of the factors and interactions that impact the capability of the Ammonium Persulfate process used in production to detect grinding burn.Presented are the metallurgical findings, load distribution analysis of actual geometry, crack propagation analysis, and design of experiment results of the Ammonium Persulfate etch process.

08FTM04	1-55589-934-9	15

The Effect of Manufacturing Microgeometry Variations on the Load Distribution Factor and on Gear Contact and Root Stresses

D. Houser

Traditionally, gear rating procedures directly consider manufacturing accuracy in the application of the dynamic factor, but only indirectly through the load distribution consider such errors in the calculation of stresses used in the durability and gear strength equations. This paper discusses how accuracy affects the calculation of stresses and then uses both statistical designs of experiments and Monte Carlo simulation techniques to quantify the effects of different manufacturing and assembly errors on root and contact stresses. Manufacturing deviations to be considered include profile and lead slopes and curvatures, as well as misalignment. The effects of spacing errors, runout and center distance variation will also be discussed.

Document	ISBN	Pages
08FTM03	1-55589-933-2	15

Effects of Gear Surface Parameters on Flank Wear

J.C. Wang, J. Chakraborty, and H. Xu

Non-uniform gear wear changes gear topology and affects the noise performance of a hypoid gear set. This paper presents the effects of gear surface parameters on gear wear and the measurement/testing methods used to quantify the flank wear in laboratory tests. Gear tooth profile, transmission error, gear tooth surface finish determined by cutting, and gear tooth surface finish determined by other processes are the factors considered in this paper. The measurements include transmission error, pattern rating, and surface roughness before and after test. The effects and interaction between controlled factors provided the information for product improvement. The action resulted from this study is anticipated to significantly improve product reliability and customer satisfaction.

08FTM02	1-55589-932-5	25

A Methodology for Identifying Defective Cycloidal Reduction Components Using Vibration Analysis and Techniques

V. Cochran and T. Bobak

For several years, predictive maintenance has been gaining popularity as method for preventing costly and time consuming machine breakdowns. Vibration analysis is the cornerstone of predictive maintenance programs, and the equations for calculating expected vibration frequencies for bearings and toothed gear sets are widely available. Cycloidal reducers present a special case due to the nature of their reduction mechanism. This paper will describe a method for utilizing vibration analysis in order to identify a defective Cycloidal ring gear housing, disc, and eccentric bearing.

08FTM01	1-55589-931-8	7

Parametric Study of the Failure of Plastic Gears

M. Cassata and Dr. M. Morris

This paper presents the results of collaboration to develop tools for the prediction of plastic gear tooth failure for any given set of operating conditions and to classify failure modes of these gears. The goal of the project is to characterize and predict the failure of plastic gears over a range of given parameters.A test plan was developed to explore the effect of rotational speed, root stress, and flank temperature on the life of plastic gears. The dependent variable for the experiments was the number of cycles (or rotations) until failure.

07FTM19	1-55589-923-3	9

How to Determine the MTBF of Gearboxes

G. Antony

Mean Time Between Failures (MTBF) became a frequently used value describing reliability of components, assemblies, and systems. While MTBF was originally introduced and used mainly in conjunction with electronic components and systems, the definition and application for mechanical components, such as gearboxes, is not broadly available, used, or recognized. In the field of gears, it is difficult to obtain an MTBF from the manufacturer due to the lack of applicable, generally recognized definitions and standards. The paper will evaluate, compare and suggest ways in determining a gearbox MTBF based on the already established, proven, design calculation standards and test methods used in the gear design.

Document		ISBN	Pages
07FTM18		1-55589-922-6	10

Bevel Gear Model

Ted Krenzer

The paper presents a method for developing an accurate generic bevel gear model including both the face milling and face hobbing processes. Starting with gear blank geometry, gear and pinion basic generator machine settings are calculated. The contact pattern and rolling quality are specified and held to the second order in terms of pattern length, contact bias and motion error. Based on the setup, a grid of tooth points are found including the tooth flank, fillet and, if it exists, the undercut area. It is proposed as the model for the next generation of bevel gear strength calculations in that the procedure produces true bevel gear geometry, uses blank design parameters as input and is vendor independent except for cutter diameter.

07FTM17		1-55589-921-9	8

Simulation Model for the Emulation of the Dynamic Behavior of Bevel Gears

C. Brecher, T. Schröder and A. Gacka

The impact of bevel gear deviations on the noise excitation behavior can only be examined under varying working conditions such as different rotational speed and torque. The vibration excitation of bevel gears resulting from the tooth contact is primarily determined by the contact conditions and the stiffness properties of the gears. By the use of a detailed tooth contact analysis, the geometry based gear properties can be developed and provided for a dynamical analysis of the tooth mesh.A model has been developed for the simulation of the dynamic behavior of bevel gears. With the aid of a load-free tooth contact analysis, the geometry-based part of the path excitation is determined. With a tooth contact analysis under load, the path excitation caused by deflections can be calculated. The geometry based part of the path excitation and a characteristic surface of the excitation values is created and provided for dynamic simulation. This dynamic model is able to consider every deviation of the micro- and macrogeometry from the ideal flank topography, i.e., waves and/or grooves in the surface structure, in combination with two and three dimensional flank deviations like profile deviations, helix deviations and twists. It is also possible to consider the influence of friction and the contact impact caused by load and/or manufacturing errors with a test rig to verify the calculations.

07FTM16		1-55589-920-2	10

Straight Bevel Gear Cutting and Grinding on CNC Free Form Machines

H. Stadtfeld

Manufacturing of straight bevel gears was in the past only possible on specially-dedicated machines. One type of straight bevel gears are those cut with a circular cutter with a circumferential blade arrangement. The machines and the gears they manufacture have the Gleason trade name Coniflex®. The cutters are arranged in the machine under an angle in an interlocking arrangement which allows a completing cutting process. The two interlocking cutters have to be adjusted independently during setup, which is complicated and time consuming.The outdated mechanical machines have never been replaced by full CNC machines, but there is still a considerable demand in a high variety of low quantities of straight bevel ears. Just recently it was discovered that it is possible to connect one of the interlocking straight bevel gear cutter disks to a free form bevel gear generator and cut straight bevel gears of identical geometry compared to the dedicated mechanical straight bevel gear generator. A conversion based on a vector approach delivers basic settings as they are used in modern free form machines. The advantages are quick setup, high accuracy, easy corrections and high repeatability.

Document		ISBN	Pages
07FTM15		1-55589-919-6	9

Experience with a Disc Rig Micropitting Test

M. Talks and W. Bennett

The experimental work carried out was aimed at developing a test method that was able to consistently produce micropitting damage and could discriminate between good oil (i.e., one that rarely produces micropitting in service) and a poor oil (i.e., one that does produce micropitting in service).

The disc rig control system allows test parameters such as entrainment velocity, contact stress and slide/roll ratio at the disc/roller contacts to be accurately and independently controlled. This enables the effect of key parameters to be studied in isolation, which is something that cannot be easily achieved using conventional gear test rigs.A test procedure has been developed which provides a good level of repeatability and discrimination between oils. In addition, a study of the effect of slide/roll ratio (SRR) has shown that the severity of micropitting damage increases as SRR increased, whereas at 0% SRR no micropitting occurred, and, at negative SRRs, microcracking occurred, but not micropitting. This is the way that SRR seems to affect micropitting in gears.

07FTM14		1-55589-918-9	8

Roughness and Lubricant Chemistry Effects in Micropitting

A. Olver, D. Dini, E. Lainé, D. Hua, and T. Beveridge

Micropitting has been studied using a disc machine in which a central carburized steel test roller contacts three, harder, counter-rollers with closely controlled surface roughness. Roughness was varied using different finishing techniques, and the effects of different oil base-stocks and additives were investigated. Damage on the test rollers included dense micropitting and “micropitting erosion” in which tens of microns of the test surface were completely removed. This phenomenon is particularly damaging in gear teeth where it has the potential to destroy profile accuracy. It was found that anti-wear additives led to a high rate of micropitting erosion, and the effect correlated more or less inversely with simple sliding wear results. There were also appreciable effects from base-stock chemistry.The key parameter affecting the severity of damage seemed to be the near-surface shear stress amplitude arising from the evolved roughness; different chemistries led to the evolution of different roughness during initial running and to different contact stresses and levels of damage.

Document	ISBN	Pages
07FTM13	1-55589-917-2	10

Influence of Grinding Burn on the Load Carrying Capacity of Parts under Rolling Stress

F. Klocke, T. Schröder and C. Gorgels

The demand for continuous improvement concerning economic efficiency of products and processes leads to an increasing cost pressure in manufacturing and design of power transmissions. Also, the power density of gears has been increased which leads to a demand for higher gear quality. In more and more cases this can only be achieved using hard finishing processes. The demand for higher gear qualities leads to an increased use of gear grinding, which incurs the risk of thermal damage, such as grinding burn on the gear flank. The influence of thermal damage on the set in operation is nevertheless hard to judge so that damaged gears are often scrapped. This leads to increasing failure costs.The lack of knowledge of the effect of grinding burn on the load carrying capacity of gears leads to the point that the same degree of damage is judged differently by different companies. Therefore, it is necessary to do trials with thermally damaged parts in order to know how much a certain degree of thermal damage influences the load carrying capacity.The investigations described in this report are aimed at determining the load carrying capacity of parts under rolling stress. Thermally damaged rollers are employed on a roller test rig, since with this analogy process the part geometry is easier to describe and easier to damage reproducibly.

Document	ISBN	Pages
07FTM12	1-55589-916-5	12

The Effect of Start-Up Load Conditions on Gearbox Performance and Life – Failure Analysis and Case Study

R.J. Drago

When gearboxes are used in applications in which the connected load has high inertia, the starting torque transmitted by the gearbox can be much higher than the rated load of the prime mover. Power plants often require several evaporative cooling towers or large banks of air cooled condensers (ACC) to discharge waste heat. Because of the very large size of the fans used in these applications, they fall into this category of high inertia starting load devices. When started from zero speed, a very high torque is required to accelerate the fan to normal operating speed. If the fan is started infrequently and run continuously for long periods of time, this high starting torque is of minimal significance. However, when the fan is started and stopped frequently, the number of cycles at the high starting torque can accumulate to a point where they can cause extensive fatigue damage, even if the gear system is adequately rated.Where the gear unit is marginally rated, very early, catastrophic gear failure is often the result. As part of the overall investigation of several failures in such gearboxes, we measured starting torque on a typical installation, examined many failed gears, and calculated the load capacity ratings for the gearboxes under actual operating conditions. This paper describes the failures observed, the testing conducted, the data analyses and the effect of the high measured starting torque on the life and performance of the gear systems. The test results revealed surprising results, especially during starts where the fan was already wind-milling due to natural air flow in the ACC bank.

Document	ISBN	Pages
07FTM11	1-55589-915-8	12

Helicopter Accessory Gear Failure Analysis Involving Wear and Bending Fatigue

G. Blake and D. Schwerin

Gear tooth wear is a very difficult phenomenon to predict analytically. The failure mode of wear is closely correlated to the lambda ratio, and can manifest into more severe failure modes, such as bending. Presented is a failure analysis in which this occurred. A legacy aerospace gear mesh experienced nine failures within a two-year time period. The failures occurred after more than eight years in service and within tight range of cycles to one another. Each failure resulted in the loss of all gear teeth with origins consistent with classic bending fatigue. Non-failed gears, with slightly lower time than the failed gears, were removed from service and inspected. Gear metrology measurements quantified a significant amount of wear. The flank form of these worn gears was measured and the measured data used to analytically predict the new dynamic load distribution and bending stress. To predict if the failure mode of wear was expected for this gear mesh, an empirical relationship of wear to lambda ratio was created using field data from multiple gear meshes in multiple applications. Presented are the metallurgical failure analysis findings, dynamic gear mesh analysis, the empirical wear rate curve developed, and design changes.

Document	ISBN	Pages
07FTM10	1-55589-914-1	11

The Gear Dynamic Factor, Historical and Modern Perspective

D. Houser and D. Talbot

The dynamic factor has been included in gear design and rating formulas since the 1930's. Its original formulation was based on an assessment of entering tooth impacts, but in modern gear design procedures, where tip relief and lead modifications are common, these impacts may be virtually eliminated. With this elimination, one finds that gear dynamics are mainly excited by steady state phenomena such as transmission error, friction and axial shuttling of the mesh force. This paper will first provide a historical progression of the dynamic factor equations that are based on impact theory and will define when this methodology is appropriate. The paper will then discuss the various steady state modeling approaches and will use one of these approaches to demonstrate the effects of manufacturing deviations on predicted dynamic loads.

Document		ISBN	Pages
07FTM09		1-55589-913-4	6

The Ikona Clutch and Differential

J. Colbourne, V. Scekic, and S. Tesic

This paper describes two devices, a clutch and a differential, which are based on the Ikona CVT. This CVT is essentially an internal gear pair, in which the pinion is mounted on an eccentric that can drive or be driven by an electric motor/generator, thus providing a variable ratio. Since this arrangement allows for “branching” of energy flow(s), it can be classified as summation-type CVT. When the CVT is used as a clutch, it would replace the friction-plate clutch in vehicles with standard transmissions, and the fluid torque converter in automatic transmissions. The new clutch will be referred to as the electric torque converter. Any excess energy is converted into electrical energy, and either stored in the battery, or reintroduced into the system through the motor/generator. Modulation of the clutch can be very smooth which is particularly advantageous when the vehicle starts from rest on uphill slopes. Since no friction element is involved, and only a fraction of torque is being manipulated, the modulation can be repeatable regardless of conditions. Finally, in a hybrid-vehicle arrangement, the clutch can be used to maintain the engine at its optimum speed (within limits), regardless of the road speed and the gearbox ratio.Similar principals apply to the Ikona differential. Unlike today's limited slip differentials, the Ikona differential allows full torque to be transmitted through one drive wheel, even though the other drive wheel may have completely lost traction. Unlike traditional differentials that allow wheels to rotate at different speeds, the Ikona differential forces the wheels to do so. Accordingly, when the vehicle is changing direction, the differential can be used to control the speed of each drive wheel, thus providing active torque steering.

07FTM08		1-55589-912-7	7

Manufacturing Net Shaped Cold Formed Gears

D. Engelmann

An innovative metal forming process has been developed for manufacturing quality, durable and cost efficient gears for high volume production. In this paper, the development of net shaped Cold Formed Gears (CFG) is presented along with their suitable applications. The manufacturing technique and equipment is introduced, as well as the advantages and limitations. Applicable materials and heat treatment practices are also discussed. Gear tooth inspection charts are presented and compared to conventional manufacturing methodologies.

07FTM07		1-55589-911-0	14

Grinding Induced Changes in Residual Stresses of Carburized Gears

R. LeMaster, B. Boggs, J. Bunn, C. Hubbard, and T. Watkins

This paper presents the results of a study performed to measure the change in residual stress that results from the finish grinding of carburized gears. Residual stresses were measured in five gears using the x-ray diffraction equipment in the Large Specimen Residual Stress Facility at Oak Ridge National Laboratory. Two of the gears were hobbed, carburized, quenched and tempered, but not finished. The remaining three gears were processed similarly, but were finish ground. The residual stresses were measured at 64 different locations on a tooth from each gear. Residual stresses were also measured at fewer points on other teeth to determine the tooth-to-tooth variation. Tooth profile measurements were made of the finished and unfinished gear samples. The results show a fairly uniform and constant compressive residual field in the non-finished gears. There was a significant reduction in the average residual stress measured in the finished gears. Additionally, there was a significant increase in the variability of the residual stress that was introduced by the grinding process. Analysis of the data suggests a linear relationship between the change in average residual stress and the amount of material removed by the grinding process.

Document		ISBN	Pages
07FTM06		1-55589-910-3	5

Using Barkhausen Noise Analysis for Process and Quality Control in the Production of Gears

S. Kendrish, T. Rickert and R. Fix

The use of magnetic Barkhausen Noise Analysis (BNA) has been proven to be an effective tool for the non-destructive detection of microstructural anomalies in ferrous materials. Used as an in-process tool for the detection of grinding burn, heat treat defects and stresses, BNA is a quick comparative and quantitative alternative to traditional destructive methods. This paper presents examples that demonstrate how BNA is used to evaluate changes in microstructural properties. Quantitative results correlate BNA test values to x-ray diffraction values for the detection of changes in residual stress. Qualitative results correlate BNA test values to acid etch patterns/colors for the detection of grinding burn defects.

07FTM05		1-55589-909-7	5

Vacuum Carburizing Technology for Powder Metal Gears and Parts

J. Kowalewski and K. Kucharski,

Carburizing is one of the leading surface hardening processes applied to the sintered, low-alloyed steel gears in the automotive industry. While diffusion of carbon in wrought steel is well documented, this is not the case for PM steel subject to carburizing in vacuum furnaces. This paper presents results that show that the density of the powder metal is the main factor for the final carbon content and distribution. Also important is the state of the surface of the part; either sintered with open porosity or machined with closed porosity. The way the carburizing gas moves through the furnace might be of some influence as well.

07FTM04		1-55589-908-0	10

Applying Elemental Gear Measurement to Processing of Molded Plastic Gears

G. Ellis

Although elemental gear inspection is rarely specified for molded plastic gears, the measurement equipment and practices can be valuable in advancing the molding processes and improving quality. After a brief description of plastic gear tooling and molding, this paper gives examples of specific elemental measurements and relates them to process changes and quality improvements. Such examples for spur and helical gears include: profile measurements, leading to gear mesh noise reduction; lead measurement, leading to increased face width load distribution and, continuing from that, even to the molding of crowned gears; and index measurement, leading to improved roundness of gears molded from fiber reinforced plastic materials.

07FTM03		1-55589-907-3	11

Material Integrity in Molded Plastic Gears and Its Dependence on Molding Practices

T. Vale

The quality of molded plastic gears is typically judged by dimensional feature measurements only. This practice overlooks potential deficiencies in the plastic injection molding process and its effect on the integrity of the plastic material. These deeper issues are often not given proper consideration until a related gear failure demands its study and evaluation. This paper identifies some of these oversights in the molding process, the resultant effect on the plastic material, and discusses their likely effect on short and long term gear performance.

Document	ISBN	Pages
07FTM02	1-55589-906-6	6

Study of the Correlation Between Theoretical and Actual Gear Fatigue Test Data on a Polyamide

S. Wasson

Fatigue tests have been run on actual molded gears in order to provide design data, using fully lubricated, plastic on plastic spur gears in a temperature controlled experiment. The purpose of the testing is to see if there is a good correlation between fatigue data, generated in a lab on test bars, versus the actual fatigue performance in a gear.In order to do this, the theories of gear calculations to get root stresses also had to be examined. Advanced FEA showed that there are corrections needed to account for high loading or high temperatures in plastic gears. The chemistry of various nylons used in gears is explained. A high crystalline nylon has been found which is an excellent material for gears in demanding applications and can withstand high torques and operating temperatures. The material has very good wear properties and excellent retention of mechanical properties (strength, stiffness, and fatigue) especially at elevated temperatures. Several commercial gear applications are currently utilizing these properties. These will be shown to demonstrate the benefits and manufacturability of this material.

Document	ISBN	Pages
07FTM01	1-55589-905-9	14

Estimation of Lifetime of Plastic Gears

S. Beermann

This paper gives an overview on the state of art in plastic gear resistance calculation. The main problem with plastics is the dependency of the stress cycle curve (Woehler line) with temperature. Today, more plastic gears (as in automobile headlights) are used in a high temperature range. Furthermore, flank resistance depends strongly on lubrication (lifetime may vary by a factor of ten and more, if oil, grease lubricated or dry running). As no secure data for plastic gears is available, how can nevertheless plastic gear design and life time prediction be improved? The best strategy is to use the feedback of existing reducers. Plastic gearboxes, before starting production in big series, are normally submitted to endurance tests. If these tests are used to check also the real lifetime limits — or by increasing test length, or by increasing applied torque — these results can be used to define the required safety factors for future gear design. This procedure has been very successful, and will be described with some examples.

Document	ISBN	Pages
06FTM16	1-55589-898-4	5

Certificate for Involute Gear Evaluation Software

F. Härtig

A test for the verification of involute gear software has been developed at the Physikalisch-Technische Bundesanstalt (PTB). This paper shows the critical influence on measurement uncertainty of uncertified involute evaluation software. Beside the test parameter information, the most dominant effects of software errors will be explained. The algorithms developed during this project should influence and help complete the existing standards and their guidelines.

Document	ISBN	Pages
06FTM15	1-55589-897-1	12

Optimal Tooth Modifications in Spiral Bevel Gears Introduced by Machine Tool Setting Variation

V. Simon

A method for the determination of optimal tooth modifications in spiral bevel gears based on load distribution, minimized tooth root stresses, and reduced transmission errors is presented. Modifications are introduced into the pinion tooth surface considering the bending and shearing deflections of gear teeth, local contact deformations of mating surfaces, gear body bending and torsion, deflections of the supporting shafts, and manufacturing and alignment of mating members. By applying a set of machine tool setting parameters, the maximum tooth contact pressure can be reduced by 5.4%, the tooth fillet stresses in the pinion by 8% and the angular position error of the driven gear by 48%, based on a spiral bevel gear pair manufactured by machine tool settings determined by a commonly used method.

06FTM14	1-55589-896-3	13

The Optimal High Speed Cutting of Bevel Gears – New Tools and New Cutting Parameters

H.J. Stadtfeld

High speed carbide dry cutting improvements have a dependency of many important parameters upon the particular job situation, which makes it difficult for a manufacturing engineer to establish an optimal cutting scenario. An analysis of the different parameters and their influence on the cutting process, allows the establishment of five, nearly independent areas of attention: blade geometry and placement in the cutter head; cutting edge micro geometry; surface condition of front face and side relief surfaces; speeds and feeds in the cutting process; and, kinematic relationship between tool and work (climb or conventional cutting, vector feet). This paper presents explanations and guidelines for optimal high speed cutting depending on cutting method, part geometry and manufacturing environment. Also, how to choose the blade system, thus giving the manufacturing engineer information to support optimizing cutter performance, tool life and part quality.

06FTM13	1-55589-895-5	6

Economic Aspects of Vacuum Carburizing

J. Kowalewski

This paper presents the aspects of vacuum carburizing technology that have an impact on process costs and quality improvements in the final product. There is an interest in furnaces for vacuum carburizing due to the demand for products with overall metallurgical quality and low unit cost. Vacuum carburizing technology produces work with minimum distortion, and desired surface metallurgy. Systems can provide “cold to cold” (cold work going in, cold work coming out) and fully automatic operation that reduces operator involvement, thus minimizing labor. Considering upstream and downstream requirements, vacuum carburizing can provide a total reduction of costs. This technology differs considerably from traditional gas carburizing both in the equipment used and in the process economy.

Document	ISBN	Pages
06FTM12	1-55589-894-7	10

A Crane Gear Failure Analysis – Case Study, Observations, Lessons Learned, Recommendations

R.J. Drago

The gearboxes used in cranes have proven themselves to be reliable. However, some gear failures have caused a reevaluation of the design, configuration, and manufacture of gearboxes in large cranes. Since crane gearboxes do not operate continuously, gear system fatigue characteristics have not been in the forefront of system operation. Studies have indicated that in many cases usage rates, loading, and in many cases both, have increased. In some applications, crane usage has increased by factors of two, or three, or even more, and gear loading has similarly increased. This higher usage makes the cumulative effects of fatigue much more important. This paper presents a case study of one particular crane gear failure, including failure analysis and resultant remedial actions, along with a discussion of the results and implications from extensive gearbox inspections that were conducted as a result of the initial failure.

Document	ISBN	Pages
06FTM11	1-55589-893-9	22

On Tooth Failure Analysis in Small-Teeth-Number Gearing: An Analytical Approach

S.P. Radzevich

This paper is an analytical study of tooth failure in gearing having small numbers of teeth. For the analysis, tooth contact stresses and combined shear stresses are investigated. The study is based on gear tooth loading, accounting for load variations with time and other gear parameters in various phases of tooth meshing. The contact and shear stresses are by simultaneous: (a) contact stresses together with (b) stresses caused by the pinion and gear sliding. While developed for use in gearing with low numbers of teeth, the method can be used for computation of stresses in gearing having more teeth. The results of the research could be used with AGMA 908-B89 for gears having less than 12 teeth.

Document	ISBN	Pages
06FTM10	1-55589-892-0	12

Fabrication, Assembly and Test of a High Ratio, Ultra Safe, High Contact Ratio, Double Helical Planetary Transmission for Helicopter Applications

F.W. Brown, M.J. Robuck, M. Kozachyn, J.R. Lawrence and T.E. Beck

An ultra-safe, high ratio planetary transmission, for application as a helicopter main rotor final drive, has been designed, fabricated and tested. The transmission improvements are reduced weight, reduced noise and improved fail-safety and efficiency. This paper discusses the fabrication, assembly and testing of the planetary transmission. An existing planetary transmission utilized a two-stage conventional spur gear design with fixed internal ring gears. The new double helical planetary (DHP) system design uses a compound planetary arrangement with staggered planets and high contact ratio gearing in a unique configuration. Double helical gears in the planet to ring meshes balance axial tooth forces without axial planet bearing reactions. The spur gear sun to planet meshes are staggered to achieve a compact arrangement. The sun gear is fully floating.

Document		ISBN	Pages
06FTM09		1-55589-891-2	7

Opportunities to Replace Wrought Gears with High Performance PM Gears in Automotive Applications

U. Engström, D. Milligan, P. Johansson and S. Dizdar

Powder metallurgy (PM) enables production of components with complex geometries such as gears. The cost-effective use of PM components in automotive applications has showed a continuous growth. This growth is due to the net shape capability, while maintaining performance. Gears for automotive applications are complex in shape and require both geometrical accuracy and high mechanical performance in terms of tooth durability. By utilizing selective densification of the teeth, these performance requirements can be met at a low cost. In this paper a PM process consisting of compaction, sintering, surface densification, and finally heat treatment has been studied to assess the feasibility of production. Helical and spur gears were used where the densification, as well as the resulting gear quality and durability, were tested.

06FTM08		1-55589-890-4	12

An Evaluation of FZG Micropitting Test Procedures and Results for the Crowned AGMA Test Gears

D.R. Houser, S. Shon and J. Harianto

This paper reports on surface fatigue testing. The goal was to develop models for predicting wear. As part of this goal, the study reports on developing an understanding of the stresses and wear predictors using FZG tests. Since the focus was on micropitting, the first tests used the method described in FVA Information Sheet No. 54/I-IV. Later, the procedure was modified to account for higher contact stress levels that are predicted for the heavily crowned and tip relieved AGMA test gears that were manufactured as a part of the AGMA tribology test program. This paper provides extensive analysis that includes detailed topography measurements of the tooth profiles, predictions of contact stresses and contact patterns. It discusses factors that affect contact stresses, flash temperatures, and test film thickness.

06FTM07		1-55589-889-0	11

Improvement of Standardized Test Methods for Evaluating the Lubricant Influence on Micropitting and Pitting Resistance of Case Carburized Gears

B.-R. Höhn, P. Oster, T. Radev, G. Steinberger and T. Tobie

Micropitting and pitting are fatigue failures that occur on case carburized gears. The performance of lubricants in regard to micropitting and pitting can be evaluated by test methods. The FVA-FZG-micropitting test consists of two parts: a load stage test followed by an endurance test. The tests require relatively high costs and are time consuming. Therefore, an analogous short test method was developed to classify candidate lubricants and supplement the existing test. The results of the short test method are given. The FVA-FZG-pitting test is for limited-life using test gears, which are ground without controlled profile or helix modifications. Although the flank roughness is restricted, the appearance of micropitting can cause a wide statistical spread of pitting test life. Thus, there was potential improvement in the test results reproducibility. In the test gears were superfinished to prevent micropitting, and given flank modifications for improved test relevance. The paper describes test procedures and shows basic examples of test results.

Document		ISBN	Pages
06FTM06		1-55589-888-2	15

An Analytical Approach to the Prediction of Micropitting on Case Carburized Gears

D. Barnett, J.P. Elderkin and W. Bennett

Micropitting is an area of gear failure that influences gear noise and transmission error. This paper outlines an approach to analyzing micropitting by looking at the critical factors for a given gear design. A practical procedure, which incorporates a three-dimensional spring model, was used to predict the micropitting wear rate and the position that wear would take place on test gear pairs. Case studies have been included that directly compare the predicted levels of micropitting with those actually measured. Simplified formulations suitable for manual calculations are also discussed.

06FTM05		1-55589-887-4	8

Development of a Gear Rating Standard – A Case Study of AGMA 6014-A06

F.C. Uherek

The AGMA Mill Gearing Committee completed AGMA 6014 for grinding mill and kiln service gear rating. The approach the committee took in the development of this standard to determine the content is reviewed. Through a review of previous standards, the performance history of applications for long life (over 20 years), and considering the large gear size, the committee achieved consensus on a rating method, which was derived from ANSI/AGMA 2001-D04. A factor comparison between 6014 and 2001 is presented, as well as their interaction, to explain the goal of the committee to develop a document that reflects actual field experience of in-service operating gear sets.

06FTM04		1-55589-886-6	11

Precision Planetary Servo Gearheads

G.G. Antony and A. Pantelides

Automated machines use servomotors to perform complex motions. Planetary gearheads are frequently used in conjunction with servomotors to match the inertias, lower the speed, boost the torque, and at the same time provide a mechanical interface for pulleys, cams, drums and other mechanical components. This paper covers topics such as: reasons why planetary gear systems are chosen for “servo applications”; what influences the planetary servo gear positioning accuracy and repeatability; rating practices to establish a “comparability” of different torques; and, an introduction of a simple method to determine the required gearbox torque rating for a servo-application based on motor torque data.

06FTM03		1-55589-885-8	11

Detailed Procedure for the Optimum Design of an Epicyclic Transmission Using Plastic Gears

I. Regalado and A. Hernández

Shows the steps to get an optimum (volume based) design for an epicyclic transmission using plastic materials, the tooth proportions of ANSI/AGMA 1006-A97, the recommendations given in ANSI/AGMA 6023-A88, and ANSI/AGMA 2101-C95. It gives the effect of changing the number of planets, the bending fatigue and contact strength of the plastic materials, and the temperature effects on the size of the gears. The design procedure starts with a preliminary analysis of gear performance in a proposed (not optimized) transmission; going step by step to an optimum design for the given load conditions and expected minimum life.

Document	ISBN	Pages
06FTM02	1-55589-884-7	12

Isotropic Superfinishing of S-76C+ Main Transmission Gears

B. Hansen, M. Salerno and L. Winkelmann

Isotropic superfinishing was applied to the third stage spur bull gear and mating pinions along with the second stage bevel gears of a Sikorsky S-76C+ main gearbox. The gearbox completed the standard Acceptance Test Procedure (ATP) and a 200-hour endurance test. During these tests noise, vibration, and operating temperatures were shown to be significantly reduced due to lower friction. A description of the tests, performance data and a general description of the process is presented.

Document	ISBN	Pages
06FTM01	1-55589-883-1	14

The Effects of Super Finishing on Bending Fatigue

G. Blake

A super finishing study was designed and conducted for bending fatigue. AMS6265 parts were created: with and without super finishing. Bending fatigue was tested using Single Tooth Fatigue (STF) and RR Moore rotating beam methods. The STF parts were designed with tooth geometry replicating a spiral bevel gear section. Two lots of material were processed. Thus, a minimum of two carburized and hardened lots, two shot peen batches and two super finishing cycles (if applicable) were processed per sample group. A detailed metallurgical evaluation was performed to characterize the material and compare to actual spiral bevel gears. Analysis of the test data concluded no statistical difference in bending fatigue strength.

Document	ISBN	Pages
05FTM20	1-55589-868-8	9

Dual Drive Conveyor Speed Reducer Failure Analysis

M. Konruff

With increasing requirements, many conveyor systems utilize dual drive arrangements to increase output. Dual drives can provide an economical solution by utilizing smaller, more efficient, system designs. However, multiple drive conveyors must proportion the load between drives and load sharing without some type of control is difficult to achieve. This paper presents a case study on a failure analysis of a coal mine dual drive conveyor system that experienced gear reducer failures between 2 to 18months. Physical and metallurgical inspection of failed gearing did not indicate material or workmanship defects, but indicated overload. In order to determine the cause of the failures, strain gage load testing was performed. The testing of the conveyor drives revealed load sharing problems which that will be reviewed.

Document	ISBN	Pages
05FTM19	1-55589-867-0	16

The Application of Very Large, Weld Fabricated, Carburized, Hardened & Hard Finished Advanced Technology Gears in Steel Mill Gear Drives

R.J. Drago, R. Cunningham and S. Cymbala

In the 1980's, Advanced Technology Gear (ATG) steel rolling mill gear drives consisting of carburized pinions in mesh with very large, weld fabricated, high through hardened gears were introduced to improve capacity. Recently, even the improvements obtained from these ATG gear sets were not sufficient to meet higher production rates and rolling loads. For greater load capacity ATG sets have been developed consisting of carburized, hardened pinions in mesh with very large, weld fabricated, carburized and hard finished gears. Single and double helical gears of this type, ranging in size from 80 to 136 inches pitch diameter have been implemented in several steel rolling applications. This paper describes the conditions that require the use of these gears and the technology required to design, manufacture, and, especially, heat treat, these very special, very large gear sets.

Document	ISBN	Pages
05FTM18	1-55589-866-1	7

Planet Pac: Increasing Epicyclic Power Density and Performance through Integration

D.R. Lucas

Epicyclical gear systems are typically equipped with straddle-mounted planetary idlers and are supported by pins on the input and output sides of a carrier. These carriers can be either one-piece or two-piece carrier designs. Traditionally many of the higher power rated epicyclic gear systems use cylindrical roller bearings to support the planetary gears. This paper will demonstrate that using a preloaded taper roller bearing in an integrated package should be the preferred choice for this application to increase the bearing capacity, power density, and fatigue life performance. Based on DIN281-4 calculations, this patented, fully integrated solution allows for calculated bearing fatigue lives to be 5 times greater than a non-integrated solution and more than 1.5 times greater than a semi-integrated solution, without changing the planet gear envelope.

Document	ISBN	Pages
05FTM17	1-55589-865-3	13

Influences of Bearing Life Considerations on Gear Drive Design

F.C. Uherek

Historically, catalog gear drives have been designed with 5000 hours of L10 bearing life at service factor 1.0 power. Advances in bearing analysis methods have brought new considerations to the design and selection process. The impact of new modeling techniques, additional considerations, and various extensions to the traditional bearing fatigue calculations are explored. The modeling of these various additions to a traditional catalog L10 calculation is illustrated by bearing selections for cases of single, double, and triple reduction gear drives. A roadmap is presented listing critical considerations when applying various bearing manufacturer recommendations.

Document		ISBN	Pages
05FTM16		1-55589-864-5	11

CH47D Engine Transmission Input Pinion Seeded Fault Test

J.P. Petrella, J.S. Kachelries and S.M. Holder, and T.E. Neupert

This paper summarizes an Engine Transmission Input Pinion Seeded Fault Test that was accomplished as a portion of the validation process for the Transmission Vibration Diagnostic System (TVDS) Analyzer. The test specimen was a high speed engine transmission input pinion with a known defect (i.e., seeded fault) machined into a high stress area of a gear tooth root. During the testing, the TVDS analyzer monitored the test pinion real time to provide a sufficient warning time of the impending failure. The TVDS data was evaluated along with a post-test evaluation of the fatigue crack. During the post-test fractographic evaluation, arrest lines and fatigue striations were analyzed to develop crack propagation data as a function of the number of applied load cycles. This data was then correlated to better understand the potential warning signals the TVDS system could provide that would allow the pilot enough time to unload the suspect engine transmission.

05FTM15		1-55589-863-7	9

Repair of Helicopter Gears

S. Rao, D. McPherson and G. Sroka,

In order to reduce costs by extending the operational life of the sun and input pinion gears of a helicopter transmission, scraped gears were subject to a superfinishing process. This process was found to remove minor foreign object damage by uniformly removing a minimal amount of material on the gear teeth, while meeting original manufacturing specifications for geometry. The process also resulted in enhanced surface quality and did not exhibit detrimental metallurgical effects on the surface or sub-surface of the teeth. The process was also found to eliminate gray staining, an early precursor to pitting. This paper describes the results of the helicopter gear repair project and includes the geometry and metallurgical evaluations on the repaired gear. Further effort to characterize the durability and strength characteristics of the repaired gear is ongoing.

05FTM14		1-55589-862-9	16

Determining the Shaper Cut Helical Gear Fillet Profile

G. Lian

This paper describes a root fillet form calculating method for a helical gear generated with a shaper cutter. The shaper cutter considered has an involute main profile and elliptical cutter edge in the transverse plane. Since the fillet profile cannot be determined with closed form equations, a Newton's approximation method was used in the calculation procedure. The paper will also explore the feasibility of using a shaper tool algorithm for approximating a hobbed fillet form. Finally, the paper will also discuss some of the applications of fillet form calculation procedures such as form diameter (start of involute) calculation and finishing stock analysis.

Document	ISBN	Pages
05FTM13	1-55589-861-0	10

Evaluation of the Scuffing Resistance of Isotropic Superfinished Precision Gears

P.W. Niskanen, B. Hansen and L. Winkelmann

Aerospace gears are often engineered to operate near the upper bounds of their theoretical design allowables. Due to this, scuffing is a primary failure mode for aerospace gears. Isotropic superfinishing improved Rolling/Sliding Contact Fatigue up to nine times that of baseline test specimens. Tests demonstrated the ability to successfully carry 30 percent higher loads for at least three times the life of the baseline samples. A study was conducted on actual gears having an isotropic superfinish. This study showed superfinishing technology increased a gear's resistance to contact fatigue by a factor of three, and increased bending fatigue resistance by at least 10 percent. The paper discusses an additional study which is underway to determine the scuffing resistance of isotropic superfinished aerospace gears to that of baseline ground gears. These tests were conducted using a method that progressively increases lubricant temperature until scuffing occurs, rather than the traditional load increasing method used in FZG testing rigs. The results of the current testing reveals that isotropic superfinished SAE 9310 specimens show at least a 40 F higher lubricant temperature at the point of scuffing compared to as-ground baseline gears.

Document	ISBN	Pages
05FTM12	1-55589-860-2	8

Modal Failure Analysis of a Gear and Drive Ring Assembly

D.D. Behlke

After years of successful reliable applications, a component failure on a new application cannot be explained with static stress analyses; modal failure analyses may be required. Finite element modal analyses were used to identify the mode and its frequency that cause a high range gear and drive ring assembly to fail prematurely. A Campbell Diagram was used to identify modes in the operating range of a six-speed transmission that could cause the drive ring to fail. Redesigning the assembly to move the critical modes out of the operating range is described.

Document	ISBN	Pages
05FTM11	1-55589-859-9	11

Low Loss Gears

B.-R. Höhn, K. Michaelis and A. Wimmer

In most transmission systems one power loss sources is the loaded gear mesh. High losses lead to high energy consumption, high temperatures, early oil ageing, increased failure risk and high cooling requirements. In many cases high efficiency is not the main focus and design criteria as load capacity or vibration excitation predominate the gear shape design. Those design criteria can counteract high efficiency. The influences of gear geometry parameters on gear efficiency, load capacity, and excitation are shown. Design preference guidelines can be followed to a varying extent which leads to more or less unconventional, but more efficient gear design. Low loss gears can save substantial energy in comparison to conventional gears. The power loss reduction is dependent on the operating conditions and can add up to 70% of the power loss of conventional gears. Such low loss gears have significant advantages in terms of energy consumption, heat development, and cooling requirements.

Document	ISBN	Pages
05FTM10	1-55589-858-0	9

Finite Element Study of the Ikona Gear Tooth Profile

J.R. Colbourne and S. Liu

The Ikona gear tooth profile is a patented non-involute tooth profile for internal gear pairs. Gears with this profile have the following properties: the teeth are conjugate; the contact ratio is very high; there is no tip interference, even when only a one-tooth difference between the pinion and internal gear; there is minimal backlash; and the gears can be cut on conventional gear-cutting machines. Large reduction ratios can be achieved by a single gear pair and a high contact ratio results in lower tooth stresses than for a similar involute gear. Plus, minimal backlash makes the Ikona profile ideal for many applications, such as servo-drives, medical prostheses, and robots. Stress analysis of these gears assumes that the contact force is equal at each contacting tooth pair. Finite element results demonstrate how the number of tooth pairs in contact may increase under load. Finally, an estimate will be presented, showing the variation of tooth force between the contacting teeth.

Document	ISBN	Pages
05FTM09	1-55589-857-2	16

Hypoid Gear Lapping Wear Coefficient and Simulation

C. Gosselin, Q. Jiang, K. Jenski and J. Masseth

Hypoid gears are usually hard finished after heat treatment using lapping. Because of the rolling and sliding motion inherent to hypoid gears, the lapping compound abrades and refines the tooth surface to achieve smoothness in rolling action and produce high quality gear sets. The pinions and gears are lapped in pairs and must therefore remain as coordinated pairs for the rest of their lives. However, heat treatment distortion can vary significantly. Thus, developing a lapping sequence for manufacturing requires both time and experienced technicians who can establish lapping operating positions and sequence times to produce quality gear sets both in terms of performance and cost. This development is generally trial and error. In this paper, the lapping process is simulated using advanced modeling tools such as gear vectorial simulation for the tooth surfaces and path of contact and reverse engineering to analyze the tooth contact pattern of existing gear sets under load (static LTCA). Test gear sets are measured using a CMM prior to a special lapping cycle where the position of the gear sets on the lapper does not change, and then re-measured after lapping in order to establish how much, and where, material was removed. A wear constant named “wear coefficient” specific to the lapping compound composition is then calculated. Based on the obtained wear coefficient value, an algorithm for simulating the lapping process is presented. Gear sets lapped on the production line are used for simulation case studies. Results show that it is possible to predict how much and where material will be removed, thereby opening the door to better understanding of the lapping process.

Document	ISBN	Pages
05FTM08	1-55589-856-4	12

New Developments in Tooth Contact Analysis (TCA) and Loaded TCA for Spiral Bevel and Hypoid Gear Drives

Q. Fan and L. Wilcox

Tooth Contact Analysis (TCA) and Loaded Tooth Contact Analysis (LTCA) are two powerful tools for the design and analysis of spiral bevel and hypoid gear drives. TCA and LTCA respectively simulate gear meshing contact characteristics under light load and under significant load. Application of CNC hypoid gear generators has brought new concepts in design of spiral bevel and hypoid gears with sophisticated modifications. This paper presents new developments in TCA and LTCA of spiral bevel and hypoid gears. The first part of the paper describes a new universal tooth surface generation model with consideration of capabilities of CNC bevel gear generators. The universal model is based on the kinematical modeling of the basic machine settings and motions of a virtual bevel gear generator which simulates the hypoid gear generator and integrates both face milling and face hobbing processes. Mathematical descriptions of gear tooth surfaces are represented by a series of coordinate transformations in terms of surface point position vector, unit normal, and unit tangent. Accordingly, a generalized TCA algorithm and program are developed. In the second part of this paper the development of a finite element analysis (FEA) based LTCA is presented. The LTCA contact model is formulated using TCA generated tooth surface and fillet geometries. The FEA models accommodate multiple pairs of meshing teeth to consider a realistic load distribution among the adjacent teeth. An improved flexibility matrix algorithm is formulated by introducing specialized gap elements with considerations of deflection and deformation due to tooth bending, shearing, local Hertzian contact, and axle stiffness. Two numerical examples, a face-hobbing design and a face milling design, are illustrated to verify the developed mathematical models and programs.

Document	ISBN	Pages
05FTM07	1-55589-855-6	20

Spiral Bevel and Hypoid Gear Cutting Technology Update

T.J. Maiuri

Spiral bevel and hypoid gear cutting technology has changed significantly over the years. The machines, tools, materials, coatings and processes have steadily advanced to the current state of the art. This paper will cover the progression from mechanical machines with complex drive trains using the five cut method of cutting gears with coolant, to machines with direct drive CNC technology dry cutting gears by the completing method with carbide and high speed steel tools. The latest cutting tool materials and tool coatings will be discussed. Production examples from the automotive and truck industries will be provided, as well as examples from the gear jobbing industry.

Document	ISBN	Pages
05FTM06	1-55589-854-8	15

A Model to Predict Friction Losses of Hypoid Gears

H. Xu, A. Kahraman and D.R. Houser

A model to predict friction-related mechanical efficiency losses of hypoid gear pairs is proposed, which combines a commercial available finite element based gear contact analysis model and a friction coefficient model with a mechanical efficiency formulation. The contact analysis model is used to provide contact pressures and other contact parameters required by the friction coefficient model. The instantaneous friction coefficient is computed by using a validated formula that is developed based on a thermal elastohydrodynamic lubrication (EHL) model. Computed friction coefficient distributions are then used to calculate the friction forces and the resultant instantaneous mechanical efficiency losses of the hypoid gear pair at a given mesh angle. The model is applied to study the influence of speed, load, surface roughness, and lubricant temperature as well as assembly errors on the mechanical efficiency of an example face-hobbed hypoid gear pair.

Document	ISBN	Pages
05FTM05	1-55589-853-3	13

Computerized Design of Face Hobbed Hypoid Gears: Tooth Surface Generation, Contact Analysis and Stress Calculation

M. Vimercati and A. Piazza

Face milled hypoid gears have been widely studied. Aim of this paper is just to propose an accurate tool for computerized design of face hobbed hypoid gears. A mathematical model able to compute detailed gear tooth surface is presented. Then, the obtained surfaces will be employed as input for an advanced contact solver that, using a hybrid method combining finite element technique with semi analytical solutions, is able to efficiently carry out contact analysis under light and heavy loads and stress calculation of these gears.

05FTM04	1-55589-852-1	11

Tooth Meshing Stiffness Optimization Based on Gear Tooth Form Determination for a Production Process Using Different Tools

U. Kissling, M. Raabe, M. Fish

The variation of the tooth meshing stiffness is a source of noise and the exact calculation of tooth form is important for the stiffness determination. For this purpose, software was written with the concept of an unlimited number of tools such as hobs, grinding disk, and honing defining a manufacturing sequence. Stiffness variation can be improved by optimization of final gear geometry with a calculation of the contact path under load. The meshing stiffness is derived making it possible to study the effect of a proposed profile correction of a gear under different loads. Calculations with AGMA2001 or ISO6336 check the point with the highest root stress. Effect of a grinding notch is also included.

05FTM03	1-55589-851-3	12

Modeling Gear Distortion

P.C. Clarke

Dealing with carburize case hardened gear distortion and growth is a challenge for the global gear industry. Attempts started in 1978 with computer programs to calculate distortion and growth, plus residual stress distributions for a gear and evolved by gathering distortion data for a wide range of sizes, shapes, grinding allowances with trends for different geometries. A spread sheet program with gear dimensional input, calculates the distortions and growths, and then calculates the modified dimensions for required protuberance and the minimum carburized case depth. Case histories illustrate the consequences of various geometries and future developments are discussed.

05FTM02	1-55589-850-5	18

The Effects of Pre Rough Machine Processing on Dimensional Distortion During Carburizing

G. Blake

A study to isolate the influence of pre-rough machine processing on final dimensional distortion. Methods are discussed to aid process development and minimize dimensional change during carburizing. The study examined the distortion during carburizing between five possible raw material starting conditions. Coupons were used and manufactured from each population of material processing. Dimensions were made before and after carburizing using a scanning coordinate measurement machine. The results show that dimensional distortion during carburizing increases with mechanical and thermal processing.

Document	ISBN	Pages
05FTM01	1-55589-849-1	11

Fine Pitch, Plastic Face Gears: Design and Manufacture

I. Laskin and E. Reiter

Face gear technology has attracted attention. Products benefiting include those which use molded plastic gears. More applications could benefit, justifying the need for more information on the special features of face gears, their design and manufacture, in comparison to other non-parallel-shaft gears. A description of manufacturing methods, particularly in plastic molding is given with inter-related design and gear performance issues. New methods of graphic modeling are included with descriptions of face gear configurations and applications.

Document	ISBN	Pages
04FTMS1	1-55589-837-8	16

Stress Analysis of Gear Drives Based on Boundary Element Method

D. Vecchiato

The stress analysis is performed as a part of TCA (Tooth Contact Analysis) for a gear drive. Unlike the existing approaches, the proposed one does not require application of commercial codes (like ANSYS or ABAQUS) for derivation of contact model and determination of contact and bending stresses. The contacting model is derived directly by using the equations of tooth surfaces determined analytically. The boundary element approach allows to reduce substantially the number of nodes of the model. Determination of stresses caused by applied load is obtained directly for the applied contacting model for any position of meshing. The developed approach is illustrated by stress analysis of helical gears with modified geometry.

Document	ISBN	Pages
04FTM9	1-55589-832-7	12

Design of a High Ratio, Ultra Safe, High Contact Ratio, Double Helical Compound Planetary Transmission for Helicopter Applications

F.W. Brown, M.J. Robuck, G.K. Roddis and T.E. Beck

An ultra-safe, high ratio planetary transmission, for application as a helicopter main rotor drive, has been designed under the sponsorship of NRTC-RITA.
It is anticipated that this new planetary transmission offers improvements relative to the current state-of-the-art including, reduced weight, reduced transmitted noise and improved fail-safety. This paper discusses the analysis and design results for the subject planetary transmission. Fabrication and testing of the transmission will be conducted in subsequent phases of the project. Typically, the final stage in helicopter main rotor transmission is the most critical and usually the heaviest assembly in the drive system for any rotary wing aircraft. The new ultra-safe, high ratio planetary transmission design utilizes a compound planetary configuration with a 17.5:1 reduction ratio which would replace a conventional two stage simple planetary transmission. The new design uses split-torque paths and high combined contact ratio gearing.

Document		ISBN	Pages
04FTM8		1-55589-831-9	13

Generalized Excitation of Traveling Wave Vibration in Gears

P.B. Talbert

Rotation of gears under load creates dynamic loading between the gears at tooth mesh frequency and its harmonics. The dynamic loading can excite traveling wave vibration in the gears. The strain associated with the traveling wave vibration can be excessive and result in high cycle fatigue of the gears. Prior investigations have examined traveling wave excitation for specific configurations, such as a sequential star system with a fixed planetary carrier. Gear mesh excitation of traveling wave vibration can be generalized to include the following: (1) any number of gears surrounding the center gear, (2) non-symmetric spacing of the surrounding gears, (3) non-equal power transfer of the surrounding gears, and (4) the effect of periodic features in the center gear. A closed form expression is developed to quantify the relative excitation of traveling wave vibration for each nodal diameter. This expression for the relative excitation is verified using analytical finite element examples.

04FTM7		1-55589-830-0	8

A Short Procedure to Evaluate Micropitting Using the New AGMA Designed Gears

K.J. Buzdygon and A.B. Cardis

At the 1998 AGMA Fall Technical Meeting, encouraging results of a prototype micropitting test using specially designed gears on the standard FZG test rig were reported. Additional gear sets became available from AGMA in 2000. Subsequently, several sets of these experimental AGMA test gears were used in an attempt to develop a relatively short test procedure to evaluate micropitting. The detailed results of these tests are discussed in the paper. The procedure involved running the test gears on the standard FZG test rig with oil circulation for 168 hours. At the end of test, the gears are rated for micropitting, weight loss, pitting, and scuffing. Five commercially available ISO VG 320 gear oils, with performance in the FVA Procedure 54 micropitting test ranging from FLS 9-low to FLS >10-high, were evaluated using this procedure. The degree of micropitting coverage ranged from 34% to 7% in the new test procedure. Micropitting generally originated in the middle of the gear tooth, instead of the root or tip. Overall, there was excellent correlation of the degree of micropitting damage between the new test procedure and FVA Procedure 54.

04FTM6		1-55589-829-7	10

The Effect of a ZnDTP Anti-Wear Additive on Micropitting Resistance of Carburized Steel Rollers

C. Benyajati and A.V. Olver

Zinc di-alkyl dithio-phosphate (ZnDTP) compounds are widely used in engine and transmission oils both as anti-oxidants and as anti-wear additives. However, recent work has shown that many anti-wear additives appear to have a detrimental effect on the resistance of gears and other contacting components to various types of rolling contact fatigue, including micropitting. The paper examines the effect of a secondary C6 ZnDTP presence in low viscosity synthetic base oil on the resistance to micropitting and wear of carburized steel rollers, using a triple-contact disk tester. It was found that the additive caused severe micropitting and associated wear, whereas the pure base oil did not give rise to any micropitting. It was further found that the additive was not detrimental unless it was present during the first 100 000 cycles of the test when it was found to exert a strong effect on the development of roughness on the counter-rollers. It is concluded that the additive is detrimental to micropitting resistance because it retards wear-in of the contact surfaces, favoring the development of damaging fatigue cracks. This contrast with some earlier speculation that suggested a direct chemical effect could be responsible.

Document	ISBN	Pages
04FTM5	1-55589-828-9	15

Investigations on the Micropitting Load Capacity of Case Carburized Gears

B.-R. Höhn, P. Oster, U. Schrade and T. Tobie

Micropitting is fatigue damage that is frequently observed on case carburized gears. It is controlled by conditions of the tribological system of tooth flank surface and lubricant. The oil film thickness has been found to be a dominant parameter. Based on the results of investigations a calculation method to evaluate the risk of micropitting respectively to determine a safety factor for micropitting on case carburized gears was developed. The calculation method is based on the result of the micropitting test as a lubricant tribological parameter, but enables the gear designer to take major influences such as operating conditions, gear geometry and gear size of the actual application into consideration. The paper summarizes important results of the continuous experimental investigations and introduces the proposed calculation method for rating the micropitting load capacity of case carburized gears.

Document	ISBN	Pages
04FTM4	1-55589-827-0	12

Influence of Surface Roughness on Gear Pitting Behavior

T.C. Jao, M.T. Devlin, J.L. Milner, R.N. Iyer, and M.R. Hoeprich

In earlier studies, surface roughness had been shown to have a significant influence on gear pitting life. Within a relatively small range of surface roughness (Ra = 0.1–0.3 micron), gear pitting life as measured by the FZG pitting test decreases as the gear surface roughness increases. This inverse relationship between gear surface roughness and pitting life is well understood in the field. To determine whether this inverse relationship is applicable to a wider range of surface roughness values, a pitting study was conducted using gears whose surface roughness ranges from 0.1–0.6 micron. The results were not completely expected. The study showed that the micropitting area is radically expanded when the gear surface roughness is close to the upper limit of the range studied. At the same time, the formation of macropitting is also greatly delayed. Not only is the pitting life significantly longer, but the initiation of macropitting can occur near or slightly beyond the pitch line. The paper discusses how high surface roughness introduces a wear mechanism that delays the formation of macropits.

Document	ISBN	Pages
04FTM3	1-55589-826-2	11

A Method to Define Profile Modification of Spur Gear and Minimize the Transmission Error

M. Beghini, F. Presicce, and C. Santus

The object of this presentation is to propose a simple method to reduce the transmission error for a given spur gear set, at a nominal torque, by means of profile modification parameters. Iterative simulations with advanced software are needed. A hybrid method has been used, combining the finite element technique with semi analytical solutions. A two dimensional analysis is thought to be adequate for this kind of work; in fact, the resulting software does not require much time for model definition and simulations, with very high precision in the results. The starting configuration is presented. At each subsequent step, little alteration of one parameter is introduced, and the best improvement in terms of static transmission error is followed, until a minimum peak-to-peak value is achieved. At the end a check is needed to verify that the tip relief is enough to avoid the non-conjugate contact on the tip corner for a smooth transfer load.

Document	ISBN	Pages
04FTM2	1-55589-825-4	9

Noise Optimized Modifications: Renaissance of the Generating Grinders?

H. Geiser

While load and stress optimized tooth modifications may be normal in production, noise and vibration optimized tooth modifications need higher production accuracies and more complex modifications than with crowning and root or tip relief. Topological modifications show advantages for low noise and vibration behavior due to the higher variability in direction of contact pattern. Unfortunately, a load optimized tooth flank modification is not always a noise optimized modification—a compromise between optimized load distribution and low noise has to be found. In a practical example the calculation possibilities will be demonstrated on how an optimized tooth modification can be found. To satisfy the new requirements the gear grinder manufacturers needed to improve their machines. This improvement was possible with the substitution for the mechanical transmissions in the grinder with the modern CNC controls. By introducing a torque motor as the main table drive of a grinder, together with the direct mounted encoder, an advantage is offered in comparison to the mechanical drive. Problems like worm gear wear, backlash and deviations are eliminated. This, and the possibility of topological modifications, could now lead to a renascence of the generating grinders.

Document	ISBN	Pages
04FTM13	1-55589-836-6	16

Superfinishing Motor Vehicle Ring and Pinion Gears

L. Winkelmann, J. Holland and R. Nanning

Today, the automotive market is focusing on “lubed for life” differentials requiring no service for the life of the vehicle. Premature differential failure can be caused by bearing failures as well as ring and pinion failure. By super finishing the lapped ring and pinion gear sets to a surface roughness less than 10 micro inch, lubricant, bearing and gear lives can be significantly increased because of the concomitant elimination of wear and the temperature spike associated with break-in. It was assumed that super finishing technology could not preserve the contact pattern of the lapped and matched gear set. This paper discusses a mass finishing operation which overcomes these obstacles and meets the needs of a manufacturing facility. Gear metrology, contact patterns, transmission error and actual performance data for super finished gear sets will be presented along with the super finishing process.

Document	ISBN	Pages
04FTM12	1-55589-835-1	16

Improved Tooth Load Distribution in an Involute Spline Joint Using Lead Modifications Based on Finite Element Analysis

F.W. Brown, J.D. Hayes and G.K. Roddis

Involute splines are prone to non-uniform contact loading along their length, especially in lightweight, flexible applications such as a helicopter main rotor shaft-to-rotor hub joint. A significantly improved tooth load distribution is achieved by applying, to the internally splined member, complex lead corrections which vary continuously along the length of the spline. Rotor hub splines with analytically determined lead corrections were manufactured and tested under design load conditions. A standard rotor shaft-to-hub joint, which uses a step lead correction between splines, was also tested as a baseline. Test data indicated that the complex lead corrections resulted in a nearly uniform contact load distribution along the length of the spline at the design torque load. The data also showed that the load distribution for the splines with the complex lead corrections was significantly improved relative to the baseline splines.

Document	ISBN	Pages
04FTM11	1-55589-834-3	8

Gear Lubrication as a Reliability Partner

M. Holloway

Performance lubrication is quickly becoming a component of preventive, predictive, proactive and reliability based maintenance programs. Using the best gear lubricant, coupled with system condition, monitoring and analysis, actually reduces overall operating expenses dramatically. Various techniques such as system conditioning, oil and equipment analysis, along with product selection and management are valuable tools which convert many maintenance departments into reliability centers. These concepts and others are discussed in this informative hands-on discussion which will review best maintenance practices from various companies and review how to implement similar programs.

Document	ISBN	Pages
04FTM10	1-55589-833-5	11

The Failure Investigation and Replacement of a Large Marine Gear

P. Hopkins, B. Shaw, J. Varo, and A. Kennedy

The paper presents details of a recent gearbox problem encountered on a naval ship and the final solution bringing the ship back to full ability. The problem occurred on the main wheel of a large, high power Naval gearbox. The investigation showed that pitting damage had developed as a result of loose side plate bolts, which led on to bending fatigue cracking. Additional investigations and monitoring established that the damage had been assisted by increased usage at high power levels, as well as a small number of significant overloads. Assessment of the gearbox design was that it had been running very close to original design limits. Repairs were then carried out to remove and arrest any damage present, and monitoring procedures were put in place to ensure no further damage developed. Risk assessments were performed to allow the ship to continue to meet its demands. Full repair options were then considered and replacement gear elements designed and produced to increase future abilities and safety factors. The paper covers the discovery of the problem, failure investigation, the in-situ repair, risk assessment of continued running, prevention of further damage, damage monitoring, the permanent repair assessment, design, manufacture and installation of replacement gears, and trials.

Document	ISBN	Pages
04FTM1	1-55589-824-6	15

Gear Noise – Challenge and Success Based on Optimized Gear Geometries

F. Hoppe and B. Pinnekamp

Airborne and structure borne noise behavior becomes more and more an important feature for industrial applications. Noise excitation requirements may differ with applications. Industrial conveyor belts or cement mills are less sensitive with respect to noise emission than military applications, such as navy ship propulsion. This paper describes requirements and solutions with regard to noise behavior focusing on examples taken from wind turbine gear transmissions and navy applications. The individual approaches have to be a suitable compromise to meet the challenge of noise requirement and cost optimization without restrictions on gear load carrying capacity. Therefore, the paper shows requirements and measurements examples from shop and field tests in comparison to gear micro geometry and calculation results.

Document	ISBN	Pages
02FTMS1	1-55589-812-2	25

Design and Stress Analysis of New Version of Novikov-Wildhaber Helical Gears

I. Gonzalez-Perez

This paper covers design, generation, tooth contact analysis and stress analysis of a new type of Novikov-Wildhaber helical gear drive. Great advantages of the developed gear drive in comparison with the previous ones will be discussed, including: reduction of noise and vibration caused by errors of alignment, the possibility of grinding, and application of hardened materials and reduction of stresses. These achievements are obtained by application of: new geometry based on application of parabolic rack-cutters, double-crowning of pinion and parabolic type of transmission errors.

Document	ISBN	Pages
02FTM9	1-55589-809-2	10

Gear RollScan for High Speed Gear Measurement

A. Pommer

This presentation features a revolutionary new method for the complete topographical measurement of gears. The Gear RollScan system is similar to one-flank gear rolling inspection. However, the master gear has measuring tracks on selected flanks. With two master gears in roll contact, both the left and right flanks of the specimen can be inspected simultaneously. After a specified number of rotations, every measuring track on the master gears will contact every flank of the specimen this measuring device will always find the worst tooth.

Document	ISBN	Pages
02FTM8	1-55589-808-4	11

Compliant Spindle in Lapping and Testing Machines

B. McGlasson

This paper presents theory, analysis and results of a novel spindle design with application to bevel gear lapping and testing machines. The spindle design includes a rotationally compliant element which can substantially reduce the dynamic forces induced between the gear members while rolling under load. The theory of this spindle concept is presented using simplified models, providing the explanation for the process benefits it brings. Analysis and simulations give additional insight into the dynamics of the system. Finally, actual lapping and testing machine results are presented.

Document	ISBN	Pages
02FTM7	1-55589-807-6	13

Selecting the Best Carburizing Method for the Heat Treatment of Gears

D. Herring, G. Lindell, D. Breuer and B. Madlock

Vacuum carburizing has proven itself a robust heat treatment process and a viable alternative to atmosphere carburizing. This paper will present scientific data in support of this choice. A comparison of atmosphere carburized gears requiring press quenching to achieve dimensional tolerances in a “one piece at a time” heat treating operation, with a vacuum carburized processing a full load of gears that have been high gas pressure quenched within required tolerances.

Document	ISBN	Pages
02FTM6	1-55589-806-8	11

Contemporary Gear Hobbing – Tools and Process Strategies

C. Kobialka

Gear manufacturing without coolant lubrication is getting more and more important. Modern hobbing machines are designed to cope with dry hobbing. In the last years, carbide hobs were prevailing in high-speed hobbing due to their excellent thermal stability. Today, this high performance rate is confronted with rather high tool costs and critical tool handling. Powder metallurgical HSS combined with extremely wear resistant coating on the base of (Ti, Al) N offer interesting alternatives for dry hobbing. It is evident that existing conventional hob geometries can be optimized respecting limiting factors like maximum chip thickness and maximum depth of scallops.

02FTM5	1-55589-805-2	9

Crack Length and Depth Determination in an Integrated Carburized Gear/Bearing

R. Drago and J. Kachelries

In an effort to determine if processing cracks posed a safety of flight concern, several gears that contained cracks were designated to undergo a rigorous bench test. Prior to the start of the test, it was necessary to document, nondestructively, all of the crack dimensions. This paper will present a specially modified magnetic rubber inspection technique to determine crack lengths as short as 0.006 inch, and a unique, highly sensitive, laboratory eddy current inspection technique to estimate crack depths up to +/– 0.003 inch.

02FTM4	1-55589-804-1	13

Multibody-System-Simulation of Drive Trains of Wind Turbines

B. Schlecht

During the last years a multitude of wind turbines have been put into operation with continuously increased power output. Wind turbines with 6 MW output are in the stage of development, a simple extrapolation to larger dimensions of wind turbines on the basis of existing plants and operational experiences is questionable. This paper deals with the simulation of the dynamic behavior of the complete drive train of a wind turbine by using a detailed Multi-System-Model with special respect of the gear box internals. Starting with the model creation and the analysis of the natural frequencies, various load cases in the time domain will be discussed.

02FTM3	1-55589-803-3	26

The Application of Statistical Stability and Capability for Gear Cutting Machine Acceptance Criteria

T.J. Maiuri

Over the years the criteria for gear cutting machine acceptance has changed. In the past, cutting a standard test gear or cutting a customer gear to their specification was all that was expected for machine acceptance. Today, statistical process control (SPC) is required for virtually every machine runoff. This paper will cover the basic theory of stability and capability and its application to bevel and cylindrical gear cutting machine acceptance criteria. Actual case studies will be presented to demonstrate the utilization of these SPC techniques.

Document		ISBN	Pages
02FTM2		1-55589-802-5	15

Development and Application of Computer-Aided Design and Tooth Contact Analysis of Spiral-Type Gears with Cylindrical Worm

V.I. Goldfarb and E.S. Trubachov

This paper presents the method of step-by-step computer-aided design of spiroid-type gears, which involves gear scheme design, geometric calculation of gearing, drive design, calculation of machine settings and tooth-contact analysis. Models of operating and generating gearing have been developed, including models of manufacture and assembly errors, force and temperature deformations acting in real gearing, and drive element wear. Possibilities of CAD-technique application are shown to solve design and manufacture tasks for gearboxes and gear-motors with spiroid-type gears.

02FTM11		1-55589-811-4	15

Gear Design Optimization Procedure that Identifies Robust, Minimum Stress and Minimum Noise Gear Pair Designs

D. Houser

Typical gear design procedures are based on an iterative process that uses rather basic formulas to predict stresses. Modifications such as tip relief and lead crowning are based on experience and these modifications are usually selected after the design has been considered. In this process, noise is usually an afterthought left to be chosen by the designer after the geometric design has been established. This paper starts with micro-topographies in the form of profile and lead modifications. Then, evaluations are made on the load distribution, bending and contact stresses, transmission error, film thickness, flash temperature, etc. for a large number of designs. The key to this analysis is the rapid evaluation of the load distribution.

02FTM10		1-55589-810-6	17

Comparing the Gear Ratings from ISO and AGMA

O. LaBath

In the early 1980's several technical papers were given comparing gear ratings from ISO and AGMA showing some interesting and diverse differences in the trends when the gear geometry was changed slightly. These changes included addendum modification coefficients and helix angle. Differences also existed when the hardness and hardening methods were changed. This paper will use rating programs developed by an AGMA committee to compare AGMA and ISO ratings while having the same gear geometry for both ratings. This will allow consistent trend analysis by only changing one gear geometry parameter while holding other geometry items constant.

02FTM1		1-55589-801-7	18

The Effect of Chemically Accelerated Vibratory Finishing on Gear Metrology

L. Winklemann, M. Michaud, G. Sroka, J. Arvin and A. Manesh

Chemically accelerated vibratory finishing is a commercially proven process that is capable of isotropically superfinishing metals to an Ra < 1.0 in. Gears have less friction, run significantly cooler and have lower noise and vibration when this technology is applied. Scuffing, contact fatigue (pitting), and bending fatigue are also reduced or eliminated both in laboratory testing and field trials. This paper presents studies done on aerospace Q13 spiral bevel gears showing that the amount of metal removed to superfinish the surface is both negligible and controllable. Media selection and metal removal monitoring procedures are described ensuring uniform surface finishing, controllability and preservation of gear metrology.

Document	ISBN	Pages
01FTMS1	1-55589-791-6	12

Optical Technique for Gear Contouring

F. Sciammarella

This paper presents an optical technique (projection moiré) that is compact and can provide a quick full field analysis of high precision gears. Comparisons are made between mechanical and optical profiles obtained of a gear tooth.

Document	ISBN	Pages
01FTM9	1-55589-788-6	11

New Opportunities with Molded Gears

R.E. Kleiss, A.L. Kapelevich and N.J. Kleiss Jr.

Unique tooth geometry that might be difficult or even impossible to achieve with cut gears can be applied to molded gears. This paper will investigate two types of gears that have been designed, molded and tested in plastic. The first is an asymmetric mesh with dissimilar 23 and 35-degree pressure angles. The second is an orbiting transmission with a 65-degree pressure angle. Both transmissions have higher load potential than traditional design approaches.

Document	ISBN	Pages
01FTM8	1-55589-787-8	16

The Effect of Spacing Errors and Runout on Transverse Load Sharing and the Dynamic Factor of Spur and Helical Gears

H. Wijaya, D.R. Houser and J. Harianto

This paper addresses the effect of two common manufacturing errors on the performance of spur and helical gears; spacing error and gear runout. In spacing error analysis, load sharing for two worst-case scenarios are treated, one where a tooth is out of position and the second where stepped index errors are applied. The analyzed results are then used as inputs to predict gear dynamic loads, dynamic tooth stresses and dynamic factors for gear rating.

Document	ISBN	Pages
01FTM7	1-55589-786-4	16

Chemically Accelerated Vibratory Finishing for the Elimination of Wear and Pitting of Alloy Steel Gears

M. Michaud, G. Sroka and L. Winkelmann

Chemically accelerated vibratory finishing eliminates wear and contact fatigue, resulting in gears surviving higher power densities for a longer life compared to traditional finishes. Studies have confirmed this process is metallurgically safe for both through hardened and case carburized alloy steels. The superfinish can achieve an Ra < 1.5 µinch, while maintaining tolerance levels. Metrology, topography, scanning electron microscopy, hydrogen embrittlement, contact fatigue, and lubrication results are presented.

Document	ISBN	Pages
01FTM6	1-55589-785-1	15

Performance-Based Gear-Error Inspection, Specification, and Manufacturing-Source Diagnostics

W.D. Mark and C.P. Reagor

This paper will show that a frequency-domain approach for the specification of gear tooth tolerance limits is related to gear performance and transmission errors. In addition, it is shown that one can compute, from detailed tooth measurements, the specific tooth error contributions that cause any particularly troublesome rotational harmonic contributions to transmission error, thereby permitting manufacturing source identification of troublesome operation.

Document	ISBN	Pages
01FTM5	1-55589-784-3	6

Traceability of Gears – New Ideas, Recent Developments

F. Härtig and F. Wäldele

Some national standard tolerances for cylindrical gears lie in, and even below, the range of instrument measurement uncertainties. This paper presents a concept based on three fundamental goals: reduction of measurement uncertainty, construction of work piece-like standards, and shortening of the traceability chain. One of the focal points is the development of a standard measuring device as an additional metrological frame integrated into a coordinate measuring machine.

Document	ISBN	Pages
01FTM4	1-55589-783-5	20

How to Inspect Large Cylindrical Gears with an Outside Diameter of More Than 40 Inches

G. Mikoleizig

This paper discusses the design and function of the relevant machines used for individual error measurements such as lead and profile form as well as gear pitch and runout. The author will cover different types of inspection machines such as: stationary, CNC-controlled gear measuring centers, and transportable equipment for checking individual parameters directly on the gear cutting or gear grinding machine.

Document	ISBN	Pages
01FTM3	1-55589-782-7	15

Automated Spiral Bevel Gear Pattern Inspection

S.T. Nguyen, A. Manesh, K. Duckworth and S. Wiener

Manufacturing processes for precision spiral bevel gears are operator intensive, making them particularly costly in today's small lot production environment. This problem is compounded by production requirements for replacement parts that have not been produced for many years. The paper will introduce a new closed loop system capable of reducing development costs by 90% and bevel gear grinder setup time by 80%. In addition, a capability to produce non-standard designs without part data summaries is reviewed. Advancements will also be presented for accepting precision gears using an electronic digital master in lieu of a physical master.

Document	ISBN	Pages
01FTM2	1-55589-781-9	16

The Ultimate Motion Graph for “Noiseless” Gears

H.J. Stadtfeld and U. Geiser

Gear noise is a common problem in all bevel and hypoid gear drives. A variety of expensive gear geometry optimizations are applied daily in all hypoid gear manufacturing plants, to reduce gear noise. In many cases those efforts have little success. This paper will present “The Ultimate Motion Graph,” a concept for modulating the tooth surfaces that uses modifications to cancel operating dynamic disturbances that are typically generated by any gear types.

Document	ISBN	Pages
01FTM11	1-55589-790-8	50

Kinematic and Force Analysis of a Spur Gear System with Separation of Sliding and Rolling between Meshing Profiles

D.E. Tananko

This paper describes a comprehensive study of the novel gear design with physical separation between sliding and rolling motions of the mesh gear contact point. The sliding motion is accommodated by shear deformation of a thin-layered rubber-metal laminate allowing very high compression loads. Several important advantages will be presented when comparing the composite gear design to the conventional involute profile.

Document	ISBN	Pages
01FTM10	1-55589-789-4	8

Design Technologies of High Speed Gear Transmission

J. Wang

This paper discusses a few critical factors and their effects on high speed gear transmissions. The first factor is centrifugal force and its effect on tooth root strength, tooth expansion and backlash and the interference fit between gear and shaft. The second is system dynamics, including critical speed, dynamic balancing and the torsional effects of flexible couplings. The third is the windage loss with different combinations of helix and rotation direction, lubricant flow rate, flow distribution and their effects on tooth bulk temperature field and tooth thermal expansion.

Document	ISBN	Pages
01FTM1	1-55589-780-0	16

Carbide Hobbing Case Study

Y. Kotlyar

Carbide hobbing improves productivity and cost, however many questions remain regarding the best application, carbide material, hob sharpening, coating and re-coating, hob handling, consistency and optimum hob wear, best cutting conditions, and concerns for the initial cutting tool investment. This paper is a case study of a successful implementation of carbide hobbing for an annual output of 250,000 gears, average lot size of about 200–300 gears, producing gears of about 150 different sizes and pitches, with 4 setups per day on average.