Load Carrying Capacity Of PVD-Coated Gearings

In 2003, the AGMA Foundation's Research Grant Program awarded Aachen University a $34,500 grant for research on the load carry capacity of PVD-coated gearings. This article details the results of that research. The AGMA Foundation, founded by AGMA members in 1994, supports applied gear technology, education, and the establishment of global standards for the gear industry. For more information on the AGMA Foundation, go to www.agmafoundation.org.

Introduction

The development of modern vehicles is characterized by a continuous rise in power densities, which imposes ever greater demands on vehicle gear systems. Because current knowledge indicates that significant increases in the performance of individual gear materials can no longer be expected, new means of enhancing gear performance are being sought. The use of PVD (Physical Vapour Deposition) coating systems has great potential for increasing sustainable tooth flank pressures. Studies show that the PVD-coating of tooth flanks with metal-carbon films can increase the resistance of gears to both corrosion and pitting.

The results of pitting tests carried out at the WZL (Figure 1) may serve as an example; standardized uncoated and PVD-coated test gearings were used [SFB03]. The influence of PVD coatings on the tooth flank resistance of current car gear systems has not yet been adequately researched.

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Objective

The main goal of the investigation was to evaluate the influence of modern and capable PVD-coating materials on the load carrying capacity of case-hardened automotive gears. For these purposes automotive gears with practice-oriented geometries were PVD-coated with so-called amorphous metal-carbon coatings and their pitting resistance was studied on power circulating (PC) test rigs. Helical gears, hard-finished by discontinuous profile grinding or shaved prior to heat treatment, were used in the tests.

To quantify the influence of the coating on load carrying capacity, the S-N curves were determined for both coated and uncoated gears. The results of these S-N tests allowed researchers to predict the potential of metal-carbon PVD coatings for increasing sustainable loads and decreasing surface fatigue on the gear flanks. Further essential features of the project were the influence of the PVD-coating process on gear materials and the behavior of PVD-coated flanks under differing loads.

Procedure

A variable 3-shaft gear test rig capable of testing small-module spur and helical gears was used for trials to determine the load carrying capacity of the tooth flanks. The difference between the new 3-shaft gear test rig and a conventional 2-shaft gear test rig, according to DIN 51354 Part 1 [DIN90], is that the center distance is variable across a range of a = 66 mm to a = 120 mm. In addition, the fact that the test pinion is positioned between two mating gears allows test times to be shortened as compared to the conventional 2-shaft gear test rig

Figure 1

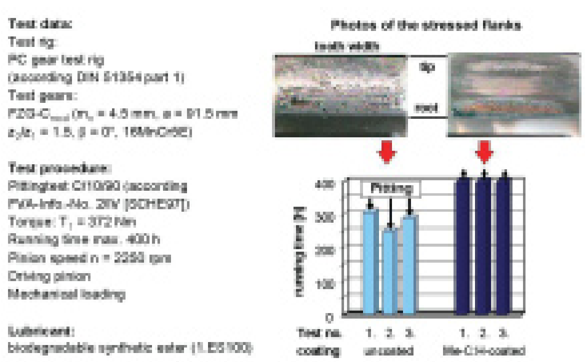

Figure 2

Description	Symbol	Pinion	Gear	Dimension
Nominal pressure angle	α	20		°
Helix angle	β	31		°
Module	m	1.65		mm
Centre distance	a	66		mm
Face width	b	14		mm
Number of teeth	$z_{1,2}$	31	39	-
Surface hardness	HV20	680-800		-
Core hardness	HV50	385-553		-
Conventional thickness	E850	0.25-0.5		mm
Material	chromium-molybdenum-steel			

source: Renault (F)

because tooth flanks are loaded twice for each full turn of the pinion.

A commercial Aral EP SAE W80 mineral oil was used as the lubricant for both the uncoated and the PVD-coated gearings. The jet temperature of the lubricant was T = 90°C. To ensure that results are valid under industrial conditions, a typical car transmission gear geometry (the fifth gear for a small car) was chosen. Renault (France) provided roughed blanks for a gearing commonly used in industry. The helical gear has a module of $m_n = 1.65$ mm and the center distance is $a = 66$ mm. The gear ratio is $z_2/z_1 = 0.795$. The material is a chromium-molybdenum steel. Following conventional heat treatment in the form of casehardening (gas carburizing and oil quenching), it is expected to display the properties shown in Figure 2.

To estimate the necessary test loads, the tooth flank pressures and tooth root stresses were calculated according to DIN 3990 [DIN87]. Values determined in this way were compared with the permissible values given in DIN 3990, Part 5. Figure 3 presents the resulting theoretical tooth root and tooth flank reliabilities. A comparison of the reliabilities indicates that increasing tooth root fractures are to be expected from a pinion torque of M = 250 Nm upwards.

Up to a loading torque of roughly 250 Nm ($\sigma_H = 1549$ N/mm^2, $\sigma_F = 945$ N/mm^2), the tooth flank reliability is lower than the tooth root reliability of the test gearing. In this load range, pitting damage, which is defined as the governing criterion for the tests, may be expected to occur before tooth root fracture.

The roughed gears were finished by grinding or shaving. The shaved variant of the test gearing was manufactured by plunge shaving in the soft state; the ground variant was produced by

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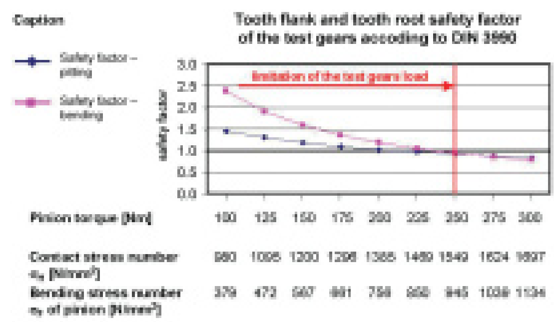
Figure 3



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profile grinding after heat treatment. Following recommendations from the Ipsen Company (Germany), the gears were heat-treated by vacuum carburization and gas quenching. This decision was taken because the chosen process causes no surface oxidation of the part, and thus creates a favorable surface state for coating-substrate adhesion on the shaved gear variant, which is not subjected to any finishing processes after heat treatment. Figure 4 contains micrographs of the uncoated gearings and compares the results of scratch tests on PVD-coated tooth flanks after gas carburization and oil quenching with those after vacuum carburization and gas quenching. The etched micrographs of the surface zones clearly indicate that, unlike gas carburization and oil quenching, vacuum carburization and gas quenching produces no detectable surface oxidation in the near-surface zones of the part.

Owing to the differing heat treatments and the consequent differences in the substrate hardness curves, unambiguous analysis of the scratch test results for the PVD-coated surfaces is not possible. It is evident from the chosen scales of the SEM scans that the selected scratch load of 80 N produced scratch paths of different width in each case.

There are differences in the behavior of the PVD film on the tooth flanks. Whereas the vacuum carburized and gas quenched tooth flanks displayed good coating-substrate adhesion, eventually destroyed by partial delamination, there is continuous smearing of the coating on the gas carburized and oil quenched variant.

Figure 5 illustrates the hardness curves for the vacuum carburized and gas carburized variants of the test gearing respectively. It is apparent that the heat treatment process employed was able to attain the gear manufacturer's values for surface hardness and casehardening depth. The core hardness is slightly below the required tolerances. The shaved gear variants exhibit similar hardness curves.

On the recommendation of Hauzer (Netherlands), a W-C:H metal-carbon film characterized by an additional Cr interface layer was used as the coating. The gears were micro-peened prior to coating. This cleans and simultaneously activates the gear surface, improving coating-substrate adhesion. The hardness curves for the ground and micro-peened gears are likewise shown in Figure 5, indicate that micro-peening slightly increases the surface hardness of the tooth flanks.

Figure 5 also indicates residual stresses at the part surface for the unpeened and peened tooth flanks. It is apparent that the peening process employed in the tests generated extremely high residual compressive stresses in the surface of the material. The level of these residual stresses is above that of the residual stresses generated by consolidation peening on casehardened gears [KOCH97].

Microhardness measurements were performed on the PVD-coated tooth flanks to determine the effects of the coating process on the substrate. As shown in Figure 6, the surface hardness of the test gearings falls by about 100 HV after the coating process. The resulting hardness is, however, still within the required tolerance range. Moreover, the compressive

Figure 4

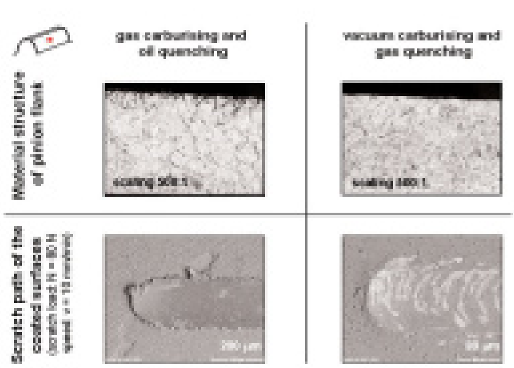


Figure 5

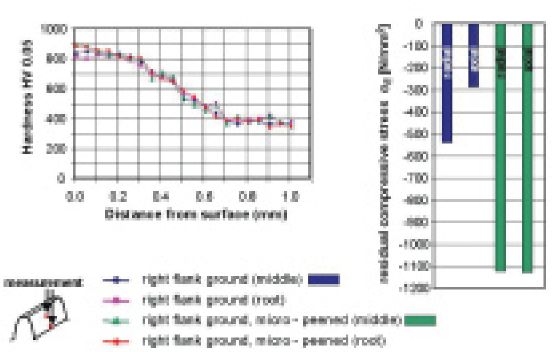
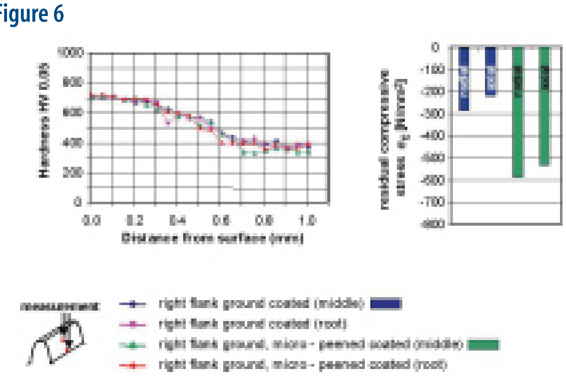


Figure 6



residual stresses of both the ground and the ground and micro-peened surface are significantly reduced by the coating process.

The coating thickness curves for the coated tooth flanks were documented by means of REM-scans. The results shown in Figure 7 indicate a clear decrease in coating thickness from the tooth crest to the tooth root. The cause lies in the characteristics of the PVD process, in which zones of the component that face the target are coated to the highest quality. The angle of incidence of the particles becomes flatter from the tooth crest to the tooth root, with negative effects on film growth and coating-substrate adhesion. To counteract this effect, the gears are rotated in the coating chamber. The low coating thickness at the tooth root is caused by the shading effect of the tooth flanks. Rotation during the coating process could not fully compensate the specific disadvantage of the low-module gear geometry used in this case. As a result, the lowest coating thickness is found in the zone of maximum tribological stress on the tooth flank, below the circle of contact.

Test Results

Figure 8 presents the results of running tests on the ground gear variant. The fatigue strength value for the uncoated gear variant is approximately M = 165 Nm. The limiting value for fatigue strength is set by increased tooth root fractures above a load of M = 225 Nm. This result correlates with the calculated results given in Figure 3.

Figure 8 also shows the running times for PVD-coated ground test gearings. It is evident that the chosen coating process has not increased the load carrying capacity of the test gearings. Tooth root fractures and pitting damage occur below the original fatigue strength level for the test gears.

Extensive metallographic tests were conducted on the part variants to identify the reasons for the fall in load carrying capacity of the coated as compared to the uncoated gear. The top section of Figure 9 shows micrographs taken after the various production steps for the ground gear variant.

Following the coating process, there is an evident change in the structure of the casehardened zone on both the unpeened and the peened ground surfaces. Because this change is not caused by the peening process, thermal stressing by the coating process is responsible for the alteration in structure. The measured decline in surface hardness on the coated as compared to the uncoated variant, and the resulting negative effects on the load carrying capacity of both the tooth flank and the tooth root on the test gearing may likewise be attributed to this cause.

The bottom section of Figure 9 shows scanning electron microscope images of the uncoated and coated tooth flank surfaces. It is apparent that the structure of the micro-peened surfaces is strongly deformed as compared to the ground tooth flanks. Obvious surface craters resulting from the

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Figure 8

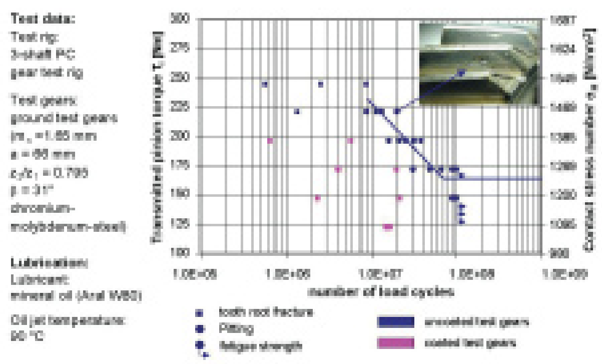


Figure 7

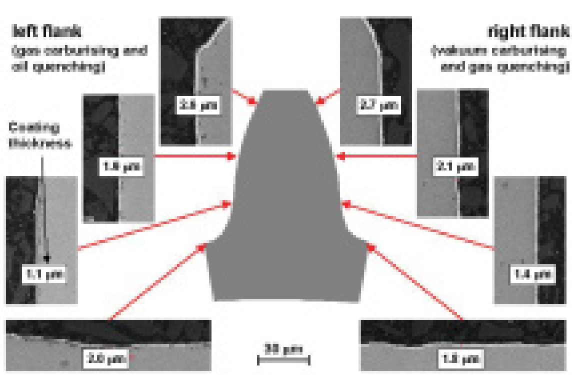
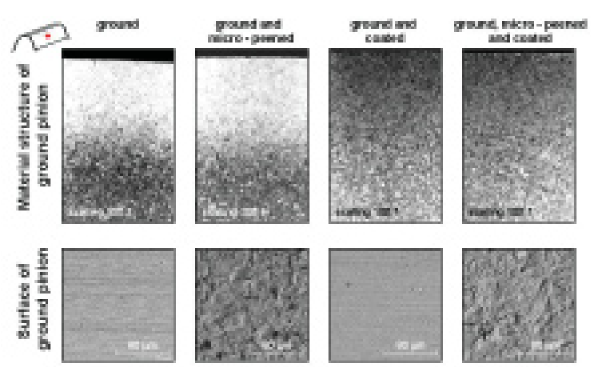


Figure 9



> In tests with gear geometries used in industrial gearings, coating the gears with metal-carbon films has led to a significant increase in tooth flank load carrying capacity.

Coated Gearings

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peening process are visible, leading to a far from negligible notching effect. In addition, excessive peening energy is probably responsible for the very high residual compressive stresses documented in Figure 5.

The shaved peened and coated test variant displays negative features similar to those of the ground gear variants already presented above, so that extensive load carrying capacity studies could be omitted in this case.

Summary And Future Prospects

Studies to determine the increase in load carrying capacity through PVD coating of ground and shaved gears were performed on a gearing geometry currently used in a car gear train. In view of the need for a non-oxidized surface, especially on the shaved gear variant, the gearings were subjected to heat treatment by vacuum carburization and gas quenching. Some of the gears were then PVD-coated with a metal-carbon film.

Investigations of tooth flank load carrying capacity for the uncoated gear produced results in line with the computed load estimates. There was, however, no increase in load carrying capacity for the coated variant. Metallographs here reveal clear thermally induced structural changes in the surface zone, influences on surface hardness and residual stresses due to the coating process, and considerable increases in surface roughness due to the peening process used to clean the parts. These results were taken as a starting point for further investigations using different coating and peening parameters. A further variant is currently being tested.

In tests with gear geometries used in industrial gearings, coating the gears with metal-carbon films has led to a significant increase in tooth flank load carrying capacity. The geometrical peculiarities of small-module gears from the automotive sector, combined with the not yet fully researched negative effects of possible thermal stressing during the coating process, indicate key areas for future research. Tests to date will form the basis for fundamental sophistication of the PVD process, yielding process parameters that reliably exclude negative effects on the structure of the substrate material.