Service Behavior of PVD-Coated Gearing Lubricated with Biodegradable Synthetic Ester Oils

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Abstract

The following article is concerned with the analysis of the wear-reducing effect of PVD-coatings in gearings. Standardized test methods are used, which under near-real conditions enable statements to be made about the different forms of damage and wear (micropitting, macropitting, scuffing).

The basic aim of the analyses is to transfer the functions of individual lubricant additives to the surface of the material via the application of wear-protection coatings in order to be able to reduce the additive content in gear lubricants. The report shows that the use of metal-carbon layers enables the omission of surfactant additives.

Introduction

Alongside performance capability and fulfillment of required specifications, the environmental compatibility of technical products is increasingly at the forefront of public interest. This trend is caused on the one hand by a general increase in environmental awareness and on the other by the increasing scarcity of non-renewable raw materials that are used as the starting materials for the commercial production of many goods.

Gearboxes are lubricated with mineral oil or synthetic-based lubricants for reasons of wear protection and for drawing off heat. These lubricants are alloyed with additives to achieve the required characteristics. The additives cause the lubricants to become potentially environmentally toxic and thereby conflict with the trend for producing environmentally sustainable products.

A first step for the improvement of environmental compatibility is the use of easily biodegradable lubricants, which nevertheless contain additives for the purposes of lubricant performance. A further step is the avoidance or reduction of additives without diminishing load-bearing capacity, wear behavior, lifetime and reliability of the gearing operated with additive-free or low-additive lubricants. Hard material, physical vapor deposition (PVD) coatings can compensate for the missing additive functions and are able to perform the functions of additives.

The first phase of the analyses on this subject was carried out at the Laboratory for Machine Tools and Production Engineering, located at Aachen University, in Aachen, Germany. In the first phase, tests were carried out on a rolling test rig to simulate the tooth flank contact with PVD-coated rollers using rapidly biodegradable synthetic esters (Refs. 1–3). Of the hard material PVD coatings used in the test—CrAlN, TiAlN, WC/C and ZrC—the amorphous metal carbon coating WC/C proved particularly effective. In the second phase, this coating system is being examined in single-stage gearing with regard to its wear protection characteristics.

Test Structure, Coating and Lubricants Used

There is a series of standardized test procedures for the analysis of the operational behavior of lubricants which are carried out on FZG back-to-back test rigs with an axle distance of a = 91.5

Table 1—Characteristics of the WC/C coating (Balzers Verschleißschutz GmbH).

Characteristics	Value
Microhardness (HV 0.05)	1,000
Friction value against steel (dry)	0.15–0.20
Coating thickness (µm)	1–4
Internal stress of coating (GPa)	–1.0
Max. application temperature (°C)	300
Coating color	black–gray
Coating structure	laminate

Table 2—Laboratory values for the test oils in the fresh state.

Specification	Reference oil CLPE 100	Basic oil COE 100
Viscosity at 40°C (mm²/s)	98	92
NZ figure (mgKOH/G)	1.4	1.3
Viscosity index (–)	180	169
Water content (%)	< 0.1	< 0.1

mm (Ref. 4). As purely lubricant tests, these procedures are generally carried out with uncoated standard gearing. By using coated gear sets, it is possible to expand test procedure statements on the behavior of coating systems to their use in real gear tooth flank contact situations. In the test procedures, the scuffing test (Ref. 5), the micropitting test (Ref. 6) and the macropitting test (Ref. 7) are seen as fundamental in the evaluation of performance and the behavior in operation of a lubricant.

The WC/C coating employed is a commercially available carbon layer with a metal content, applied by means of a PVD-sputter process. The characteristics of this coating are given in Table 1.

Table 2 contains the basic specification data for the rapidly biodegradable synthetic ester, which is used both with additives (reference oil, CLPE 100) and without additives (basic oil, C0E 100).

Analysis in Accordance with FZG Scuffing Test Method

So-called FZG-A gearing, which displays a distinct one-sided profile displacement, is used in the scuffing test in accordance with DIN 51 354 Part 2 (Ref. 5). The result is a high sliding speed on the tooth flanks and consequently a particular sensitivity to scuffing.

Two sets of gears, one uncoated and one WC/C-coated, were provided for the analyses. Each one was tested in combination with the reference oil and the basic oil. Figure 1 gives the mass loss figures for the uncoated test gears relative to the respective load levels applied.

With the reference oil, there was no significant increase of mass loss during the test period. The reference oil can therefore be certified as achieving a damage load level > 12, according to the test method specified in DIN 51 354 Part 2. On the contrary, during the scuffing test with the basic oil, traces of scuffing were detected on the pinion and gear from load level 8 onwards. In order to compare the development of the scuffing damage with that of the coated gearing, the scuffing test was continued up until load level 12, although the damage criterion had already been achieved after load level 8. The scuffing on the pinion leads to progressive mass loss, which after load level 10 amounts to Δm = 60 mg and after load level 12 Δm = 169 mg.

Figure 2 shows photographs of the uncoated pinion at the end of the test. The bottom photo shows slight scratches running in the direction of the profile on the flanks of the pinion teeth which were lubricated with the reference oil. The surface structure produced by the Maag crossgrinding, however, is observed to be practically unaltered after the conclusion of the analyses. The pinion tooth flanks lubricated with the basic oil, though, reveal distinct scuffing in the area above the rolling circle. That scuffing has led to a complete destruction of the top surface of the tooth flank.

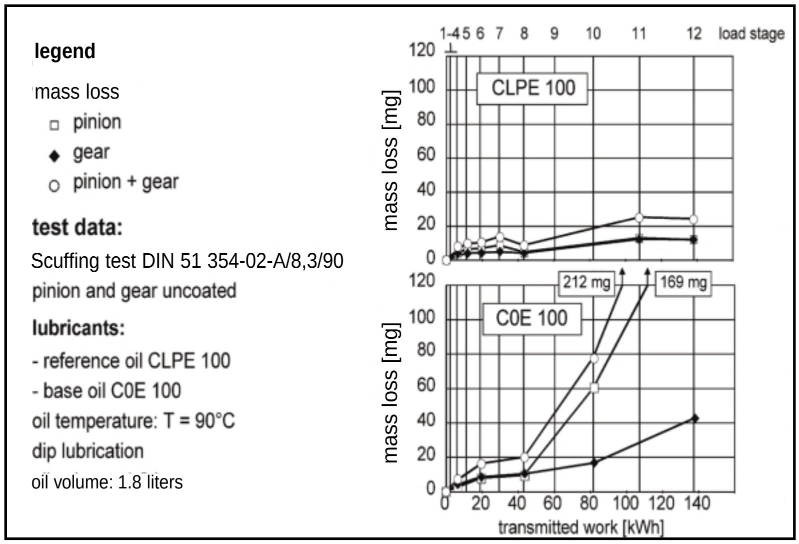

Figure 1—Mass loss of uncoated gear sets in the scuffing test with reference and basic oils.

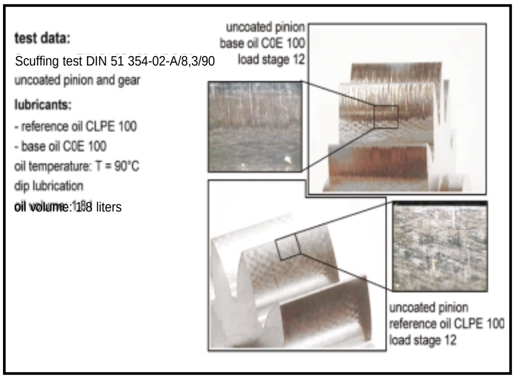

Figure 2—Photographs of the uncoated pinion at the end of the test (after load stage 12).

Scuffing tests with the reference and basic oils were also carried out under identical test conditions on WC/C-coated gear sets. The mass loss of the pinion and gear determined after each load level is shown in the diagrams in Figure 3.

In the scuffing test with the reference oil, the WC/C-coated gear set displays a linear progression of mass loss over the test period. This mass loss results from the continuous abrasion of the WC/C coating, which is increasingly evened out due to its laminate structure.

In this case, mass loss is observed on the test gear. The abraded particles of the coating settle at the bottom of the oil sump in the test gears in the

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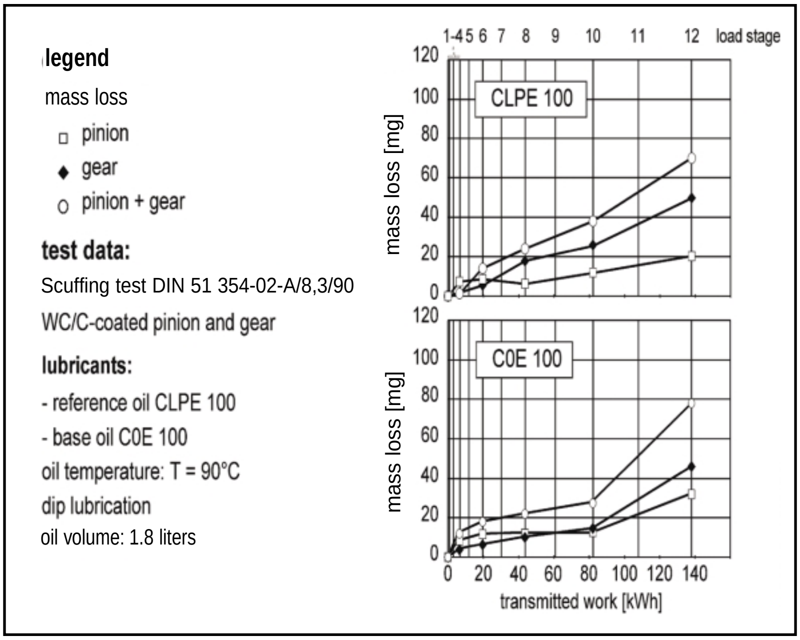

Figure 3—Mass loss of WC/C-coated gear sets in the scuffing test with reference and base oils.

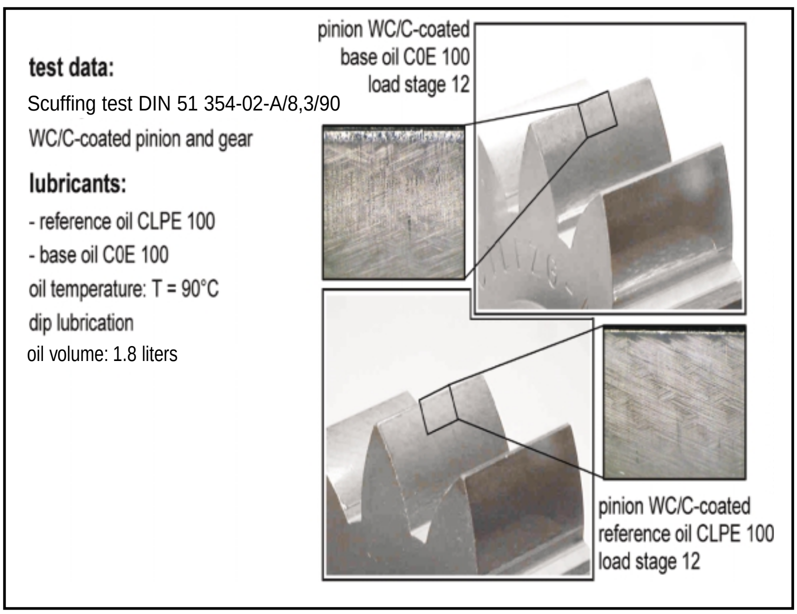

Figure 4—Photographs of the WC/C-coated pinion at the end of the test (after load stage 12).

form of black sludge. Direct contact of the metallic surface of the tooth flanks can be ruled out because examination under a light-optical microscope after the end of the test revealed no exposed flank areas either on the pinion or on the gear.

The scuffing test with the WC/C-coated gear set in combination with the basic oil shows the wear-protecting effect of the WC/C-coating.

After completion of the test to load level 12, the total mass loss recorded with the basic oil is practically identical to the total mass loss of the tooth flanks lubricated with the reference oil with additives within the bounds of measurement reproducibility when determining mass loss.

Photographs of the WC/C-coated tooth flanks of the pinion are shown in Figure 4. Under the light-optical microscope, small areas of wear can be seen in the WC/C coating after load level 12 on the tip of the pinion and at the root of the gear, giving rise to direct contact with the metallic surface. The coating must be improved in this respect.

In conclusion, comparing the scuffing tests of the uncoated and WC/C-coated gear sets with the synthetic ester's basic oil, we can determine that the WC/C coating under the specified test conditions leads to significantly less wear of the tooth flanks of the coated gear set. The reduced wear is expressed in an approximately 2.5-fold less mass loss of the coated pinion and gear compared with the uncoated pinion and gear.

Furthermore, the comparison of the two scuffing tests with WC/C-coated gearing shows that the wear-reducing effect of the WC/C coating is evidently not dependent on the lubricant's additives. In accordance with the current stage in the analyses, the wear protection effect of the reference oil additives appear to exercise no effect on the coated surface and is largely assumed by the coating.

Since the wear-reducing effect of the WC/C coating is temporally limited due to the abrasion, ultimately the scuffing resistance of the combination of the uncoated gear set and the reference oil with additives must be estimated to be greater than the combination of WC/C-coated gearing and basic oil.

Consequently, there is a need for further research and development in order to be able to make improvements to the behavior in operation and the wear resistance in particular of the coating and to match the coating to the requirements.

Analysis in Accordance with the FZG Micropitting Test Method

The influence of lubricants and their additives on the development of micropitting are quantitatively defined with the aid of a micropitting test (Ref. 6). The micropitting test is in two parts and encompasses a load stage test and a subsequent endurance test. In the load stage test, the micropitting resistance of the tribological system gear lubricant is determined in the form of a damage load level in given operating conditions. The endurance test gives information about the progression of damage over greater load cycles.

The standard test gearing used in the micropitting test is the unmodified FZG-C test gearing. As shown in previous analyses carried out by the authors (Ref. 8), the entry impact of these gear teeth caused by the absence of tip relief leads to damage of any coating applied, thereby impeding any wear-reducing effect. For this analysis, therefore, modified test gearing is used, with crowning and tip relief on the pinion and gear.

In these analyses, micropitting tests were carried out with two sets of gears, one uncoated and one PVD-coated, and the rapidly biodegradable synthetic ester with additives (reference oil CLPE 100). The mean pinion profile form deviation measured in these tests is shown in Figure 5. The results of micropitting tests with the unmodified FZG-C test gearing variant are also shown (Ref. 8).

In Figure 6, the profiles of the unmodified and modified test pinions are documented. If we look at the mean profile form deviation of the unmodified pinion variants, we observe an almost continuous increase in both instances. This is largely affected by the cratering caused by the entry impact in the root region of the gear tooth. Micropitting was also detected over the entire width of the tooth of the uncoated pinion in the initial meshing contact area (see Fig. 7).

Under the same test conditions for the WC/C-coated pinion, no micropitting was recorded. Nevertheless, very small pits had developed in the initial meshing contact area.

If we look at the mean profile form deviations measured on the corrected uncoated test pinion in Figure 6, it is clear that the entry impact is sufficiently reduced by the tip relief to prevent cratering in the tooth engagement area, while a practically constant profile form deviation of f_{fm} = 3.5 µm is measured over the entire test period. The WC/C-coated corrected test gearing displays a practically identical progression of measured profile form deviations.

Analyses in Accordance with the FZG Macropitting Test Method

The so-called FZG macropitting test is a short test to determine the macropitting resistance of a gear set (Ref. 7). It is a repeated single-stage test of deep fatigue strength. This test procedure is also carried out on the FZG back-to-back test rig (Ref. 4). The test gearing has the same gearing data as the test gearing for the micropitting test, but with less roughness (R_a = 0.2 . . . 0.4 µm).

One uncoated and one WC/C-coated variant of the modified FZG-C gearing is analyzed in conjunction with the reference and basic oils. The stress cycle limit in the standardized FZG macropitting test (Ref. 7) is specified as $40 \cdot 10^6$ stress cycles on the driving pinion. For improved differentiation of the test results, within the context of

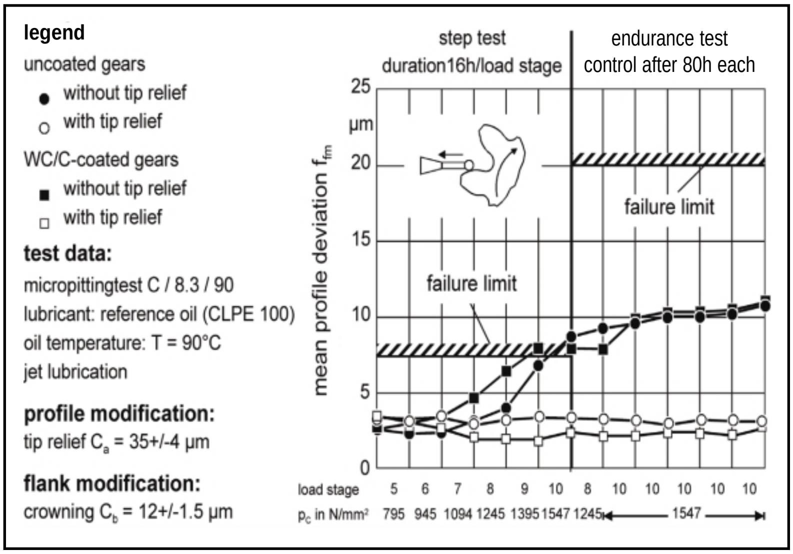

Figure 5—Mean profile form deviation measured at the unmodified and modified test pinions in the micropitting test.

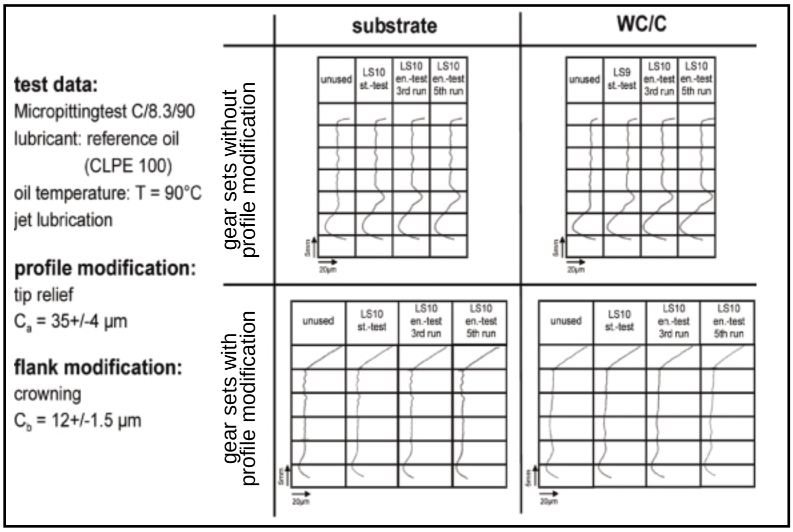

Figure 6—Profile measurement on unmodified and modified test pinions in the micropitting test.

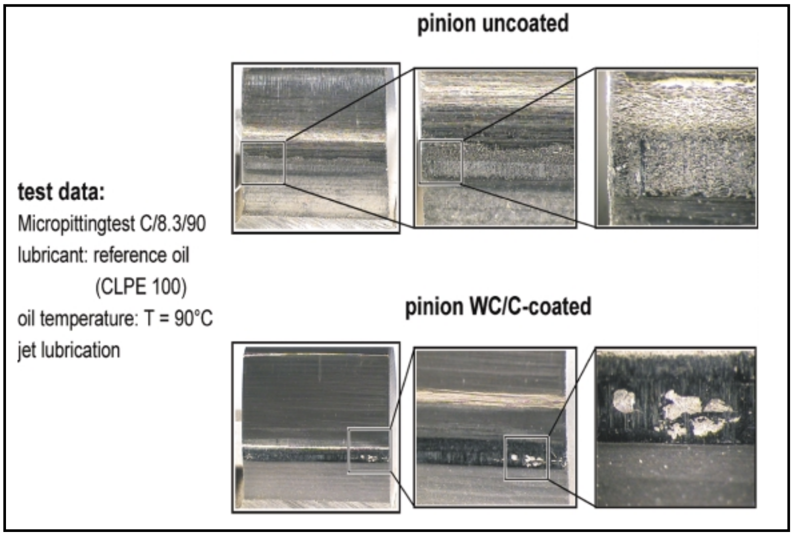

Figure 7—Photographs of the uncoated and WC/C-coated tooth flanks of the unmodified pinion after the end of the micropitting tests.

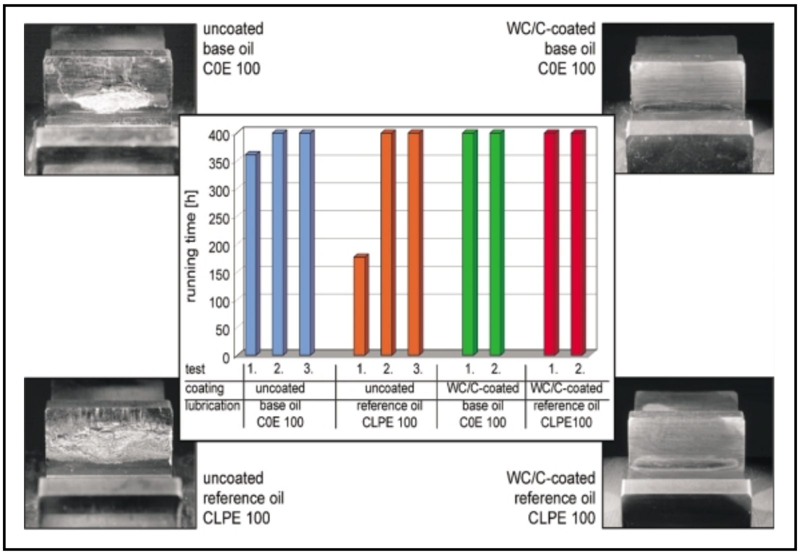

Figure 8—Run times in the macropitting test.

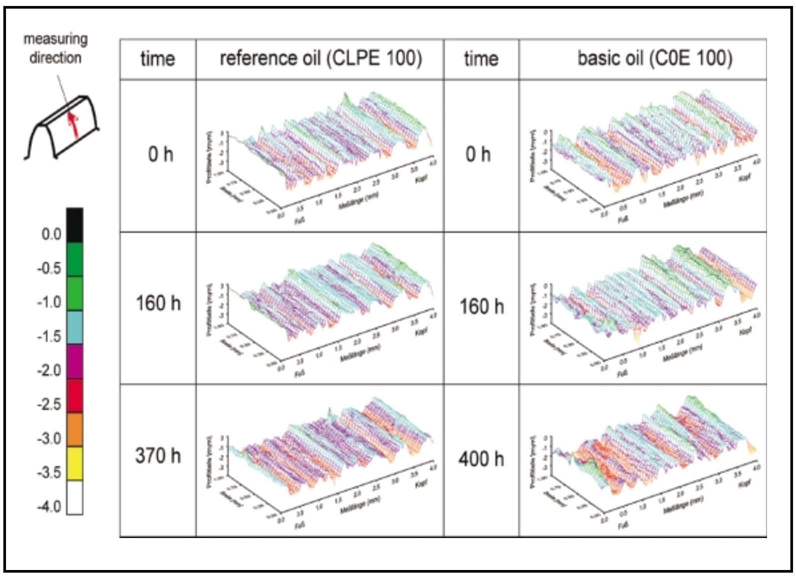

Figure 9—Surface structure of the uncoated pinions.

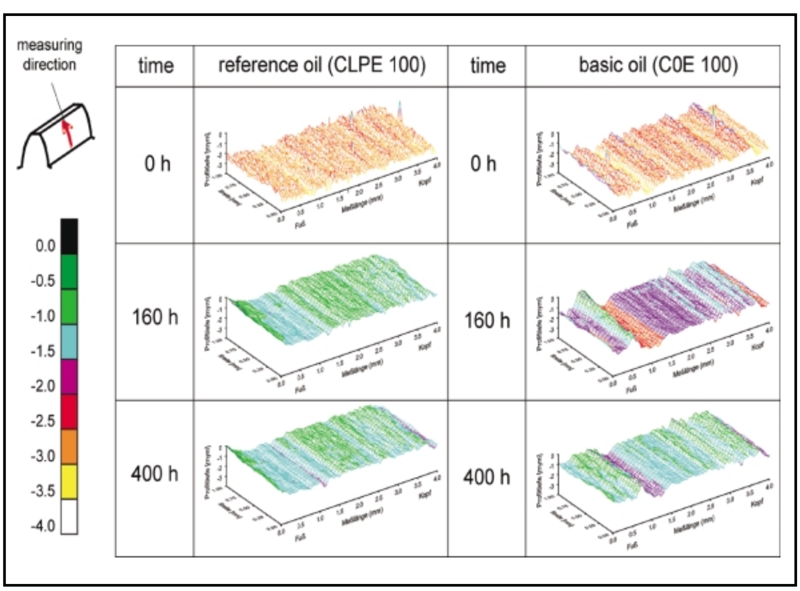

Figure 10—Surface structure of the WC/C-coated pinions.

this analysis, a stress cycle limit of $54 \cdot 10^6$ (test duration 400 hr.) is set. The results of the macropitting tests carried out on the test gearing are documented in Figure 8 on the basis of the run times achieved and in the form of photographs of tooth flanks at the end of the test.

It is essentially possible to determine that the natural macropitting resistance of the basic oil without additives is already so high that the test gearing in two out of three tests endured $50 \cdot 10^6$ stress cycles without macropitting damage. Taking into account the stress cycle limit of $40 \cdot 10^6$ stipulated in the test specification, all three test gear sets would be evaluated as fatigue-tested without damage.

The macropitting tests with the rapidly biodegradable synthetic ester with additives also produced two fatigue-tested specimens without damage in three tests. The flank photos in Figure 8 nevertheless also document that massive macropitting damage occurred in one each of the test sequences of the uncoated variants.

The results of the macropitting tests with WC/C-coated test gear sets are also shown in Figure 8. In this case, two tests were carried out respectively with the reference oil and with the basic oil. In those tests, the stress cycle limit without damage of $54 \cdot 10^6$ was achieved. This result therefore implies a positive influence of the WC/C coating on the tooth flank resistance and/or on the stress cycles endurable without damage.

In order to obtain additional information about the condition of the tooth flanks, as well as visually inspecting the tooth flanks of the test pinion, individual specimens were examined after preset run times with the aid of a contact stylus instrument and a device for measuring the 3-D surface roughness. Figures 9 and 10 show 3-D contact stylus measurements of uncoated and WC/C-coated pinions, respectively.

The measurements were carried out before the start of the macropitting test, after 160 hours of run-time and at the end of the test. The measurement process was designed to enable measurements to be carried out in the same area of the tooth flank in each case.

If we look at the surface structures of the uncoated pinions shown in Figure 9, we can observe grinding marks running in the direction of the tooth width resulting from the hard fine machining with Maag finish grinding. The initial roughness of the tooth flanks in the direction of the profile is approximately $R_z = 2.4$ µm. No obvious alteration of the surface structure of the tooth flanks during the test period can be observed on the gearing lubricated with reference oil nor on the uncoated test gearing lubricated with basic oil.

The measurements of the WC/C-coated pinions in Figure 10 show that the tooth flanks after coating—that is, before running—display an isotropic surface structure in which the grinding marks are no longer clearly discernible, although all test gear sets (uncoated and WC/C-coated) come from the same production batch. The cause is the microblasting treatment of the gearing. This treatment was carried out as standard by the coater before the coating.

As the run-time of the macropitting tests is increased, the WC/C-coated pinions display an evening of the surface roughness in the form of a significant reduction of the roughness peaks and troughs. This evening out of the surface roughness, which can also be observed in analyses of WC/C-coated rollers not shown here (Refs. 1–3 and 8), leads to an increase in the supporting area of the tooth flanks in comparison with their uncoated states and thereby to a reduction of the local loading on the tooth flank edge zone. This behavior of the coating, in combination with the low friction value of the coating, may be the cause of a positive influence on the macropitting resistance.

Random Tests on the Load-Bearing Capacity with Increased Run Time

In order to be able to gain a more precise indication of the macropitting resistance of WC/C-coated gearing in comparison to uncoated gearing, two random tests with increased run-time were carried out. The results are given below. One uncoated gear set and one WC/C-coated gear set were chosen for each random test. Both gear sets had been previously used in a micropitting test. These two gear sets had each undergone a full micropitting test with a run-time of 576 hours with identical load sequences and using the reference oil. In this initial state, both gear sets were subjected to a trial run under Hertzian compression at the pitch point normally used in the macropitting test of p_C = 1,659 N/mm^2.

Figure 11 shows the profile measurement recordings for the pinions at the start and the end of the first performed micropitting test. It is possible to see that only a minimal profile form deviation occurred during the progress of the micropitting test. The test gear sets were inspected at regular intervals throughout the macropitting test and after defined run times on a gear measurement rig.

In the case of the uncoated set of gears, massive macropitting damage occurred in the macropitting test after a run-time of 60 hours. Scuffing was also detected at the tip of the pinion tooth which had resulted, however, from meshing interference as a result of the large area of macropitting damage. A photo of a tooth flank is shown at the top of Figure 11. In comparison, the WC/C-coated test gearing was free from damage at the end of the macropitting test after 400 hours, as documented at the bottom of the figure on the basis of the recorded profile measurements and the flank photographs.

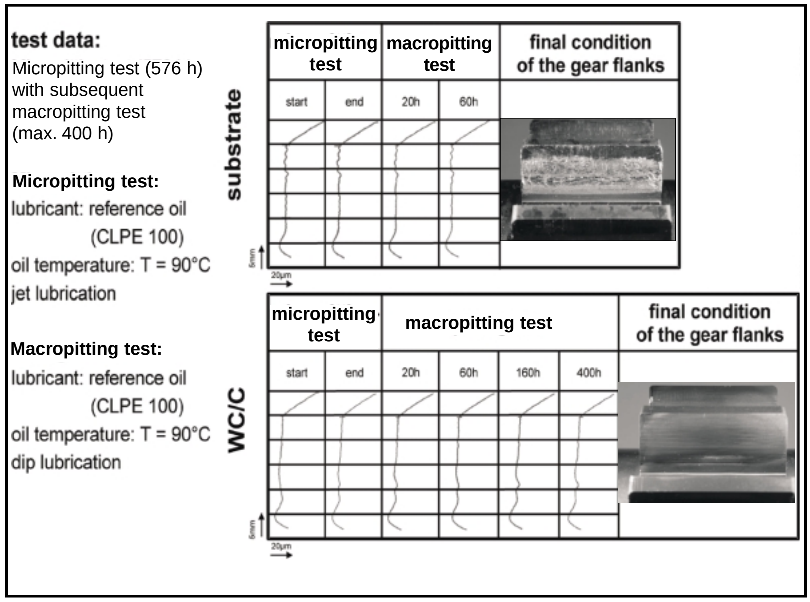

Figure 11—Profile tracings and flank photos of the pinions in the random test.

The result of this random test further clarifies the positive influence of a WC/C coating on macropitting resistance and endurable stress cycles.

Summary

This report documents the results of analyses of the amorphous metal-carbon coating WC/C applied by means of the PVD process in the tribological system of tooth flank contact. It presents test-bed analyses in which the use in operation of uncoated and WC/C-coated gear wheels were tested in combination with a rapidly biodegradable synthetic ester and its basic oil. As well as determining the load-bearing capacity of WC/C-coated gearing, investigations were also carried out to the extent that the wear protection functions of the surfactants contained in lubricants can be assumed by the coating.

The analyses with uncoated and WC/C-coated gear wheels in combination with synthetic ester and basic oil revealed a significant difference, particularly in the scuffing test, with regard to wear on the tooth flanks. Under the specified test conditions, approximately 2.5-fold less mass loss of pinion and gear was recorded in the case of the WC/C coating using base oil in comparison with the uncoated gears.

In the micropitting test, it was determined that there is no sign of the recognized damage form of micropitting in the case of the WC/C coating. At the same time, it is evident that comparable profile form deviations of uncoated and WC/C-coated test pinions occurs with unmodified test gearing.

In the macropitting tests, a clear increase in the stress cycles endured without damage was observed on the part of the WC/C-coated test gearing as opposed to the uncoated gearing. This resulted in particular from a significant evening out of the tooth flanks and from the low friction value of the coating. As a result, the supporting area of the tooth flank increases and the local load is lowered.

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