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TRIBOLOGICAL BEHAVIOUR OF TUNGSTEN-DOPED DLC COATED GEARS

Abstract

The development of new transmissions and gearboxes is characterized by increasing levels of torque and power, improved efficiency, increased life expectancy, prolonged service intervals, reduced amount of lubricant, and more stringent noise and environmental requirements. The environment, as a new factor in the design process, increases the focus on product improvements that are designed to avoid environmental problems before they occur. Surface coating is one of the future technologies for improving performance of case hardened gears.

A main limiting factor to extend the use of hard coatings to machine component application is the lack of knowledge how these inert coatings perform under lubricated conditions, using today's lubricants, originally designed for the steel/steel contact situations. The influence of ester based lubricant on scuffing capacity of WC-containing DLC coated spur gears was evaluated in a non-standard FZG test procedure. The properties of the formulated ester based lubricant were investigated in comparison with the conventional mineral gear oil. The results show that under present conditions W-DLC coated gears could provide satisfactory wear resistance for moderate loads.

1 Introduction

Generally, the gears for power transmission drives are lubricated with the lubricants based on petroleum derived base stocks. With the rapid advancement of gear design and manufacturing technology, gearboxes have become smaller, and output power has increased significantly. The net results are higher contact stresses, higher speeds and lower amounts of lubricant. With the decreased oil capacities, the lubricant must provide appropriate lubrication at higher operating temperatures, more effective cooling and suspension of contaminants. Therefore, selecting the high performance lubricants becomes more and more important. Moreover, there is also a clear trend to use lubricants that cause less harm to the environment.

The current view is that the depletion of scarce resources and the increasing environmentally pollution cannot continue in the same way for the next 50 years as they have in the past 50, without drastically affecting our quality of life. Use of environmentally adapted lubricants is one of the lubrication strategies to avoid environmental problems before they occur. Very good or even superior technical performance of some esters combined with very favorable ecological properties enable the formulation of high performance lubricants, with extremely low evaporation rates, very high viscosity index and good boundary lubrication characteristics.

Diesters, polyol and complex esters are biodegradable in the terms of one of the internationally recognized test methods, and they have low aquatic toxicity. Their advantage is also that they can be partly derived from the renewable resources, including vegetable oils and animal fats. From an ecological point of view, the prospects for using renewable raw materials are favorable, provided the full potential of natural synthesis by means of energy from the sun is used. The production of vegetable oils constitutes a cycle in which no net release of carbon dioxide occurs [1,2].

During recent years, significant progress has taken place in the development of advanced coatings used in tribology technology. The unique tribological properties of diamond-like carbon (DLC) films, such as low friction, high wear resistance and low deposition temperature, have made them very attractive for machine element applications. DLC films doped with metal (Me-C:H) have advantages over pure carbon coatings as internal stress is reduced and adhesion to steel substrates is improved. Beside tools and dies, diamond like and related coatings are starting to find application in some mechanical component applications, including bearings and gears. They provide a great opportunity to improve durability and to reduce frictional losses of machine components [3,4].

The present work attempts to combine the excellent friction properties of W-DLC coating with the established lubricating abilities of ester based lubricant for improving the gear performance. The modified FZG scuffing tests were carried out to investigate and compare the scuffing capacity of uncoated steel gears and W-DLC coated gears, lubricated with the conventional mineral gear oil and environmentally adapted ester based formulation.

2 Experimental

2.1 Test equipment

The gear tests were performed on an FZG back-to-back test rig. Test conditions were similar to the standard procedure for load carrying capacity of lubricants according to ISO DIS 14 635-1 [5].

The test oils were subjected to the load, increased through 12 load stages, defined in the above-mentioned standard. Duration of each load stage was 20 minutes (29,000 revolutions of the motor) at constant pinion shaft speed of 1,450 rpm. Starting bath oil temperature in each load stage was 50 °C and was allowed to rise freely during the test. As the duration of load stages was prolonged with regard to the standard A/8.3/90 test procedure, the total work transmitted by the test gears up to the end of load stage, was 25 percent higher. At the end of the last load stage, total work transmitted by the test gears was 184 kWh.

The gear teeth flanks were visually examined after each load stage for cumulative damage in particular scuffing marks and excessive wear. Also, test gears were weighted to the nearest milligram after every third load stage.

The method used for the quantitative evaluation of the wear particle concentration was a direct reading (DR) ferrography. Ferrography is a kind of oil analysis technology, which separates particles from the lubricant by magnetic force. By trending DR results the wear condition of lubrication system could be established. Additionally, wear particles from some oil samples were separated and prepared for microscopic examinations. The visual inspection of those particles by a bicromatic microscope could identify the abnormality of wear.

2.2 Test gears

Test gears used were standard FZG type “A” spur gears. The test gears have been designed with a large profile shift, which increases their sensitivity to adhesive wear modes of failure.

Uncoated test gears were made of DIN 20MnCr5 steel and case carburized. The surface hardness after tempering was 60 to 62 HRC and a case depth of 0.6 to 0.9 mm. The surface roughness was Ra=0.35 μm for the pinion and Ra=0.30 μm for the wheel.

The W-DLC coatings were deposited onto case carburized type “A” spur gears by using a magnetron sputter deposition process, at a substrate temperature of about 200°C. The microhardness was about 1,200 HV. The prim ary coating constituents included W, C and H, with Cr used as a thin adhesion layer (150 nm). The coating thickness of W-DLC layer was typically 1 μm at the root of the gear teeth and 2 μm at the tip.

2.3 Lubricants

The test lubricants were a complex ester formulation and a conventional mineral based ISO VG 68 gear oil. Physical properties of the test lubricants are summarized in Table 1. The saturated complex ester was composed of multifunctional synthetic alcohol, some petrochemical di-acids and some short chain (C8–C10) fatty acids from natural resources. The complex ester used as a base stock was nearly non-toxic for aquatic organisms and, according to the OECD 202 method, was classified as relatively harmless. Primary biodegradation in the CEC-L-33-A-93 test was 76.7 % and ultimate biodegradation in OECD 301F test was 62.2 %. The degradation results identify a material that can be rapidly and extensively biodegraded in the environment.

Esters are inherently good boundary lubricants. However, some performance additives are still necessary. The additive system selected was based upon ashless components with mild EP being provided by an organic phosphorous-based chemistry. The EP additive was an amine neutralised phosphoric acid ester, a common type of general purpose EP additive. The AW additive was a dialkyl ditiophosphate ester. Each additive was blended with the complex ester in the concentration of 1 % (wt).

Table 1: Properties of mineral oil and ester formulations

Property	Unit	Test method	Mineral	Ester
Density at 20 °C	kg/m³	ISO 12185	887	921
Viscosity @40 °C	mm²/s	ISO 3104	68	48
Viscosity @100 °C	mm²/s	ISO 3104	8.6	8.0
Viscosity index		ISO 2909	96	138

According to the producer, the reference petroleum-based oil is recommended for heavily loaded gearboxes with surface hardened tool metallurgies. The mineral oil's viscosity was made one ISO viscosity grade higher than that of the ester-based oil to compensate for the effect of viscosity index difference, thus achieving about the same viscosity for the oils at working temperature (see Tab. 1), which was roughly around 100 °C at higher loads.

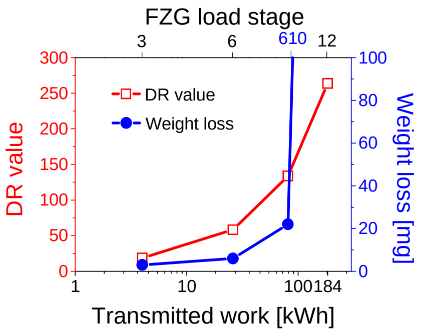
3 Results

The most informative method for plotting wear results was found to be cumulative plots of the test gears' weight loss and wear particle concentration on the same graph with the reference to the total work transmitted and FZG load stage.

The results of the scuffing investigations for steel test gears are presented in Fig. 1. It is evident that the scuffing load capacity of the ester formulation is higher compared to the mineral oil formulation. For the mineral oil the weight loss of test gears is within the acceptable limits until 140 kWh of total work transmitted was reached. At 184 kWh, the cumulative weight loss of pinion and gear equals 610 mg, and all pinion flanks were damaged. With the ester formulation, the test gear's weight loss is much lower. After the test, cumulative sum equals only 18 mg, and just a few scoring marks above the pitch line could be noted. The wear particle concentration results follow the gear's weight loss trend for both oils. The rate of wear particle concentration for the mineral oil gave rather high values, especially after the 6th load stage.

Use of the ester formulation resulted in higher weight loss, while the wear particle concentration was lower compared to the mineral oil formulation. For ester formulation, scuffing marks became visible after 8 kWh of work transmitted and started at the root and later at the tip of the pinion teeth. After 15 kWh, most pinion tooth flanks were tiny polished. The first breakthrough of the W-DLC coating was observed at the root of the pinion after 26 kWh of work transmitted.

Figure 1: Wear measurement results for uncoated steel gears: a) lubricated with the mineral oil formulation, b) lubricated with the ester formulation.



a)

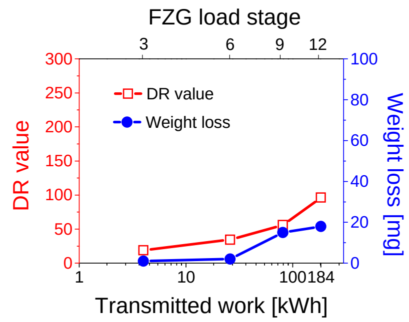


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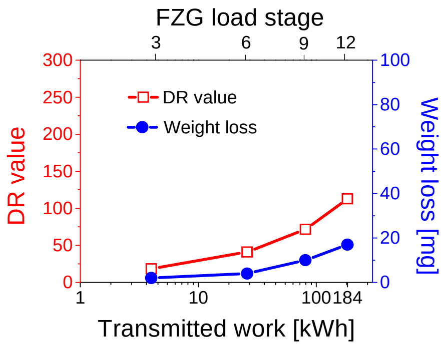
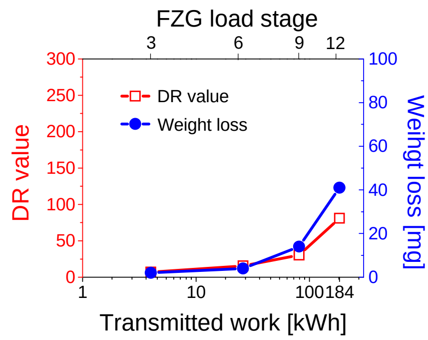
Figure 2: Wear measurements results for W-DLC coated gears: a) lubricated with the mineral oil formulation, b) lubricated with the ester formulation.



a)

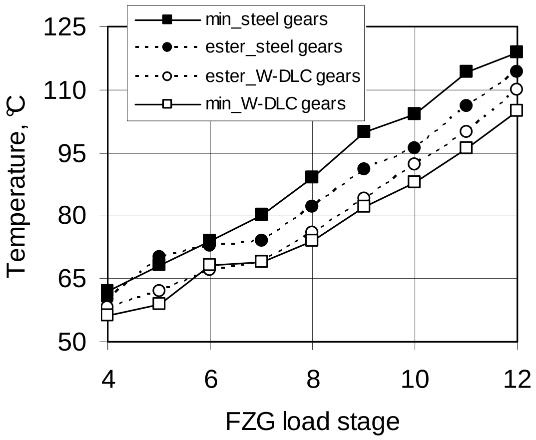


b)

For the mineral oil formulation, the coating breakthrough started at the same time after 26 kWh of work transmitted, but visible damage was more severe. Developing scoring damage was observed during the subsequent runs for both oils. After the the test, the pinion flanks were polished, and the W-DLC coating was totally worn out through at the root of the pinion. The wear results for W-DLC coated gears as presented in Fig. 2 and show a steady, progressive increase in the test gear's weight loss and wear particle concentration for both oils.

Figure 3 shows the increase of bath oil temperature at the end of each scuffing load stage for both oils with uncoated steel and W-DLC coated test gears. The temperature increases steadily with the applied load for the oil and material combinations. Tests with the W-DLC coated gears resulted in lower temperatures, suggesting the surface tooth flank material is stronger influence factor on temperature rise than lubricant used. The lowest oil bath temperature was found for the W-DLC coated gears lubricated with the mineral oil formulation.

Figure 3: Bath oil temperature after the completion of load stage.



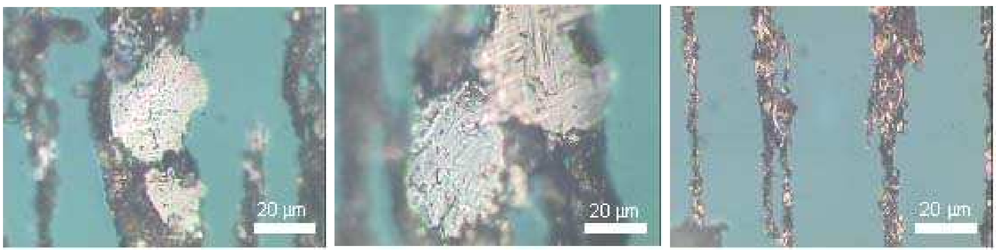
4 Discussion

Wear results for mineral oil formulation suggest that scuffing capacity is strongly influenced by the surface material of the test gears (see Figs. 1a and 2a). The mineral oil and steel gear test combination exhibited the highest wear. Visual inspection of the pinion tooth flanks indicates the failure in the 12th load stage after 184 kWh of work transmitted. On the other hand, the mineral oil in the combination with W-DLC coated gears resulted in significantly lower wear and passed the 12th load stage. In contrast, when using the ester formulation, wear results for steel and W-DLC coated gears are comparable and of lower magnitude.

Additional information about wear mode and mechanism could be obtained with the analytical wear particle analysis. Wear particles are the final product of surface damage, and their shape, morphology, size and concentration can give some information on the mode and the mechanism of wear. The wear particles are first fixed to a glass slide and then analyzed under an optical microscope.

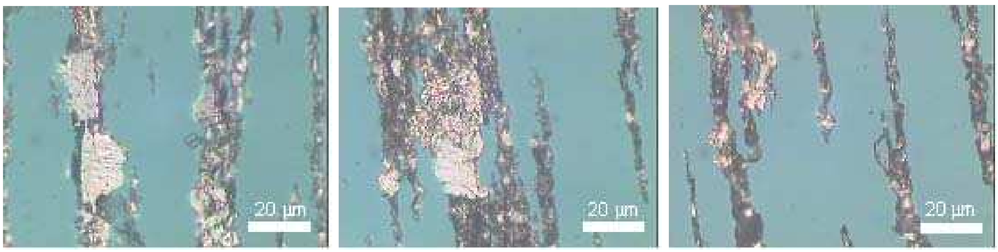
Figure 4 displays the particles separated from the mineral oil formulation, and Fig. 5 displays the particles separated from the ester formulation after 146 kWh total work transmitted, which is equivalent to the 11th test run in the modified FZG test procedure. Figures 4a, 4b, 5a, and 5b present typical wear particles from the entry region of the glass substrate. Particles at this location are typically the largest particles separated from the oil because the magnetic force, which attracts the particles, is proportional to the volume, whereas the viscous resistance of the particles to motion in the fluid is proportional to surface area. Comparing the photos, it is evident that wear particles obtained from the tests with W-DLC coated gears are larger than wear particles from the lubricants tested with uncoated steel gears. It can also be observed that wear particles from mineral oil are larger than particles from the ester formulation for both gear tooth flank materials.

Figure 4: Entry region of the glass slide made from the mineral oil, magnified 500 times. a) uncoated steel gears; b) W-DLC coated gears; c) W-DLC coated gears – the largest cutting wear particles



a) b) c)

Figure 5: Entry region of the glass slide made from the ester formulation, magnified 500 times. a) uncoated steel gears; b) W-DLC coated gears; c) W-DLC coated gears – the largest cutting wear particles



a) b) c)

The larger size of the wear particles separated from the mineral oil formulation for steel gears is expected because the coefficient of friction for ester-based lubricants and steel contact surfaces is typically lower [6,7]. The lower bath oil temperature (see Fig.3) also indicates the lower coefficient of friction for the ester formulation.

Even though the particles found in different gear material combinations discussed above are of different sizes and compositions, most of them are flat flakes having irregular shapes and generally featureless surfaces without characteristic striations indicating severe wear. In fact, this is the morphology observed for the majority of wear particles larger than 15 μm. This implies that the particles were all produced by the same wear mechanism. However, wear particles produced by the interaction of two component surfaces, such as gear teeth, are subjected to continuous high contact pressures and would therefore have a strong tendency to be flattened and smoothed by the forces acting on them. This process would account for the typical particle morphology observed and suggests considerable alternation to wear particle morphology occurs after the particles are produced.

Another characteristic group observed is cutting wear particles, presented in Fig. 4c and Fig. 5c. Cutting or abrasive wear particles are produced by the penetration, ploughing or cutting of one surface by another. They take the form of miniature spirals, loops and bents. Their presence is abnormal. These types of particles are found only on the glass slides from the tests with the W-DLC coated gears. They are not found on slides made from lubricants obtained from the tests with steel gears. Also distinctive are very large flat particles obtained from test with the mineral oil formulation and W-DLC coated gears. Figure 6 shows the largest particles separated from the oil. They ranged from 70–125 μm in major dimension, indicating a severe wear mode.

Figure 6: Glass slide made with the mineral oil from the test with the W-DLC coated gears, after 146 kWh work transmitted, magnified 500 times a) large particles; b) the largest particle; and c) the largest particle, magnified 100 times.

a) b) c)

Very large wear particles and the presence of abrasive particles indicate the wear mechanism for uncoated and W-DLC coated gears is different. For the W-DLC coated gears, the wear probably started under the surface, while the prevailing wear mechanism for the uncoated gears is adhesive wear that started from the surface.

5 Conclusions

The following conclusions can be derived from this study:

- In tests with steel gears, the ester-based formulation resulted in higher scuffing load capacity than the mineral oil formulation.
- The scuffing performance of the mineral oil and W-DLC coated gears is significantly improved compared with the steel gears. However, some particles exciding 100 μm in the major dimension indicate a severe wear mode. With the ester-based formulation, the wear rates for steel and W-DLC coated gears are similar.
- The surface tooth flank material is a stronger influence factor on temperature rise than the lubricant used.
- The wear mechanism for uncoated and W-DLC coated gears is different.

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UDK	ključne riječi	key words
539.375.6	trošenje zupčanika, FZG test	FZG gear wear test
621.385.6	prevlačenje magnetronskim rapršivanjem u vakumu	coating by magnetron sputter deposition
546.78	volfram (W)	tungsten (W)
546.78 : 546.26-162	prevlaka volframom i ugljikom dijamantne strukture	tungsten and diamond like carbon coating
621.892.2	mazivo ulje, mineralne osnove	mineral base oil
621.892.28	mazivo ulje, sintetske osnove	sinthetic base oil

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