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Scuffing resistance of DLC-coated gears lubricated with ecological oil

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Abstract. This research was aimed to the elaboration of a new technology for heavy-loaded machine elements, lubricated with ecological oils without or with very limited amount of usually harmful AW/EP additives used in gear oils. The main objective of the study was the investigation of the effect of DLC coatings on scuffing resistance of coated gears. Three kinds of DLC coatings were tested: a-C:H:W, a-C:Cr and a-C:H. The gear tests were preformed using FZG A/8.3/90 method, employing the T-12U gear testing rig. The gears were lubricated with eco-oil. For the a-C:H:W coated gears, lubricated with ecological oil, the oil temperature was lower by 20 °C, and the friction was lowered by 20% compared with uncoated steel gears, lubricated with high-performance GL-5 gear oil. Thus it has been shown here that under extreme pressure conditions low friction coatings can take over the functions of AW/EP additives and make it possible to use ecological oils for lubrication.

Key words: DLC coatings, gear test rig, scuffing, ecolubricants.

1. INTRODUCTION

In practice most of heavy-loaded machine components, like gears, are made of steel. These heavy-loaded machine components are mainly subjected to two kinds of severe wear: scuffing and pitting. To protect them against severe wear they are lubricated with high-performance oils. Unfortunately, such oils contain additives, usually anti-wear (AW) and extreme pressure (EP), that are in most cases very harmful for environment.

In this situation the main candidate for environmentally friendly lubricants are oils without toxic extreme-pressure and anti-wear additives. The crucial aspect in environmentally friendly lubricants is their effective lubricating action under extreme pressure conditions. If in the steel–steel tribosystem the lubricating oil does not contain lubricating additives, there is no protection against severe wear.

The application of lubricants without environmentally hazardous additives will be possible if the function of lubricating additives is taken over by thin, hard coatings, deposited on sliding elements. The protection of rubbing surfaces can be achieved by applying a thin coating with low chemical affinity to the steel partner, giving a reduction in the tendency of adhesive bonds creation. In this situation active additives, being toxic from their nature, do not have any significance, and may be removed from the lubricant without a risk of a radical increase in wear [1,2].

The future technologies for heavy-loaded steel parts are thin hard coatings, especially the so-called low-friction coatings. The coatings containing carbon exhibit unique properties, which depend on the deposition method, hydrogen content and doped elements [3]. Surface coating technology has been significantly improved in the last years, allowing higher loads and higher protection of surfaces by DLC coatings [4–6]. The application on gears is still in an exploratory stage [7–10]. In gears, DLC coatings can increase the scuffing resistance, decrease wear intensity and the oil temperature [11,12].

Today the expansion of knowledge on factors, affecting the possible synergetic action between the lubricant and coating, is crucial [13–15]. It is obvious that none of the coatings used today are known to interact chemically with lubricants or their additives in the way metals do.

In the near future, surface coatings will probably contribute to the reduction or elimination of non-biodegradable and toxic lubricant additives and promote the use of environmentally friendly lubricants [16–17].

2. TESTED COATINGS

DLC coatings basically consist of a mixture of the diamond (sp^3) and graphite (sp^2). The relative amounts of these two phases will determine much of the coatings properties. Three various types of DLC coatings (a-C:H:W, a-C:H and a-C:Cr) were used for investigation. The coatings properties are summarized in Table 1.

The a-C:H:W coating is of the DLC type, representing the a-C:H:Me group. The a-C:H:W coating was deposited by the PVD (Physical Vapour Deposition) method with reactive magnetron sputtering [18]. The a-C:H:W coating consists of an elemental Cr adhesion layer adjacent to the steel substrate, followed by an

Table 1. The characteristics of investigated coatings

Coating	Interlayer	Thickness, μm	Nanohardness, GPa	Roughness R_a, μm	Critical load (scratchtest), N
a-C:H:W	Cr, WC	2.0	10.8	0.093	100
a-C:Cr	Cr, C/Cr	2.5	17.9	0.030	90
a-C:H	Cr, CrC	1.6	14.5	0.037	90

intermediate transition region consisting of alternating lamellae of Cr and WC, and an outermost W, containing a carbon (a-C:H:W) layer.

The a-C:Cr coating is a hydrogen-free carbon–chromium multilayer coating, with dominating sp^2 structure, deposited by Closed Field Unbalanced Magnetron Sputter Ion Plating (CFUBMSIP) from carbon and chromium targets [19].

The a-C:H coating is deposited on Cr and CrC layers. The coating contains some amount of Cr in the DLC layer. It is a hydrogenated carbon coating, with dominating sp^3 structure, deposited by Plasma-Enhanced Chemical Vapour Deposition (PECVD) from a hydrocarbon precursor gas [19]. The a-C:H coating is deposited on the Cr layer. The amount of hydrogen is bigger than in the a-C:Cr coating.

3. GEAR TEST METHOD

The load-carrying capacity of coated gears was examined using T-12U Back-to-Back Gear Test Rig, employing test conditions according to standards DIN 51 354 [20] and IP 334 [21], procedure A/8,3/90. The test gears were made of case-hardened 20MnCr5 steel. The surface hardness after tempering was 60 to 62 HRC, roughness $R_a = 0.3$ to 0.7 μm. The surface was Maag–Cross hatch ground. In gear tests both gears were coated.

The test gear was lubricated with an eco-oil. The eco-oil is fully formulated vegetable-based, environmentally friendly oil without classical AW/EP additives used for steel couples. This oil has been developed at ITeE-PIB. As a reference commercial automotive gear oil of API GL-5 performance level was used.

4. RESULTS AND DISCUSSION

The gear rig tests were performed for three kinds of DLC coated gears and for uncoated gears. The gears were lubricated with the eco-oil. The failure load stage (FLS) for the tested materials are presented in Fig. 1.

For uncoated gears, lubricated with the GL-5 oil, maximum 12th stage was achieved without scuffing, but for the eco-oil only the 10th failure load stage was achieved. The application of coatings a-C:H:W or a-C:H increased the FLS. They passed maximum 12th stage without scuffing. Only a-C:Cr coating did not improve the scuffing resistance of the tested gears.

The failure load stage, obtained for a-C:H:W and a-C:H coated test gears, lubricated by the eco-oil without any AW/EP additives, is the same as obtained with commercial gear oils, containing toxic AW/EP additives (GL-5 oil).

Apart from wear assessment at various load stages, additionally motor load (measured indirectly as a percentage of rated current) and oil temperature was measured. The results of temperature measurements at loads from 8th up to 12th stages are presented in Fig. 2.

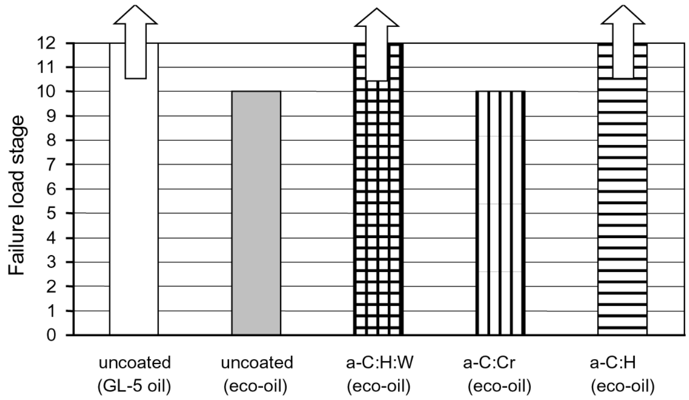

Fig. 1. Failure load stages for uncoated steel gears, lubricated with eco-oil and GL-5 oil and for teeth, coated with DLC coatings, lubricated with eco-oil (A/8.3/90 method).

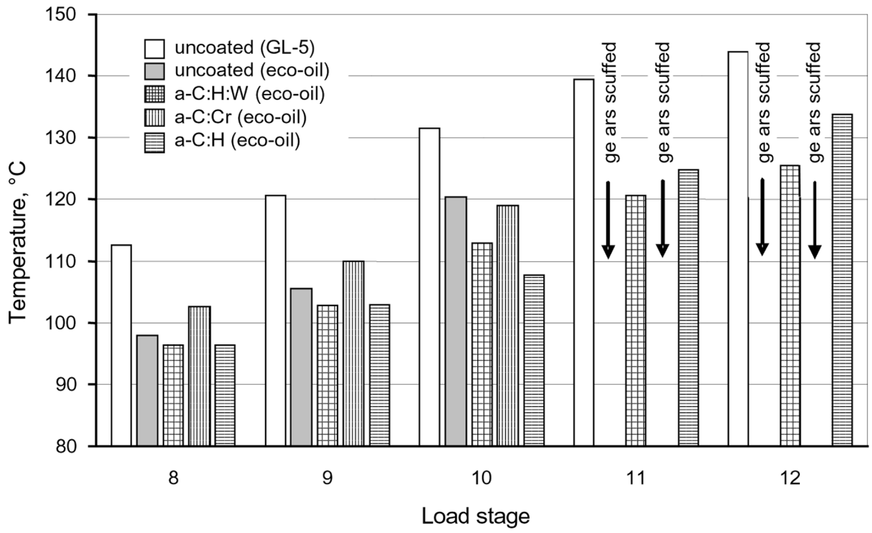

Fig. 2. The oil temperature in the test gear chamber for uncoated steel gears, lubricated with eco-oil and GL-5 oil and for teeth, coated with DLC coatings, lubricated with eco-oil (A/8.3/90 method).

Increasing the gear temperature is connected with energy dissipation. For gears, coated with a-C:H:W at 12th load stage, lower temperature was achieved than for a-C:H coated gears. For the a-C:H:W coated gears, lubricated with eco-oil, the oil temperature was lowered by 20 °C compared with uncoated steel gears, lubricated with high-performance GL-5 gear oil.

The results of motor load measurements, calculated as a percentage of the rated current [% J], at loads from 8th up to 12th grade are presented in Fig. 3.

The motor load at the highest stages (11th and 12th) was lower for a-C:H:W than for a-C:H. For the a-C:H:W coated gears, lubricated with ecological oil, the

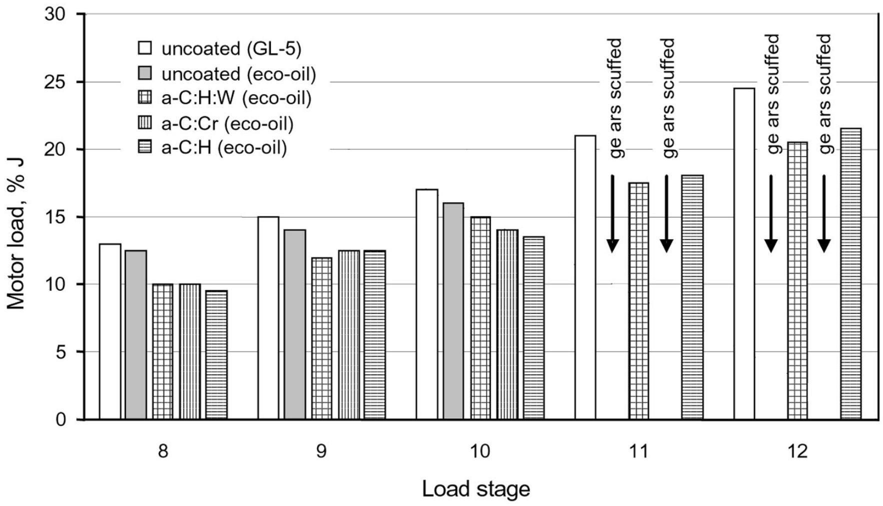

Fig. 3. Motor load for the T-12U gear rig for uncoated steel gears, lubricated with eco-oil and GL-5 oil and for teeth, coated with DLC coatings lubricated with eco-oil (A/8.3/90 method).

friction (measured as a power loss) was lowered by 20% compared with uncoated steel gears, lubricated with high performance GL-5 gear oil. The a-C:Cr coating is completely scuffed at the 10th load stage. For a-C:H:W and a-C:H coated teeth the scuffing did not occur. Regardless of the high hardness, the a-C:H:W coatings during the wear process are polished and become smoother.

5. CONCLUSIONS

The beneficial influence of the presence of a-C:H:W coatings on scuffing prevention implies a possibility for their application with heavy-loaded machine components. The results indicate that under extreme-pressure conditions DLC coating can take over the functions of AW/EP additives and through this it is possible to minimize the application of toxic lubricating additives and achieve "ecological lubrication".

Additionally, for the a-C:H:W coated gears, lubricated with ecological oil, the oil temperature was lowered by 20 °C, and the friction was lowered by 20% compared with uncoated steel gears, lubricated with high performance GL-5 gear oil.

Thus manufacturing heavy-loaded machine components of steel, covered with low-friction coatings, makes it possible to use environmentally friendly oils. This will reduce pollution of the environment.

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Teemandilaadse süsinikpindega (DLC) kaetud hammasrataste sööbekulumiskindlus ökoloogilise määrde kasutamisel

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Uuringu eesmärgiks oli uuete lahenduste väljatöötamine raskkoormatud masinaosade hõõrdkulumise probleemide lahendamiseks, kasutades määrdeainena väiksema saastemõjuga õlisid, mis ei sisalda või sisaldavad minimaalses koguses kahjulikke kulumisvastaseid ja ülisuurtel koormustel aktiveeruvaid (AW/EP) manuseid. Uudse lahendusena oli välja pakutud käigukasti hammasrataste katmine teemandilaadse süsinikpindega (DLC). Katsed viidi läbi kolme tüüpi pinnetega: a-C:H:W, a-C:Cr ja a-C:H. Pindade triboomaduste määramiseks viidi läbi katsed pinnatud hammasratastega, kasutades FZG A/8,3/90- (standard DIN ISO 14635-1:2000) meetodit ja katseseadet T-12U. Leiti, et a-C:H:W-pindega kaetud ja kahjulikke määrdemanuseid mittesisaldava õliga määritud hammasrataste kulumiskindlus on samaväärne tulemusega, mis saavutatakse parimate API GL-5-tüüpi sünteetiliste õlidega. Lisaks leiti, et antud pinde kasutamine võimaldab umbes 20% alandada hõõrdekadusid (mõõdetud katsetusmasina ajami tarbitud võimsuse baasil) ja vähendada tribokontaktides tekkivat soojushulka. Demonstreeriti, et triboloogilistes rakendustes, mida iseloomustavad suured erisurved, on võimalik kasutada DLC-pindeid kombinatsioonis kahjulikke määrdemanuseid mittesisaldava õliga, vähendades keskkonnakahjulike määrdemanuste kasutamist.