On the effect of DLC coating on full film EHL friction

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1. Introduction

The performance of machine components working under the Elasto Hydrodynamic Lubrication (EHL) regime is governed by several factors such as load conditions, speed, slide to roll ratio (SRR), temperature, surface roughness and lubricant properties. Increasing demands on improved efficiency, sustainability and longer service life have led to improvements in lubrication technology and surface finishing techniques as well as geometrical changes to components to improve the performance. In the last decades tribological coatings have been more frequently used to improve the performance of machine components. Some machine components like journal bearings are mainly operating in the full film regime, while other components like rolling contact bearings, gears and cam followers are operating in a range from boundary or mixed to full film EHL. The tribological coatings have shown improvements in several areas such as running in performance, increased wear resistance and reduced friction.

Diamond like carbon (DLC) coatings are the subject of many studies since they possess properties such as low friction characteristic, high wear and corrosion resistance, chemical inertness, thermal stability, as well as high hardness and high elastic modulus. While most studies in literature focus on the wear and friction behavior of DLC coatings in boundary lubrication and pure sliding contacts, few studies can be found concerning rolling and sliding EHL friction, especially in the mixed and full film regime. Renodeau *et al.* used a mini traction machine (MTM) to test discs coated with four different commercially available DLC coatings against a steel ball with four different lubricants under rolling and sliding conditions [1]. The entrainment speed used in the tests was adjusted to simulate mixed lubrication. Friction and wear measurements for the four different coatings showed dissimilar results, some combinations showed lower friction and wear compared to the steel-steel system while some combinations showed higher friction and wear. Topolovec-Miklozic *et al.* also performed tests in a MTM where the focus was the effect on boundary friction on two different DLC coatings with several types of additives [2]. They used two commercially available DLC coatings, one hydrogenated diamond like and the other Cr-doped, non-hydrogenated and graphitic. The study reported lower friction coefficients for the coated specimens in both boundary and mixed lubrication. It is however not clear if the friction reduction in the mixed lubrication regime was only due to asperity interactions or if there also was a beneficial effect of the coatings on the hydrodynamic part of the total friction. Evans *et al.* performed tests in a WAM (Wedeven Associates Machine) tribotester where discs with three different coatings were compared to an uncoated disc [3]. All discs were run against an uncoated steel ball. One of the tested coatings was a silicon incorporated diamond like carbon (Si-DLC). At lower entrainment speeds where the asperity interactions between the mating surfaces are large the Si-DLC showed lower friction than the uncoated surface. At higher entrainment speeds where full film lubrication was assumed the Si-DLC also showed lower friction coefficients than the uncoated surface even though there was no contact between the surfaces. The reason for this was hypothesized to be due to boundary slip between smooth, non-wetting surfaces as addressed by Choo *et al.* [4]. An interfacial slip would lead to lower shear stresses and thus lower friction in the EHL contact. In the work presented by Evans *et al.* low surface energy is correlated with low friction as the Si-DLC coating has lower surface energy compared to the steel-steel reference. Another possible explanation of the full film friction reducing properties of DLC is thermal insulation and was proposed by the present authors [5].

In this work the frictional behavior of two different DLC coatings were studied under full film lubricating conditions in a WAM tribotester. In addition, tests were performed with one additional lubricant to investigate the lubricants role in the friction reduction. The tests were conducted using two different contact pressures, and a wide range of SRRs.

2. Method

In the following section a description of the ball on disc test rig is given together with test specimens, lubricants and coatings. A description of the test procedure is also given.

2.1. Ball on disc tribotester

A WAM ball on disc tribotester was used to perform the experiments. The lubricant is supplied at the center of the disc, and a lubricant dispenser ensures an even oil distribution onto the disc surface. The lubricant is circulated in a closed loop from the oil reservoir, through a hose pump to the lubricant dispenser at the center of the disc. A flow of approximately 140 ml/min is supplied by the hose pump. The test setup utilizes three thermo couples, one located in the lubricant reservoir, one in the outlet to the lubricant dispenser, and one trailing in the lubricant film close to the inlet region of the ball on disc contact. A more in depth view of the test rig and its features is presented in previous work [6].

2.2. Test specimens and lubricants

All specimens used in the experiments, both balls and discs were made from AISI 52100 bearing steel. The balls are grade 5 with a 13/16 inch (20.637 mm) outer diameter and a hardness of about 60 HRC. The discs have a 4 inch (101.6 mm) outer diameter and are trough hardened to about 60 HRC. Two different commercially available DLC coatings were used in the investigation, Tribobond 43 and Tribobond 44. Tribobond 44 is an a-C:Cr coating deposited using reactive PVD processes with a deposition temperature of 200ºC. Tribobond 43 is a hydrogenated amorphous carbon (Cr+) a-C:H applied through Plasma Assisted Chemical Vapor Deposition (PACVD). The thicknesses of the coatings were measured with calotest to 2 and 2.8 μm respectively. Tribobond 43 has a hardness of more than 2500 $HV_{0.05}$, while Tribobond 44 has a hardness of 1500 $HV_{0.05}$.

The experiments were conducted using two different lubricants. Squalane, a commercially available low molecular weight branched alkane (2, 6, 10, 15, 19, 23-hexamethyltetracosane) and a pure mineral base oil (SL326). The ambient viscosity of Squalane is 15 mPas, and 95 mPas for Sl326. The pressure viscosity coefficients are in the range of 18-19 GPa^{-1} for both lubricants. Lubricants without additives were chosen to minimize the effect of possible tribochemical reactions on the friction coefficient.

2.3. Test procedure

The WAM tribotester was used to generate friction data from a broad range of operating conditions. The friction tests were performed with several contact pressures, entrainment speeds, slide to roll ratios, lubricants and coatings. A summary of the tested cases is presented in Table 1. For each test case there was also a reference test made under the same conditions, but with no coating on the steel surfaces. In all cases with coated surfaces both ball and disc are both coated with the same coating. The authors have investigated the effect on friction when only coating one, or both surface with DLC in previous work [5]. The entrainment speed is the mean surface velocity of the two bodies that drags lubricant into the contact. SRR is defined as the speed difference divided by the mean entrainment speed. All tests were performed with positive sliding, which means that the ball was rotating faster than the disc. Both specimens were cleaned with heptane and ethyl alcohol before starting the experiments for each of the test cases. The tribotester and specimens were warmed up to the desired operating temperature (40ºC) for approximately 60 minutes with lubricant circulated over both ball and disc to ensure temperature stability. When thermal stability was reached a load corresponding to the desired contact pressure was applied and the machine calibrated for pure rolling by adjusting spindle angle and positioning of the ball to ensure a condition of no, or negligible sliding. Subsequently the test cycle was started where the entrainment speed of 6.144 m/s is held constant and the SRR is varied from 0.0002 to 1.05. Each test case was performed seven times to ensure repeatability. During the test the temperature is typically deviating less than ±1.5ºC. The actual contact temperatures are however higher due to frictional heat generation and will be discussed in more detail.

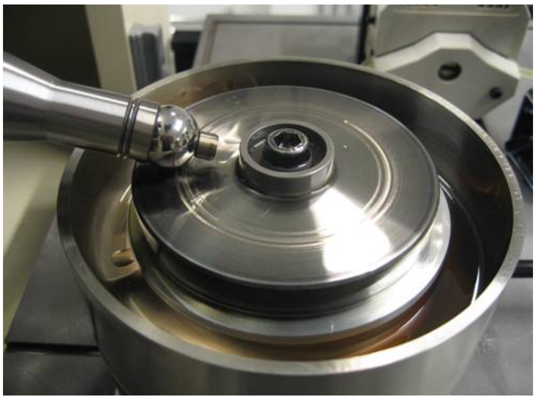

Figure 1 WAM Ball on disc device

Table 1 – Test conditions

#	Coating	Lubricant	Pressure [GPa]	SRR	Speed [m/s]
1	-	SL326	1.25 and 1.94	0.0002-1.05	6.144
2	-	Squalane	1.25 and 1.94	0.0002-1.05	6.144
3	Tribobond 44	SL326	1.25 and 1.94	0.0002-1.05	6.144
4	Tribobond 43	Squalane	1.25 and 1.94	0.0002-1.05	6.144
5	Tribobond 43	SL326	1.25 and 1.94	0.0002-1.05	6.144

3. Results and discussion

The results from the experiments can be seen in Figs. 1-3. Figure 1 includes the measurements from experiments 1, 3 and 5. Here two different DLC coatings are compared in terms of friction coefficients to uncoated steel at two different pressures using the SL326 mineral oil. All tests were performed at an entrainment speed of 6.144 m/s to ensure full film lubrication conditions. It is evident that the DLC coatings provided lower friction coefficients than the uncoated steel at both pressure levels. The biggest reduction was measured with the Tribobond 43 coating at both pressures. The reduction in friction with the Tribobond 43 coating at the higher pressure is so large that it at the highest slide to roll ratios provides lower coefficients of friction than both the uncoated and Tribobond 44 coated surfaces at the lower pressure.

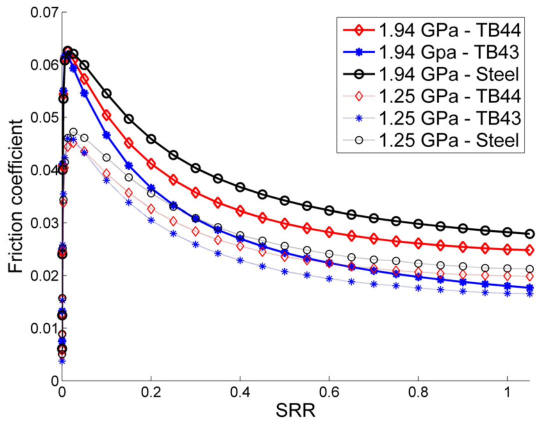

Figure 2 Friction coefficient versus SRR for Tribobond 44, Tribobond 43 and uncoated steel with SL326 at 6.144 m/s entrainment speed.

Figs. 3 and 4 include the results from the investigation of friction reduction with DLC coatings in combination with different lubricants, case 1, 2, 4 and 5 in Table 1. They were all performed with Tribobond 43, and with uncoated steel as a reference. The tests were performed with both lubricants, SL326 and Squalane. The measurements show that the friction reduction when using Tribobond 43 coated surfaces were greater with Squalane compared to SL326 at both pressures.

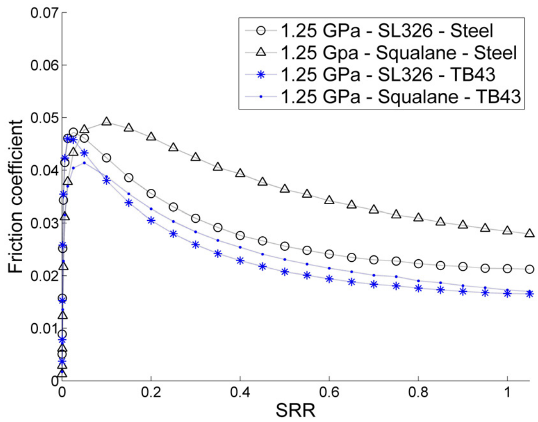

Figure 3 Friction coefficient versus SRR for Tribobond 43 and uncoated steel with Squalane and SL326 at 6.144 m/s entrainment speed and 1.25 GPa maximum Hertzian contact pressure.

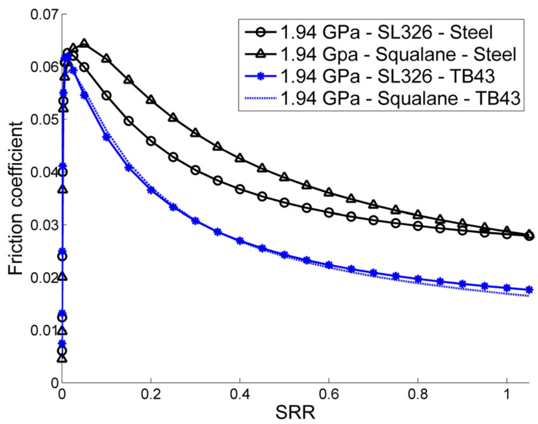

Figure 4 Friction coefficient versus SRR for Tribobond 43 and uncoated steel with Squalane and SL326 at 6.144 m/s entrainment speed and 1.94 GPa maximum Hertzian contact pressure.

4. Discussion

By looking at the results (Figs. 2-4) it is obvious that the DLC coatings reduces the contact friction coefficient even in the full film regime where there is no contact between the two surfaces and all load is carried by the lubricant film. It can also be seen that the friction coefficients increase with pressure, which is not surprising considering the increase of viscosity and limiting shear stress with pressure. In all cases the friction curves follow the trend by a linear, steep increase in friction at low SRR's to level of in a non-linear increase until a limiting value is reached. When sliding is increased from the limiting value the coefficient of friction is starting to decrease with increased sliding as more heat is generated in the contact and thermal effects starts to dominate the friction behavior.

As mentioned in the introduction some authors have explained the reduction in friction coefficient in the full film region when using DLC coated surfaces with boundary slip effects [4, 7, 8]. Slip at the boundary would lead to lower shear stresses and thus lower friction in the EHL contact. However, it has also been observed that for boundary slip to take place, two factors must be fulfilled. First of all it has to be non- or partial wetting between the solid surface and the lubricant. In addition, the surfaces must be very smooth, generally below 6 nm RMS [4, 9, 10, 11]. In a previous study made by the current authors, friction reducing effects by using DLC coatings in the full film EHL regime was shown even with surfaces with a combined RMS roughness in the range of 155-355 nm [5]. It was therefore concluded that the observed friction reduction most likely was not an effect of boundary slip, but more likely caused by some other effect, possibly in combination with boundary slip. The authors proposed that the friction reduction could be a result of thermal insulation as a result of low thermal conductivity (in the range of 1-3 W/m·K) observed for some DLC coatings [12-14]. A one dimensional numerical model was developed where the temperature increase in the oil film was calculated for coated and uncoated cases at several operating conditions. The result showed significant higher temperatures in the oil film for the case when one, or even more so, when two of the surfaces were coated with DLC. Such an increase in temperature would have a negligible impact on the film thickness, since the film thickness is governed by the viscosity in the inlet of the contact which is not very much influenced by the temperature increase inside of the contact. The temperature increase inside the contact would however have a much larger effect on the friction coefficient, since the viscosity and limiting shear stress will be reduced. It is therefore likely to believe that the difference in friction reduction between the two tested DLC coatings shown in Figure 2 are due to different thermal properties of the coatings. The coating Tribobond 44 which had the lowest friction reduction of the two were also the thinnest, that would also reduce the insulating effect even if they had the same properties.

The potential for friction reduction with DLC coatings is greatly influenced by the lubricant used as indicated in Figs. 3-4. Under these conditions the tests performed with the lubricant squalane had a much larger friction reduction with the DLC coating compared to the SL326 mineral oil. The main difference between the two lubricants is their viscosities, where squalane has a much lower viscosity (15 versus 95 mPa·s), and will thus build thinner lubricant films. Assuming that the DLC coating will act as an insulating layer will have greater influence if the film is thinner since more heat generated in the contact will be transferred to the surfaces compared to a case with thicker film.

5. In conclusion

DLC coatings are shown to reduce the contact friction coefficient in full film lubricated EHL contacts. Two different commercially available DLC coatings were tested that performed different levels of friction reduction. The authors believe that the thermal insulation of the DLC coatings is the main reason for the friction reduction. One of the DLC coatings was tested with two different lubricants that showed different levels of friction reduction. The difference in friction coefficient between the two lubricants is most likely an effect of different film thicknesses on the heat transfer in the lubricant contact. The friction reduction potential is greater for thinner lubricant films since more of the heat generated in the contact will reach the surfaces.

6. Acknowledgement

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