42nd Leeds-Lyon Symposium on TRIBOLOGY

LaMCoS

SEPTEMBER 7-9, 2015

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MEASUREMENT AND MODELLING OF CONTACT STIFFNESS FOR ROUGH CONTACTS

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ABSTRACT

It is now nearly 50 years since Greenwood and Williamson's ground-breaking paper on the contact of rough surfaces [1]. It is also over 30 years since the lead author of the current article first became interested in rough contact through undertaking his final year undergraduate project under Jim Greenwood's supervision. It therefore seems particularly apt to report current progress in the measurement and analysis of rough contact behaviour.

In the years since Greenwood and Williamson's paper, finite element analysis has become an everyday tool for design engineers, bringing the ability to analyse the behaviour of complex systems of components. However, significant uncertainties remain which affect the accuracy of such analyses. Petrov and Ewins [2] have pointed out that it is now possible to predict the resonant frequencies and mode shapes for the resonance of a single component to better than the differences caused by typical manufacturing tolerances. However, the same is not true for systems consisting of assemblies of components, and the principal uncertainties are associated with unknown behaviour at the contact interfaces. Finite element software typically treats contacts as smooth, with either zero or Coulomb (Amontons [3] friction. One consequence of this approach is that the (local) contact stiffness is assumed to be infinite. In practice, surface roughness introduces additional compliance at the interface which is not captured in the models [4]. This, in turn affects the predictions of resonant frequency for the system.

The paper will describe measurements of normal and tangential contact stiffness made at the centre of a 10 x 8 mm contact using digital image correlation (DIC). The results show that both normal and tangential contact stiffness vary with normal load. This has significant implications for FE models, which, if they include a separate contact stiffness term, normally assume that it is constant. The experimental results are compared to a simple elastic model for stiffness [5], built on similar principles to those in Greenwood and Williamson's approach. The comparison shows that it is important to include asperity interaction in models appropriate for loading at normal engineering levels. This has been acknowledged by Greenwood in his 2008 paper with Ciavarella and Paggi [6]. The implications of the results for the design of engineering systems are discussed.

ACKNOWLEDGMENTS

The work described in this abstract was undertaken with the support of the Engineering and Physical Sciences Research Council (Project EP/E058337/1) and Innovate UK (SILOET II Project 17).

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STATISTICAL MODELS OF NEARLY COMPLETE ELASTIC ROUGH SURFACE CONTACT-COMPARISON WITH NUMERICAL SOLUTIONS

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ABSTRACT

In the area of the homogenous, isotropic, elastic nominally flat rough surfaces contact, the limiting case, in which the real area of contact is relatively small in comparison to the apparent area of contact, is extensively studied since the Greenwood-Williamson (GW) model. Another limiting case, where the real area of contact is nearly the same as the apparent contact area, has received much less attention. This case is referred to as *nearly complete contact*. In a recent paper (*Xu et al., 2014, Int. J. Solids. Struct.,* **51**, *pp. 1075-1088*), Xu et al. developed an approach of modeling the nearly complete contact. This approach is based on the fracture mechanics, contact mechanics and the statistical method. Each non-contact region is treated as a mode-I crack. The distribution of the non-contact regions is equivalent to that of the valleys of the "pressure surface" (the geometry of the pressure distribution when complete contact occurs) and can also be described by Nayak's random theory if the corresponding contacting rough surfaces are Gaussian. Three statistical models, namely, (i) the modified Greenwood-Williamson (GW) model, (ii) the modified Nayak-Bush model and (iii) the modified Greenwood model, are considered. In the current paper, (i) a general relation between the spectral moments of the rough surface and that of the "pressure surface" is found; (ii) the above three statistical models, together with Persson's model, are compared with the FFT models developed by Yastrebov et al. (*Yastrebov et al., 2015, Int. J. Solids. Struct.,* **52**, *pp. 83-102*) and ourselves, respectively. Two relations, namely, (a) contact ratio to the average pressure relation and (b) the contact ratio to the average interfacial gap relation, predicted by three statistical models are compared with that of the FFT models.

EFFECT OF ROUGHNESS ON SURFACE FORCE DISTRIBUTIONS MEASURED BY NEWLY DEVELOPED SURFACE FORCE ANALYZER WITH ULTRA-HIGH ACCURACY

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INTRODUCTION

Surface force measurement is a remarkably important for surface engineering, but they are usually estimated by contact angle measurements or by force curves obtained at AFM measurements. These measurements are performed usually under the atmospheric environments or by using undefined AFM tips, thus the results are affected by several factors such as oxidized films, air contaminants and evaporation of drop-liquid with time, and by artificial factors at AFM tip. In the present paper we are introducing a newly developed surface force measurement system (Figure 1), in which 1) the surface force between sample plate and glass sphere is measured in vacuum, 2) the sphere is detached from the sample directly by a magnetic force, and 3) the displacement and the detaching force of the sphere are measured with ultra-high resolution of 0.3 pm and 0.4 nN, respectively.

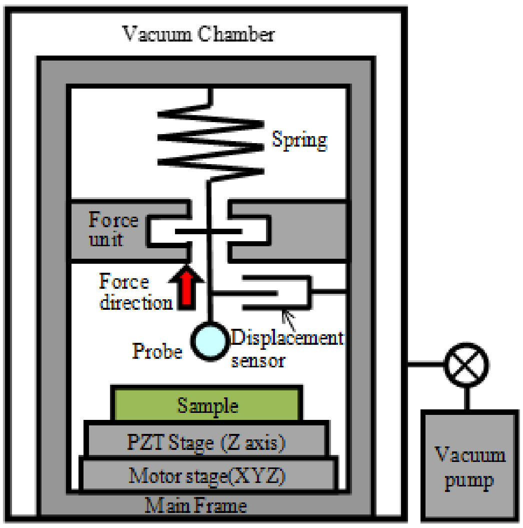

Figure 1. Newly developed Surface Force Analyser

MEASUREMENTS

Using this apparatus, the surface force distributions of $SrTiO_3$ crystal, Si crystal, Glassy Carbon (GC) and Diamond-like carbon (DLC) coated on Si substrate are measured at the square area of 15μm x 15μm. Their surface roughness R_a is 1.6, 2.0, 3.6 and 5.1 nm, respectively. It will be shown that the relative standard deviation (RSD = $\langle\sigma^2\rangle^{1/2}/\langle x\rangle$) of the measured surface force depends on surface roughness (both on R_a and R_z) as shown in Figure 2.

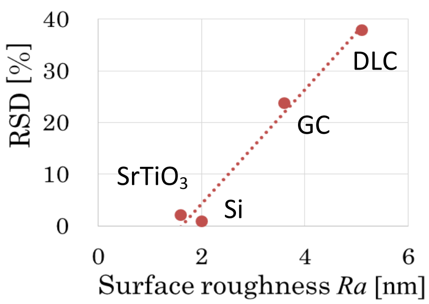

Figure 2. Relation between RSD and R_a

ANALYSIS USING GW MODEL

Assuming that the surface is aggregation of small spheres with the same radius and that the surface height distribution is described by Gaussian distribution function, the surface force is simulated using Greenwood and Williamson Model (GW model). The calculated surface force for Si, GC and DLC surfaces are compared with the measured data. It will be shown that the smaller the standard deviation of the surface height, the larger the surface contact force.

SUMMARY

Using newly developed surface force analyzer, contact forces between glass probe and sample plates of $SrTiO_3$, Si, GC and DLC are measured and the effect of surface roughness on the surface force is investigated. The contact force is simulated by GW model and compared with the measured data.

NUMERICAL APPROACHES TO ROUGH CONTACT MECHANICS: RECENT ADVANCEMENTS AND CHALLENGES

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ABSTRACT

Modern mechanical design requires the full solution of many contact mechanics problems in terms of stresses, strains, friction and dissipation. Particularly important is the surface roughness at the different space and, consequently, time scales; indeed, the complexity of the problem is strictly related to this issue. A further element to be accounted for is the possibility of having materials with non-elastic time dependent behavior. This is quite common in rubber and rubber-based composites, where viscoelastic effects are prominent. On the other hand, adhesion is often an issue to be dealt with. Given the importance of the theme, a lot of scientific contribution have been dedicated to shed light on the related issues. From an analytical point of view, the first pioneering approaches are included in the so-called multi-asperity models [1]: the surface is considered as constituted by asperities -with a certain distribution of radii of curvature and height distribution- which behave as independent Hertzian punches. An alternative approach has been proposed by Persson in the last decade ([2]): this model shows that the contact pressure probability distribution is governed by a diffusive process as the magnification at which we observe the interface is increased.. The model, being able to account for the interaction between the contact regions, is exact in full-contact conditions, but, in the case of partial contact, the theory is only approximate. Limitations of numerical approaches make clear the necessity of reliable simulation techniques. Finite element methods (FEM) are widespread in literature, but, usually, in the case of rough contact, they are not able to provide an accurate estimate of the stresses and strains at the interface. This problem may become significant in the case of rough viscoelastic contact, since roughness introduces a very large number (covering even six orders of magnitudes) of length-scales and time-scales, which would require a very fine discretization grid and would lead to impracticable computation times. For this reason, in this paper, our aim is to focus on Boundary element numerical methodologies capable of determining the elastic and viscoelastic rough contact solution [3-6]. In the elastic case, the importance of the adhesion effects is also included and discussed [7]. Indeed, by applying the theory presented by the authors in [3,4], novel boundary element techniques are introduced. The computational complexity of the contact domain is faced up by employing the adaptive non uniform mesh developed by the authors in [3-6]. This scheme allows to strongly decrease the number of elements needed to solve the problem, thus significantly reducing the computation time. An alternative possibility relies on the solution, in the Fourier space, of the convolution integral, governing the problem. Such an approach can result useful especially when large contact area are considered. In this case, a uniform mesh must be used. Finally, the numerical predictions are compared with experimental outcomes. Particular attention is paid to the viscoelastic friction.

ACKNOWLEDGMENTS

C.P. gratefully acknowledges the support of Marie Curie IEF project SOFT-MECH (grant no. 622632).

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NORMAL STIFFNESS AND DAMPING AT LIGHTLY LOADED ROUGH PLANAR CONTACTS

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ABSTRACT

Two features of contact between rough surfaces are localized interactions between asperities and the presence of an air film in the gap. This gives rise to a contact compliance, a static (and local) property and, with contact vibrations, mechanical damping. Qualitative and quantitative insight into both of these properties can be obtained from the Greenwood-Williamson paper [1] that we are honoring.

INTRODUCTION

Various approaches have been used to characterize the mechanical properties of stationary and sliding contact regions. Since the interface region has properties different from the bulk, power law constitutive relations, intended to capture the nonlinear compliance and damping present at the interface have been proposed. [2], though seldom used. During sliding, only the normal compliance and damping are of interest, and that is the focus here.. The local compliance (stiffness per unit area) can be deduced [3] from the Greenwood–Williamson paper and is $k = p/\sigma$ for an exponential distribution of asperity heights and higher $k \approx 3p/\sigma$ for a Gaussian distribution [4]. p is the nominal pressure and σ is the combined rms surface roughness. However, the damping at the contact depends on the dimensions of the contact and hence is not a local property. We show below that simple squeeze film damping can explain the observed damping in our tests.

EXPERIMENTS AND RESULTS

A simple spring-mass system is used to measure the contact damping and stiffness. The interface is created from new and worn segments of electromagnetic (mild steel) clutch segments with varying surface roughness and wear histories. The nominal contact pressure can be varied from 0.3 to 1.5MPa. The effective mass, M, is 0.225 Kg. The total stiffness, K= kA, where A=Lw, the length (81mm) x width (1.85 mm) of the contact. The combined surface roughness for four test ranged from 1.0 to 3.0 µm (1.7µm avg), allowing the contact stiffness to be estimated. If we assume squeeze film damping to be the primary damping mechanism, the viscous damping constant, b, for a long, narrow parallel plate geometry can be estimated from [5] as $b = 96\mu Lw^3/\pi^4c^3$

This damping model assumes smooth surfaces, which is reasonable for light loads with small real areas of contact. The gap, c, we take to be $\approx 4\sigma$. µ is the viscosity of air. There is some scatter in the data but, overall, the measured damping constants fall between 30 and 180 N-s/m (avg = 85 N-s/m), with higher roughnesses, i.e., gaps, resulting in lower damping. The calculated damping ranged from 6 to 160 N-s/m (avg= 70 N-s/m). Damping ratios, $\zeta = b/2(KM)^{1/2}$ from 0.01 to 0.06 systematically decrease with increasing pressure due, primarily, to the aforementioned increase in stiffness with pressure.

CONCLUSIONS

While other mechanisms of damping (normal component of local oscillating slip, wear particles) are possible, we see no reason to explore other mechanism in the present instance. The agreement between calculations and experiments could be improved with better-controlled tests. Reasoning, informed by the landmark Greenwood-Williamson paper, is all that is needed to bring theory and experiment together. This could have been done in 1966, but wasn't!

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T3-1 In situ

IN-SITU OBSERVATION OF THE MAGNETIC DOMAIN STRUCTURE IN THE PROCESS OF PURE FE/FERROALLOY FRICTION

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ABSTRACT

An in-situ observation system was developed to monitor the magnetic domain structure in the process of friction. By means of this system, the magnetic domain structure on the side surface near the sliding contact area were observed while a carbon steel 1045/316L stainless steel pin specimen was rubbing on a pure iron block specimen under certain loads. Then the variations of the magnetic domain structures near the rubbing surface with the increasing of rubbing cycles were characterized. Furthermore the effects of the tribo-component materials, loads and rubbing cycles on the magnetic domain structure were discussed.

INTRODUCTION

Tribo-magnetization phenomenon has been known and used for a long time. However, seldom researches were put into its micro-mechanism and its relationship with the tribological effect [1]. This paper paid attention to the changes of magnetic domains on the side surface of the sliding contact area in the process of friction under different conditions for understanding the relationship between magnetization with tribological effect.

THE EXPERIMENTS

The in-situ observation experiment methods

The schematic of the in-situ observation system of the magnetic domain structure in the process of friction is shown in Fig.1. In the system, a kind of nanometer magnetic suspension is used to infiltrate the XY-surface of the block for revealing the magnetic domains on the surface.

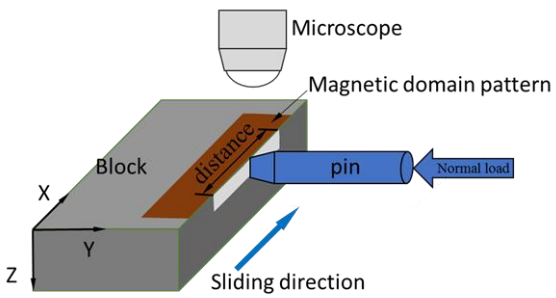

Fig.1 the in-situ observation system of the magnetic domain

Experimental result and discussion

Fig.2 and Fig.3 show the variations of the magnetic domain structure while carbon steel 1045 /316L stainless steel pin rubbing on the pure iron block.

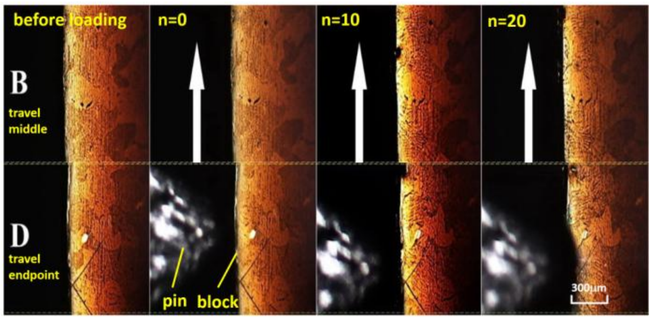

Fig.2 magnetic domain change in Fe/1045 rubbing cycles

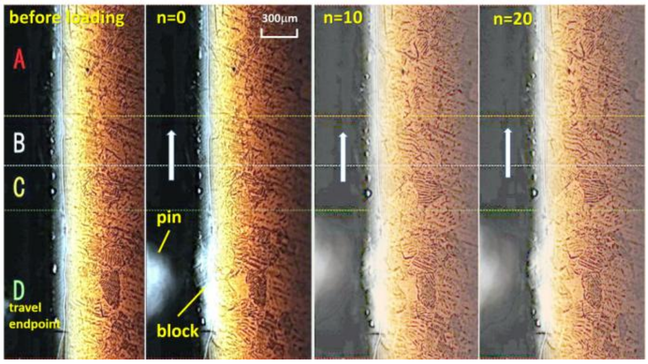

Fig.3 magnetic domain change in Fe/316L rubbing cycles

ACKNOWLEDGMENTS

This research was supported by the national natural science foundation project.

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STUDY ON DETECTION OF WEAR TRANSITION POINT USING ACOUSTIC EMISSION TECHNIQUE

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ABSTRACT

In tribological phenomena, properties of adhesive wear and abrasive wear are very different. So, it is very crucial to identify the changes in wear state of machineries. In this study, to detect wear transition point, changes in the acoustic emission (AE) signals were examined by performing sliding wear tests using metal pin and abrasive paper. It was found that the wear transition point could be evaluated from the occurrence of high frequency AE signals and the changes in the maximum amplitude of AE signals.

INTRODUCTION

Acoustic emission (AE) is the phenomenon of radiation of elastic stress waves in solids that occurs when a material deforms and fractures. In our previous study [1], it was found that the features of frequency spectrum of AE signals differ from wear mechanisms. Since these findings were obtained by individual wear mechanism, wear transition from abrasive wear to adhesive wear in single wear process has not been examined yet. In this study, we carefully looked at the changes in AE signals to detect when wear mechanism shifts.

EXPERIMENTAL METHOD

Pin-on-disk sliding wear tests were performed by mounting a wide-band type AE sensor onto the upper part of an aluminum pin specimen and slid onto an abrasive paper bonded onto a steel disk to reproduce wear transition from abrasive wear to adhesive wear. Three abrasive papers with different abrasive grains (P600, P1000 and P2000) were used to compare the transition point. The experiments were performed with a normal load of 0.98 N and a sliding velocity of 13 mm/s under dry condition in an open environment at room temperature.

EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 1 shows micrographs of the sliding surfaces of the P1000 abrasive paper and the pin specimen after rubbing. In the initial stage, abrasive wear occurs mainly, however, it gradually shifts to adhesive wear by loading (sticking to) abrasive paper as shown in Fig. 1(b). At this point, high frequency AE signals were detected. And, the occurrence of high frequency AE signals increased as wear progresses.

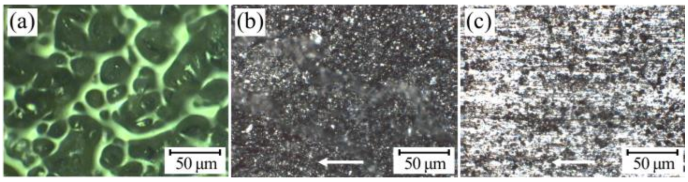

Fig. 1. Micrographs of the sliding surfaces: P1000 abrasive paper (a) before and (b) after sliding, and (c) pin specimen after rubbing

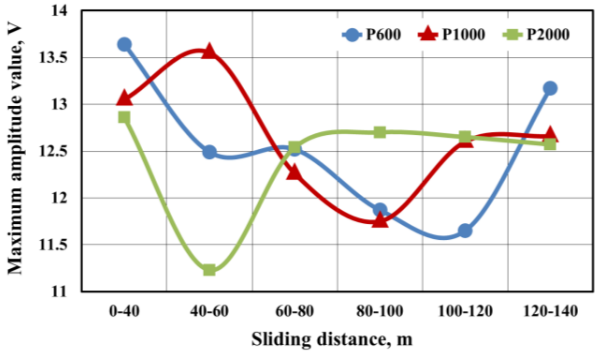

Fig. 2. Changes in the maximum amplitude of AE signals for each abrasive paper

From the changes in the maximum amplitude of AE signals shown in Fig. 2, the wear transition can be identified at the point where the amplitude increased again after it dropped once. The starting point of a wear transition could be identified by a high frequency AE signal. And, the completion of a wear transition could be identified and located by the inflection point of the changes in the maximum amplitude of AE signals.

CONCLUSION

Wear transition point could be evaluated from the changes in the maximum amplitude of AE signals and the occurrence of high frequency AE signals.

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Proceedings of the 42nd Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France

MEASUREMENT OF ROLLING CONTACT SURFACE DEFORMATION IN MICRO SCALE

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ABSTRACT

A new test rig is developed to measure the progressive surface deformation in rolling contact. The rig size is relatively small to the infinite focus microscope to enable experiment to be carried out under the scope. The online measurement of surface deformation is performed periodically at the early cycle of rolling contact. The effect of surface roughness parameter on the surface deformation, contact area, pressure and friction are discussed.

INTRODUCTION

In rolling contact, the geometry of the interacting surfaces play important role. A change in macro-geometry may lead to the vibration while the change in micro scale i.e. roughness level may improve the friction performance. The evolution of surface roughness during running-in has been carried out extensively experimentally and numerically [1, 2]. However, few works have looked at the surface deformation at asperity levels [5, 6]. The measurement of progression in localized surface deformation requires a very precise positioning method. The aim of this study is to develop an online surface monitoring system to quantify surface deformation and wear without dismounting the sample. It is important to establish the similar datum for the correct measurement of volume loss from the surface. The progress of the wear over the rolling cycle is important in order to get a better understanding of the wear mechanism in rolling motion for both the dry and lubricated condition.

METHODOLOGY

The experimental setup consists of a new developed test rig and infinite focus microscope (IFM) as shown in Figure 1. The rig is designed to be small enough to fit into the IFM and consists of two rollers, bearing and stepper motor.

RESULTS AND DISCUSSION

Figure 2 shows plastic deformation of the surface asperities after 1 cycle for low hardness mild steel (E = 2 GPa) in contact with through hardened chromium steel (E = 11GPa). The asperity heights of a certain peaks are reduced resulting in increased surface conformity.

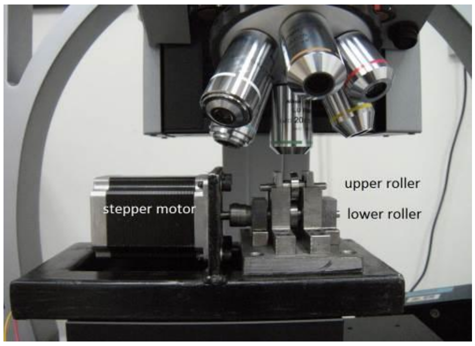

Figure 1 Experimental setup

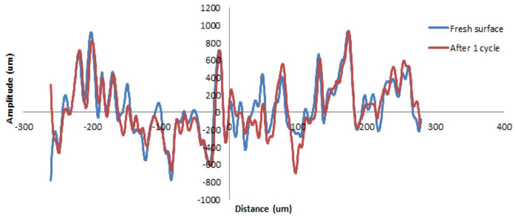

Figure 2 Plastic deformations of asperities

CONCLUSIONS

A new experimental test rig for measurement of micro surface deformation in rolling contact is developed. The rig enables the surface profile of the test roller to be monitored for successive revolution without dismounting the sample. The effect of roughness parameters i.e. amplitude, directional and autocorrelation function on the surface deformation, contact area, pressure and friction are discussed.

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TRIBOPLASMA GENERATION AT POLYMER CONTACTS

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INTRODUCTION

In a gaseous environment, the electric field created by tribocharging, causes an electron avalanche process to take place that leads to gas breakdown and plasma generation [1]. Previous studies of triboplasma focused only instantaneous measurements of ceramics and DLC coatings (*e.g.* [1]).

In this study we measure triboplasma from three polymers used in tribological applications while viewing the contact through the stationary sliding partner (*i.e.* the pin specimen) and monitoring variations over time. The results show triboplasma being generated in front, inside, and at the rear of the contact. Although the relative magnitudes of plasma intensities increases with material resistivity, the transient variations in intensity measurements between specimens suggests that electrical resistivity is not the primary factor controlling triboplasma generation, as previously thought.

EXPERIMENTAL PROCEDURE

A PCS EHL rig was converted into a pin-on-disc configuration, with the pin specimen being a single crystal Al_2O_3 hemisphere. This allowed the contact to be viewed from above using a UV sensitive camera (Hamamatsu BT600) in order to image the triboplasma generated while sliding (see Fig 1). Poly-ether-ether-ketone (PEEK), polytetrafluoroethylene (PTFE) and ultrahigh molecular weight polyethylene (UHMWPE) were used as the disc specimens. Tests were performed for a range of speeds, loads and with both 2 and 5 mm diameter pins.

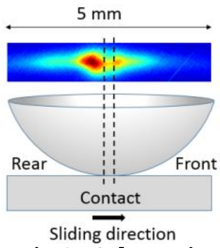

Fig 1. Schematic diagram of test setup

RESULTS

Figs 2a-c and 2d-f shows the variation in triboplasma for each of the different materials, sliding against both the 5 and 2 mm diameter pins respectively. It can be observed that the intensity of plasma depends heavily of the type of polymer tested and contact geometry. It is also evident that the size of the plasma region is an order of magnitude larger than those previously reported.

UHMWPE showed highest plasma intensity which was distributed both infront of and behind the contact. This is possibly due to the electric field created due to tribocharging. Conversly, PEEK showed no plasma emission, possibly due to higher conductivity facilitated by its aromatic structure.

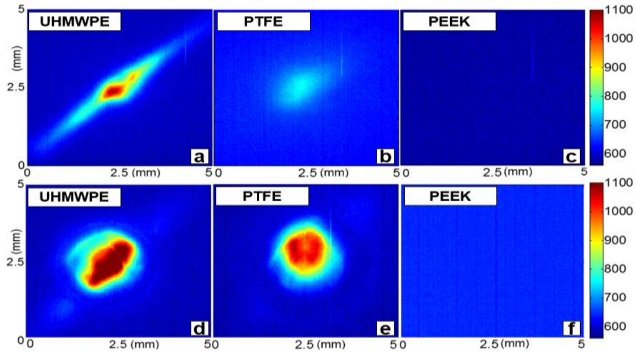

Fig 2: Triboplasma observed from each polymer, all at a speed of 2.6 m/s. (a) – (c) obtained using 5 mm, and (d) – (f) obtained using 2 mm diameter pin.

Fig 3 shows the variation in maximum plasma intensity over time. Here, UHMWPE shows intermittent variations in plasma intensity, possibly due to a charging/discharging cycle. For PTFE, the intensity of plasma decreases monotonically, probably due to the formation of wear debris.

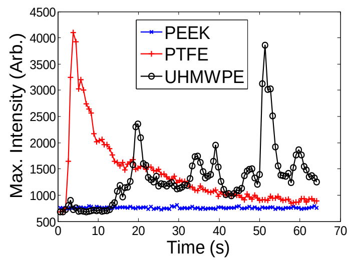

Fig 3. Maximum emission intensity with time

SUMMARY

- A new configuration to visualize plasma through stationary sliding partner is developed.
- Triboplasma generated from polymers supports Nakayama's triboelectrification model.
- The spread and intensity of triboplasma is also dependent on contact geometry.
- The variation of triboplasma generation with time is studied and links between triboplasma generation and wear is discussed.

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OBSERVATIONS ON THE ACOUSTIC EMISSIONS FROM A LINE CONTACT COMPRESSED INTO THE PLASTIC REGION

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ABSTRACT

This paper presents some observations on the Acoustic Emissions (AE) generated during compressive testing between a bearing inner raceway and a cylindrical rolling element. It is well known that crack formation, plastic deformation, friction and stress can generate AE within a solid. AE are elastic stress waves generated as a result of a change in the internal structure of a material. The results presented here have been gathered during the contact loading of the bearing raceway, for which AE measurements have proven useful in determining when the material has yielded, before the damage is evident in the surface. The load required to yield the material, a 52100 alloy steel, has been estimated using a Tresca criterion to be 1000 kN. Large bursts of AE are observed between 800 kN and 1200 kN, and surface damage is visible beyond 1250 kN. Other smaller bursts are also observed at smaller loads during the loading and unloading process. Several tests were carried out using different loading rates, and the results are presented for these. Whilst it is difficult to model the AE generating mechanism due to the nature of it being at an atomic level, there have been numerous recent contributions in this field. The AE gathered from these compression tests are put in the context of these new developments in numerical modelling and simulation, in order to try to establish what could be inferred about the state of the material from the AE signature during the loading process.

T4-1 Joint Tribology

THE INFLUENCE OF VARIATIONS IN INSERT THICKNESS ON TOTAL KNEE REPLACEMENT POLYETHYLENE WEAR

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ABSTRACT

The effects of total knee replacement insert thickness on the contact pressure, sliding distances and polyethylene wear was investigated using computational simulations. Although insert thickness was demonstrated to affect polyethylene wear rates, the change in overall wear remained small for the modern insert materials and range of insert thicknesses considered.

INTRODUCTION

The availability of total knee replacement (TKR) inserts with a wide range of thicknesses may be essential to ensure properly balanced soft tissues and to achieve high levels of patient satisfaction [1]. Therefore, it is important to understand the range of permissible insert thicknesses which will still result in sufficient polyethylene (PE) wear performance, as well as understand how changes in insert thickness may generally affect the wear of modern bearing materials.

METHODS

The PFC-Sigma (Sigma, DePuy Orthopedics Inc., Warsaw, IN) was selected for the analysis with insert thicknesses ranging from 5-25mm. The FE simulations were conducted under the displacement and loading conditions of ISO 14243-3; 2009, according to a previously established protocol by O'Brien et al. [2]. Non-linear material models were used for the PE and XPE materials to represent non-oxidized materials, characteristic of modern TKRs [2]. The well established wear model of Turell et al [3] was implemented for the computational wear simulations.

RESULTS

Increasing insert thickness was found to cause a small decrease in articular peak contact pressure (≈4%) and a small decrease in the wear rate of the articular surface (≈5%, Fig. 1). For the backside surface, increasing insert thickness was found to cause a small decrease in peak contact pressure (≈4%), greatly increase sliding distances (≈101%) and greatly increase wear (≈38%). Increasing the interference fit of the PFC-Sigma's tibial peripheral locking mechanism did not lead to a substantial improvement in backside wear performance (Fig. 1).

DISCUSSION

Increased insert thickness was found to enable lower peak contact pressures due to the elastic deformation of additional

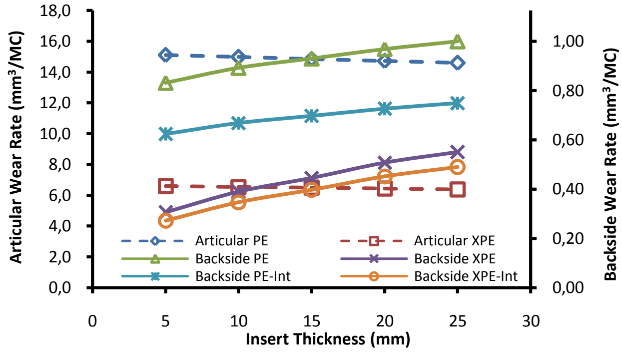

Figure 1: Computational wear predictions of articular, backside, and backside with increased interference fit (Int) wear rates for PE and XPE

material [4]. Increased insert thickness also increased the moment arm between the surface at which forces were applied (articular surface) and the locking mechanism which resists backside sliding movements, thereby leading to increased backside sliding with increasing insert thicknesses.

CONCLUSION

PE wear was observed to be affected by insert thickness. However, for the modern insert materials and thickness range of 5-25mm, alterations in insert thickness resulted in only small changes to the overall wear rate. These results are contrary to what has previously been observed for gamma-in-air sterilized PE inserts [4], and may be attributed to the improved mechanical properties of these modern bearing materials.

ACKNOWLEDGMENTS

The authors would like to thank Depuy-Synthes for providing the CAD models of the PFC-Sigma, as well as NSERC Discovery Grant (JMB) and PGS-D (SO) for providing funding.

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SOME INSIGHTS FROM CERAMIC HIP JOINTS, *IN VITRO = IN VIVO*?

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ABSTRACT

The degradation and therefore limited lifetime of ceramic hip joints is a major research topic in orthopedics. To understand and predict the degradation of articulating components (head and cup), many works do attempt to find the best correlation between *in vitro* analysis and *in vivo* observed behavior. The present study seeks to explore the combined effects of shocks and hydrothermal ageing on the wear of Zirconia Toughened Alumina (ZTA) components. It shows that shocks under microseparation coupled with ageing might cause significant well known degradations. Wear stripes have been observed on femoral heads and have been linked to increasing wear volume and zirconia phase transformation. New well established methods for measuring wear volume by 3D-profilometry and phase transformation by µ-Raman spectroscopy have been developed. Finally, *ex vivo* components have been characterized and also revealed considerable zirconia phase transformation inside wear track areas, *in vitro* might be close to *in vivo* comparison.

INTRODUCTION

Ceramic hip joints are submitted *in vivo* to several degradation mechanisms, including wear, shocks under microseparation conditions and hydrothermal ageing for zirconia based components. *In vitro* studies mostly work on reaching heads and cups behavior against one of these mechanisms. In particular the shock degradation, leading to wear areas on femoral heads, is quite unknown due to the lack of controlled microseparation conditions during *in vitro* testing. The aim of the present study was to characterize the shock degradation on ZTA prosthetic components and the potential subsequent effect of hydrothermal ageing on this degradation.

MATERIALS AND METHODS

In vitro testing

ZTA femoral heads (diameter of 36 mm) and cups were submitted to *in vitro* testing. Tests on a shock machine were conducted under controlled microseparation conditions [1]. Hydrothermal ageing were complementary performed in an autoclave under water pressure (134°C and 2 bars).

Surface characterization

Wear volume on femoral heads was measured from 3D profilometry. A new method has been developed to calculate it from 2D profiles collected along wear stripes width thanks to Matlab® software associated with the pristine one. The zirconia phase transformation has been quantified from µ-Raman spectroscopy inside and out of wear areas.

RESULTS

Femoral heads have shown the apparition of two wear stripes due to severe microseparation conditions as expected. From them, the wear rates measured here range between 0.2 and 0.7 mm^3/ equivalent *in vivo* year. The monoclinic content has known a significant increase inside wear stripes reaching an average value of 40% (maximum value 65%) against 10% out of wear. Pure hydrothermal ageing has led to monoclinic content around 15% (maximum value 35%) all around the head. *Ex vivo* components analyses have revealed monoclinic content around 60% inside wear areas and 35% out of wear.

CONCLUSION

This study shows that shocks under severe microseparation lead to important degradation characterized by the apparition of wear stripes. The effect of hydrothermal ageing has been identified on unworn areas but must not be prejudicial for lifetime components. The first comparison with *ex vivo* components corroborates that ZTA composites undergo zirconia phase transformation inside wear areas.

ACKNOWLEDGMENTS

The authors acknowledge the Region Rhône-Alpes and ARC 2 for the financial support. Due to confidentiality reasons two companies from the orthopedic field that are following and supporting these investigations are gratefully acknowledged.

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Proceedings of the 42nd Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France

A COMPARATIVE STUDY ON THE IMPACT WEAR BEHAVIORS OF HUMAN TOOTH ENAMEL, Ti_6Al_4V ALLOY AND HYDROXYAPATITE CERAMIC

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ABSTRACT

Tooth wear is inevitable due to oral physiologial functions, such as mastication [1-3]. Generally the wear of tooth occlusal surface is the combination of sliding wear and impact wear under the occlusal load [2]. Nowadays, a few studies have been conducted on the sliding wear of human teeth, while few effort has been made to study the impact wear of teeth.

To extend the understanding of enamel wear mechanism, the impact wear behavior of human tooth enamel has been studied by comparing it with that of Ti_6Al_4V alloy and hydroxyapatite ceramic in this paper, using a self-made small energy impact test machine. Tests lasting up to 5 000, 50 000, 250 000, 550 000, 800 000 and 1 000 000 cycles were conducted, respectively. Wear was assessed by sample wear volume.

Results showed that the wear volumes of enamel, Ti_6Al_4V alloy and hydroxyapatite ceramic were increased nonlinearly with the number of impact cycles, and the wear loss of hydroxyapatite ceramic was much higher than those of enamel and Ti_6Al_4V alloy, as shown in Fig. 1. For the enamel and Ti_6Al_4V alloy, the wear morphologies were characterized mainly by plastic deformation at the early stage of impact wear. With the number of impact cycles increasing, adhesion delamination occured on the worn surfaces, then causing a rapid increase of wear volume. No cracks were observed on the cross section of wear scars for either the enamel or Ti_6Al_4V alloy (Fig. 2). For the hydroxyapatite ceramic, lots of microcracks appeared on the worn surface at the very early stage of impact wear, and then obvious brittle delamination occurred. The wear volume increased rapidly with the number of impact cycles. As the wear proceeded further, the hydroxyapatite surface was gradually covered with a wear particle layer, and the wear rate decreased. Obvious cracks appeared on the cross section of wear scars for the hydroxyapatite ceramic (Fig. 2). Also found was that with the number of impact cycles increasing, the surface hardness of both the enamel and Ti_6Al_4V alloy increased. And colorful rings appeared on the worn surfaces of enamel and Ti_6Al_4V alloy during the impact wear process. But these phenomena did not happen to the hydroxyapatite ceramic. In summary, the impact wear behavior of human tooth enamel was more similar to that of the ductile material of Ti_6Al_4V alloy than that of the brittle material of hydroxyapatite ceramic. Compared with the hydroxyapatite ceramic, both the enamel and Ti_6Al_4V alloy have a better resistance against impact wear. The results would be helpful to fully understand dental wear.

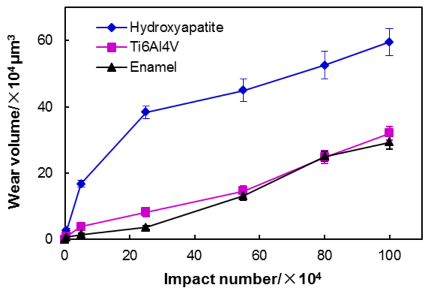

Fig.1 Variation of wear volume with the number of impact cycles

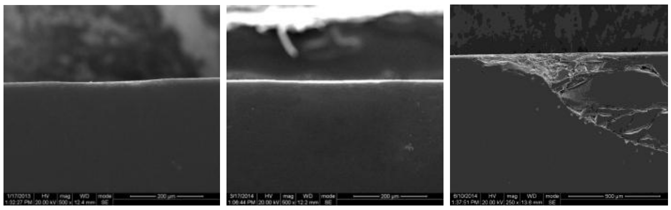

Fig.2 SEM micrographs of the cross section of wear scars, (a) enamel; (b) Ti_6Al_4V alloy; (c) hydroxyapatite ceramic

KEYWORDS: Human tooth enamel; Ti_6Al_4V alloy; Hydroxyapatite ceramic; Impact wear behavior.

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ADHESIVE POTENTIAL OF BIO-INSPIRED MUSHROOM-SHAPED CONTACTING COUNTER-SURFACES OF DIFFERENT ROUGHNESS

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OBSTRACT

To elucidate the effect of the substrate roughness on adhesion of mushroom-shaped microstructure, we have replicated topography of 12 different surfaces and, using replicas made of the same material, measured pull-off forces of microstructured and smooth samples. It was found that classical roughness parameters, such as average roughness Ra and others, cannot be utilized to explain topography-related variation in pull-off force. This has led us to the development of an integrated roughness parameter capable of explaining results of pull-off measurements. Using this parameter, we have also found that there is a critical roughness, above which neither smooths, nor microstructured surface could generate any attachment force, which may have important implications on design of both adhesive and anti-adhesive surfaces.

INTRODUCTION

The problem of quick and easy reversible attachment has become of great importance in different fields of technology. For the reason, during the last decade, a new emerging field of adhesion science has been developed. Essentially inspired by some animals, like geckos, spiders, flies and beetles which, during their natural evolution, have developed high performance biological attachment systems allowing them to be able to adhere and run on walls and ceilings [1,2]. One of the well-known prototypes for bio-inspired attachment systems is the mushroom-shaped contact elements [3,4]. Inspired from the male beetles of the family Chrysomelidae, this kind of attachment system is famed to perform especially well on smooth substrates and to generate strong pull-off even without requiring any preload. Several recent publications have focused on the understanding of the physical background of these attachment systems [5,6]. However, the influence of counter-surface roughness and its relationship with the adhesion force generated in contact with mushroom-shaped fibrillar have yet to be fully analyzed and understood.

EXPERIMENTAL APPROACH

Mushroom-shaped fibrillar was manufactured by Gottlieb Binder GmbH (Holzgerlingen, Germany) while counter-surfaces were all made of the same epoxy material by replicating different objects having different surface roughness. Counter-surfaces were then characterized under a 2D mechanical profilometer to determine the surface roughness parameters. Finally, adhesion force was measured using a home-made special tribometer.

MEAN RESULTS

It is shown in this study that the adhesion force generated by mushroom-shaped fibrillar is non-depending on the average roughness Ra or any of the classical roughness parameters considered separately. However, it was found to be depending on a non-dimensional roughness parameter NDRP obtained by combining different parameters which are the mean asperity radius of curvature (R), the asperity density (η), and the deviation of asperities high (σ). In this work we show also that by choosing correctly the rough counter-surface with convening parameters, it is possible to achieve high adhesion force comparable to that obtained with smooth surface like glass..

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WEAR MODELING OF METAL-ON-METAL ARTIFICIAL HIP JOINTS BY COMBINING TRIBOCORROSION AND LUBRICATION ASPECTS

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ABSTRACT

Wear is a major problem causing the failure and limiting the long-term performance of artificial hip joints, especially for the polymer acetabular cup. The micro-sized polymer particles cause the adverse reaction of the tissue and afterwards induce the osteolysis, which is called particle disease. As alternative, metal-on-metal (MoM) couplings offer a unique combination of wear and impact resistance, but the continuous release of nano-sized metal particles and ions into the body is of long-term concern as it can cause allergies and other toxic reactions. In order to better control the release of metal ions, the wear mechanisms should be identified and predictive models should be developed.

The femoral head and the acetabular cup are surrounded by synovial fluid, which act as lubricant, alleviating the wear of implants but also introduce corrosion. The interaction of mechanical wear and electrochemical corrosion, nominally tribocorrosion, has been proposed as one of the crucial degradation mechanisms of implants [1,2] and recently saw significant progress in mechanistic understanding and modeling [1-4]. However, these studies neglect lubrication effects in the overall degradation. Indeed, Dowson [5] showed a clear relation between wear and hydrodynamic lubrication of MoM artificial hip joints.

A wear model for passive metals undergoing plastic deformation at asperity contacts combining mechanical wear (Archard's law), chemical wear (wear accelerated corrosion) and hydrodynamic lubrication was proposed in this study to quantitatively describe and predict material damage.

As applied to CoCrMo sliding tribocorrosion contacts, the model predicts remarkably well wear rates observed in tribometers and the running-in wear rate in simulators, as shown in Fig. 1. In the case of MoM hip joints, the model predictions concerning the effect of parameters such as normal load, head radius and clearance closely correlate with experimental observations.

According to the model, both mechanical and chemical wear significantly contribute to hip joint degradation. Thus predictions based on only one mechanism likely lead to erroneous conclusions. This is for example the case of head radius that while having a significant effect on mechanical wear little affects chemical wear.

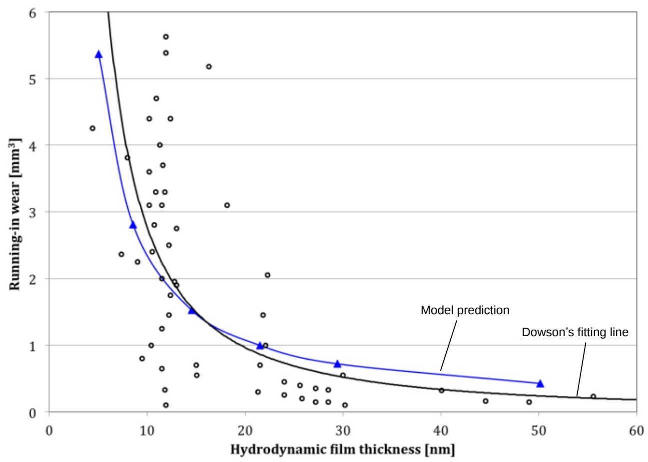

Fig. 1 The simulator running-in wear results (circular dots) with different film thicknesses and fitting line from [5] and model predicted values (triangular dots and interpolation) (R=18 mm, c_R=200 μm, 100 μm, 50 μm, 30 μm, 20 μm and 10 μm, successively)

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T2-1 Tribo (hard) materials

NANOLUBRICANTS DEVELOPED FROM TINY CuO NANOPARTICLES

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ABSTRACT

The paper aim was to evaluate the tribological properties of tiny CuO nanoparticles at low concentrations. The nanoparticles were synthesized in microwave and their average size was 5 nm. After that, the nanoparticles were covered with oleic acid and added three different concentrations of PAO oil. The tribological performance of these oils was evaluated in HFRR tribometer under boundary lubrication conditions. The results showed that is possible to reduce the friction coefficient using tiny nanoparticle and decreasing the percentage of CuO addition in lubricating oil.

INTRODUCTION

Inorganic nanoparticles are not suitable for lubricating oils because they have poor disperse capacity therein [1]. A solution for this problem is the surface modification technique. The dispersion capacity of inorganic nanoparticles in organic solvents and lubricating oils was improved by nanoparticle surface modification with high molecular weight hydrocarbons. The size of the particle is another factor that needs attention to anti wear additives in oils, which may affect the type of nanoparticles action mechanisms in lubricants. Numerous researches used nanoparticles as oil additives and commonly they present a size between 10 and 80 nm diameter of copper oxide and percentage of additive above 0.5% by weight [2-3].

This study examined the tribological properties of lubricating oils with tiny nanoparticles of CuO at low percentage of additive. The friction and wear experiments were performed to evaluate the friction reduction and anti-wear abilities of these tiny nanoparticles, and their friction reduction mechanism. In addition, more investigations were performed using transmission electron microscope (TEM), optical microscope (OM), scanning electron microscopy (SEM), and Raman spectroscopy to evaluate the effect of size in the mechanisms of lubrication and wear with these tiny nanoparticles.

EXPERIMENTAL

CuO nanoparticles were prepared by an alcothermal method using copper nitrate, sodium hydroxide, and ethanol as starting materials in microwave reactor. They were characterized by DRX and MET. After that, the nanoparticle were covered with oleic acid for surface modification, and added three different concentrations of PAO oil. The tribological test was conducted under boundary lubrication conditions in HFRR equipment. A hard steel ball (570–750 HV) of 6.0 mm diameter reciprocates on a soft steel disk (190–210 HV) of 10 mm diameter fully submerged by oil with a normal load of 10N and a 1mm stroke length at a frequency of 20Hz for 60 min. Both ball and disk were made of AISI52100 steel. The lubricant temperature was kept at 50° C. The friction coefficient was measured by a piezo-electric force transducer and the formation of electrically insulating films at the sliding contact was measured by the ECR (Electrical Contact Resistance) technique. This test was realized for nanolubricants and PAO. The friction reduction and wear mechanisms of nanoparticles and PAO were analyzed through wear track formed on the disk after the tribological test by SEM and Raman spectroscopy.

RESULTS

According to results, tiny CuO nanoparticles promote friction reduction as well as it allows the decrease of CuO concentration in lubricating synthetic oil (PAO). With tiny CuO nanoparticles, the friction reduction is proportional to decreasing concentration. In addition, the wear mechanism in disc worn surface was different when nanoparticle was added to PAO in comparison with pure PAO. The mechanism observed for PAO without additives was abrasion, while for PAO added with CuO nanoparticle the main wear mechanism was delamination.

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STATISTICAL APPROACH TO THE FRICTION MODELING IN BOUNDARY LUBRICATION

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INTRODUCTION

Friction modeling [1] is a developing area of Tribology, however, despite all of the progress made so far, primarily in EHL and mixed regime, modeling of Boundary Lubrication (BL) is still in its beginnings. One of the main reasons is that due to the many asperity-asperity interactions and use of various additives there is an overlap of many different mechanical, chemical and physical effects as well as their interactions. This makes exact phenomenological modeling in BL regime very difficult.

During the past decade many efforts have been placed in the understanding of tribochemistry of different diamond like carbon (DLC) coatings [2]. However, there are not many results that can predict behavior of DLC coating combined with different additives in boundary lubrication regime. Moreover, advantage of DLC coatings over the classical steel system is still debated and it is often unclear in which conditions this advantage can be gained

Accordingly, another option is to reveal the BL friction of DLC systems trough statistical approach, where a variety of conditions can be simulated and the differences in BL friction recognized with a span of accuracy, typical for well-understood mapping concept. Of course, these results can then be compared to more detailed phenomenological understanding that is coming along the way.

EXPERIMENTAL

Design of Experiment

In order to test as many parameter variations as possible, Design of Experiment method was employed for the planning of experiment [3]. In this way we have gained multiparameter test matrix, which is providing us with information on the system behavior across the broad range of parameters. Variations of contact pressure, speed, roughness and pressure were evaluated (Table 1).

Tribotests

DLC samples were tested against DIN 100Cr6 steel ball using SRV Optimol Tribometer. Sliding distance was set to 100m and median friction coefficient over the last 30m was used for further analysis. Three oils have been tested: base oil, base oil additivated with w.t. 1% of ZnDDP and fully formulated engine oil.

Normal load [N]	Speed [m/s]	Roughness [μm]	Temperature [°C]
10	0.02	0.01	50
31.3	0.06	0.055	100
71	0.1	0.1	150

Table 1 Variation of experimental parameters

RESULTS

We have identified which experimental parameters have statistically significant influence over the coefficient of friction, as well as their interactions. Friction prediction curves for different test parameters have been obtained and are presented as BL friction maps

CONCLUSIONS

Proposed method is a promising one when it comes to prediction of friction and establishing friction trends over the broad range of contact parameters. Further analysis of statistically significant parameters and their interactions showed good agreement with previously published literature about steel – DLC contacts and their interaction with different additives.

ACKNOWLEDGMENTS

This study was funded by the FP7 program MC-ITN “ENTICE - Engineering Tribochemistry and Interfaces with a Focus on the Internal Combustion Engine” [290077] and was carried out at the Laboratory for Tribology and Interface Nanotechnology, at University of Ljubljana.

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TRIBOCHEMICAL WEAR OF TETRAHEDRAL AMORPHOUS CARBON IN A LOW-FRICTION TRIBOSYSTEM

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ABSTRACT

Super- and ultra-low friction of hydrogen-free amorphous carbon coatings has been studied with several lubricants by various authors, however without special focus on wear.

Here, we report on a high wear mechanism found for some lubricants in the ultra-low friction state under boundary lubrication. By means of tribological testing we demonstrate the influence of sp^3-content and amorphous nature of the coating, lubricant chemistry, and material of counter body.

From friction and wear analysis we conclude that the wear phenomenon is of chemical nature and directly linked with the state of ultra-low friction.

INTRODUCTION

Hydrogen-free tetrahedral amorphous carbon (ta-C) coatings offer unique tribological properties due to high hardness, high chemical inertness and low friction. Recently, ta-C coatings gain more attention as industry-scale PVD technology became available and first mass produced applications were introduced to the market.

Besides their good performance in conventional mineral oil lubricated tribosystems, super-low and ultra-low friction was found for several lubricants like short chain polyols[1] (e.g. glycerol) and long chain fatty acid-based lubricants[2] (e.g. glycerol mono-oleate and oleic acid).

While the phenomenon of low friction is supported by some studies on surface hydroxylation[1], lubricant degradation with formation of water, and a possible hydration lubrication mechanism[3], no reports of significant wear can be found in the literature.

EXPERIMENTAL

Using an oscillating ball-on-flat setup we tested an uncoated ball running against a coated disk in lubrication. Coatings were a-C, ta-C and single crystalline diamond. As lubricants we used glycerol, and fatty acid-based lubricants like glycerol mono-oleate (GMO), oleic acid methyl ester and food grade rape seed oil. As counter body balls made from two chromium containing steels, cemented tungsten carbide, aluminum oxide, and silicon nitride were investigated.

RESULTS

Ultra-low friction ($\mu \leq 0.04$) was obtained for all lubricants. For glycerol, no wear could be measured. In contrast wear of at least two orders of magnitude higher was found for some other experiments.

High-wear conditions were only observed with fatty acid-based lubricants, regardless their chemical head function. Furthermore, wear was observed on sp^3-rich ta-C coatings only, not on sp^2-rich a-C coatings or single crystalline diamond. Additionally, the ball material can influence the wear behavior tremendously even when steels have similar properties or ceramics have similar hardness.

In all cases of observed wear, the phenomenon was directly linked to the state of ultra-low friction which had to be activated above a certain threshold. While some tests were instantly activated at the beginning of the test, other spontaneously activated after a certain time or stayed on a high-friction level ($\mu > 0.06$) with no wear for the test duration, sometime even within the same set of materials and lubricant.

Conclusion

We assume a tribochemical reaction of long-chain organic molecules with sp^3-rich amorphous carbon, causing high wear to the coating and at the same time providing low friction conditions similar to the ones obtained with glycerol. While such a sudden nonlinear occurrence of wear can hardly be explained by abrasive mechanisms, a possibly radical reaction is considered, where the counter body material has a mainly catalytic influence.

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TRIBOLOGICAL PROPERTIES OF SOFT-METAL / DLC COMPOSITE COATINGS PREPARED BY RF MAGNETRON SPUTTER USING COMPOUND TARGETS

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ABSTRACT

We have investigated the tribological properties of soft metal / DLC composite coatings deposited by RF magnetron sputter using compound targets.

INTRODUCTION

Diamond-like carbon (DLC) coatings have been widely studied by many researchers as excellent tribo-materials [1]. However, DLC coatings cannot be applicable for electric contact, because of their poor electrical conductivity. In addition to that, the friction coefficient of DLC is sensitive to the sliding conditions such as loading condition and surroundings. Adding metals to DLC coatings (Me-DLC) is thus considered as effective method to reduce the sensitivities of the tribological properties under the various loading conditions. Soft metals, such as copper and silver, are good candidates as additives because of their low shearing strength and high electric conductivity. In recent years, one of the authors has reported the tribological properties of the Copper/DLC nanocomposite coating (Cu-DLC) and Silver/DLC nanocomposite coating (Ag-DLC) which were prepared using hybrid deposition process composed of plasma enhanced chemical vapor deposition (PECVD) and DC magnetron sputtering of metal target [2, 3]. The idea of the hybrid deposition process is that the DLC matrix was synthesized by PECVD process using C2H2/Ar gas mixture, and then Ag or Cu vapor flux was supplied simultaneously by DC magnetron sputtering. Since the tribological properties of DLC depend upon its own structure, the tribological properties of Me-DLC would be changed when the structure of DLC matrix is changed.

PREPARATION OF SOFT-METAL / DLC COMPOSITE COATINGS

Cu-DLC and Ag-DLC were deposited on an Si(100) wafer by RF magnetron sputtering. In this study, metal/carbon compound target was employed for RF magnetron sputtering process. The circular tablet of silver or copper with a thickness of 2 mm was located in the center of sintered graphite disk with a diameter of 50 mm to avoid surplus addition of Cu or Ag in to Me-DLC coatings, because the sputtering yield of Cu and Ag are much higher than that of carbon. In addition, sputter rate in the center of target is low during RF magnetron sputtering process. As a result, Cu-DLC with 24~55 at.% of Cu and Ag-DLC with 26~65 at.% of Ag have been obtained. Transmission electron microscopy (TEM) observation showed that the nano-size clusters of metals were dispersed homogeneously in the coating. The I_D/I_G ratio of Raman spectroscopy of the coatings decreased as increasing metal concentration in the coatings.

TRIBOLOGICAL PROPERTIES OF SOFT-METAL / DLC COMPOSITE COATINGS

The friction coefficient of Cu-DLC showed relatively higher than that of the pure DLC deposited by RF magnetron sputtering, but was relatively stable than that of the pure DLC. The similar tendency was observed in the friction tests of Ag-DLC. The result of scanning electron microscope (SEM) observation and energy dispersive spectroscopy analysis showed that almost non-oxidized metal transfer (tribofilm) was formed on the worn surface of counter material. In this study, tribological properties of Cu-DLC and Ag-DLC by RF magnetron sputtering using solid compound targets have been discussed as a function of the nano-structure of the coatings and the formation process of metal-rich tribofilm.

ACKNOWLEDGMENTS

This work was partly supported by Grant-in-Aid for Scientific Research (C) (26420093) of Japan Society for the Promotion of Science (JSPS), Collaborative Research Project (J12061, J13083 and J14038) of the Institute of Fluid Science of Tohoku University, and the research expenses from Ube National College of Technology.

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T3-2 Mechanisms

Proceedings of the 42th Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France

TRANSFER-GROOVING MECHANISM BETWEEN BLADES AND ABRADABLE COATINGS: CONSEQUENCES ON BLADE VIBRATION

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The efficiency of aeronautical compressors is directly affected by the clearance between rotating blades and stationary casing. Reducing the in-service clearance to a few tenths of a millimeter has been shown to reduce leakage flows and consequently improve efficiency. However, rotor-stator relative displacements may lead to blade-casing contacts. In order to accommodate blade incursions, AlSi-based materials are used as inner coatings of compressor casings. Depending on materials and incursion conditions, wear and damage mechanisms of abradable coatings vary. At low incursion rate and low temperature, abradable material can be transferred onto the blade tip, forming localized protrusions, while the coating is simultaneously grooved. Recent studies have been conducted to identify the conditions leading to this unfavorable transfer-grooving mechanism [1,2]. In this paper, the consequences on the blade-casing clearance and the blade vibrations are investigated.

INFLUENCE OF THE TRIBO-MECHANISM ON THE BLADE-COATING CLEARANCE

Blade-abradable interactions were conducted on the ONERA test rig [3], with a flexible blade and an AlSi-Polyester abradable coating. Analyses of blade deflection, estimated interaction force and estimated blade tip-coating distance showed that a series of blade-coating contacts occurred – with a significant increase of blade vibrations – while a theoretical blade-coating clearance of few tens of micrometers was expected. Post-mortem profilometry measurements of blade tip and abradable coating were then achieved: the height of the protruding transfers (Fig. 1a) was found to be higher than the depth of the corresponding grooves (Fig. 1b), leading to a local increase of the blade length and consequently to the closure of the theoretical clearance.

ANALYSIS OF THE TRANSFER-GROOVING MECHANISM

Both rubbed coatings and blade tips were examined in order to interpret the tribo-mechanism. A transfer on the blade tip is formed by successive adhesions of micro-layers of abradable coating. This description is consistent with the results published in [2,4]. The adhesion process constitutes a part of the wear flow, while the other part corresponds to the abrasive action of the transfer onto the coating, leading to grooving and ejection of wear debris.

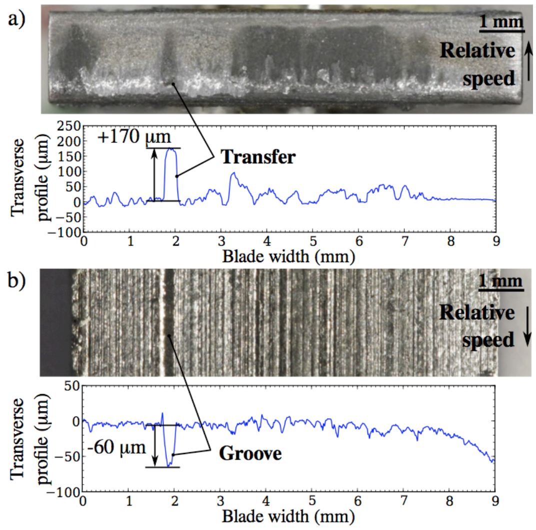

Fig. 1 Blade-tip protruding transfers
and corresponding abradable-coating grooves

CONCLUSIONS AND PERSPECTIVES

The present study brings a new approach to the transfer-grooving mechanism, as the couplings with occurrences of contact and blade vibrations were not studied so far. Moreover, the experimental data provided should help to strengthen the numerical wear laws used in blade-casing contact models [5].

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EFFECT OF WOVEN LINERS TREATED BY $LaCl_3$ AND CeO_2 SOLUTIONS ON FILM FORMATION MECHANISMS OF SELF-LUBRICATING SPHERICAL PLAIN BEARINGS

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ABSTRACT

The PTFE / Kevlar fabrics liners were treated by $LaCl_3$ and CeO_2. The tribological properties of self-lubricating spherical plain bearings with those liners were tested by self-lubricating spherical plain bearing tester, the film formation and wear mechanism were analyzed based on observation of the worn surfaces with SEM and EDS. The results showed that after treated the bearings tribological properties were improved, especially the wear resistance of bearings treated by CeO_2 were remarkable improved under higher swaying cycles, but the anti-friction properties and cooling effects of bearings treated by $LaCl_3$ were better under lower swaying cycles. The bearings with liners treated by $LaCl_3$ and CeO_2 only appeared slightly adhesive and abrasive wear, but untreated liners occurred serious adhesive and abrasive wear under higher swaying cycles.

INTRODUCTION

PTFE fiber is the ideal material being used as the self-lubricating liner for its special properties [1]. The PTFE fibers weaved with other functional fibers such as Kevlar fibers have been extensively studied by many Chinese and other country scholars [2-3]. The liners treated by rare earth solutions could improve the interface bonding force with substrate. The film formation mechanisms of the liners were investigated and analyzed through experiments.

EXPERIMENT AND RESULTS

The tested bearings is GE20UK 2RS, as shown in Fig. 1. The bearing tribological properties were tested by a self-lubricating spherical plain bearing tester. The swaying frequency f is 2.5 Hz, the swaying angle is $\pm 10^\circ$, and the specified contact pressure p is 30 MPa, the swaying cycles N were respective 0.75×10^4, 1.5×10^4, 2.25×10^4, 3.0×10^4, 3.75×10^4, 4.5×10^4 and 5.25×10^4. The experiment under same woking conditions was carried out three times and the average values were adopted.

The tribological properties varied with the swaying cycles for the untreated bearings and the treated ones at 2.5 Hz and 30 MPa are shown in Fig. 2. The SEM and EDS micrographs of the friction surfaces of liners untreated and treated by different solutions under different swaying cycles were observed and analyzed.

CONCLUSIONS

(1) The tribological properties of the bearings with liners treated by $LaCl_3$ and CeO_2 solutions were significantly improved compared with untreated ones

(2) Under higher swaying cycles, the uniformity and continuity of PTFE transfer film were improved after the liners were treated by $LaCl_3$ and CeO_2 solutions. While under lower swaying cycles, the anti-friction and cooling effects of bearings treated by $LaCl_3$ solution were farther improved. The anti-friction properties and cooling effects of bearings treated by CeO_2 being lower than the ones treated by $LaCl_3$.

(3) The bearings with liners treated only appeared slightly adhesive and abrasive wear, but the untreated bearings occurred heavy wear when the swaying cycle reached to $N=5.25\times10^4$.

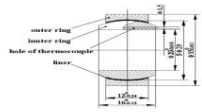

Fig.1.The structure of self-lubrication spherical plain bearing

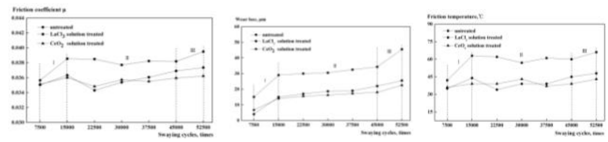

Fig.2. Tribological properties curves

ACKNOWLEDGMENTS

The authors are grateful to the National Natural Science Foundation of China (Grant No. 51275155), Outstanding Youth Fund Projects of Henan Province (No. 114100510002), and Innovation and Research Team of Science and Technology in Universities in Henan Province (No. 13IRTSTHN025).

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UNDERSTANDING THE BEHAVIOUR OF SILVER AS A LOW FRICTION COATING IN AEROSPACE FASTENERS

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ABSTRACT

The aim of this research is to investigate the frictional behaviour of silver coated threaded fasteners with a self-locking feature; focusing on the mechanism through which silver reduces friction and prevents seizure, with the long term goal of identifying an alternative coating to replace silver. The coefficient of friction of the crimped joint has been experimentally investigated, and the mechanical response of the silver coating analysed. In addition, the complete tightening process has been dynamically modelled using Finite Element Analysis techniques, in order to determine local contact pressures.

INTRODUCTION

Aero-engine manufactures use fasteners made from heat resistant super-alloys, as they must withstand high temperatures. In this study, Inconel 718 and Waspaloy fasteners are investigated, which are used in aero-engines over a range of temperatures from –50 to 760 °C.

When used in a like couple super-alloys have high coefficients of friction, and seizure frequently occurs. To prevent this, in aerospace applications, silver coatings are normally placed on the nut threads.

To prevent vibration loosening, a radial crimp is added to the end of the nut, localizing the stresses respectively in two small areas, providing a locking feature but also increasing the risk of removing the silver from the nut threads.

EXPERIMENT

To investigate the fasteners behaviour a new test rig has been built, as shown in Figure 1, with the aim of measuring the clamp load, the torque and the tightening angle, as a function of time. Through this approach it is possible to calculate the coefficient of friction on the threads, a key parameter in understanding the screw mechanism.

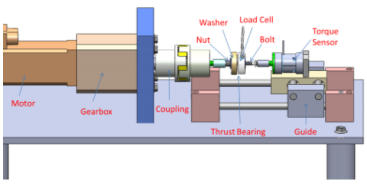

Figure1: Test rig

FINITE ELEMENT ANALYSIS

In this study a full 3D dynamic FE model has been created, inclusive of the self-locking feature. The coefficient of friction of the coating as a function of contact pressure has been studied using a ball on flat test, and the resulting relationship used as an input in the FE model.

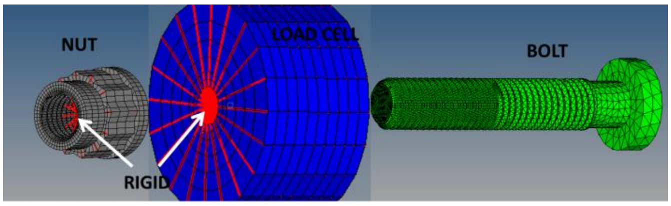

Figure 2: FE parts

The FE Analysis has been validated using the experiment results, as the boundary conditions and geometries are the same. The torque required to tighten the nut, the sum of the torque required to overcome the friction in the threads and to stretch the bolt, has been plotted along with the clamping load.

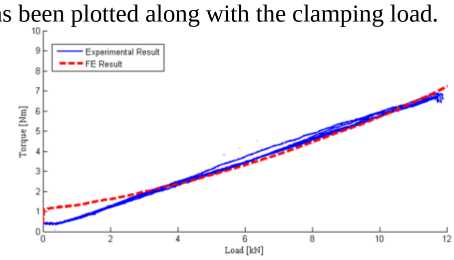

Figure 3: FE validation

Using this approach local aspects of the behaviour of the silver coating have been analysed.

CONCLUSION

The tightening process has been investigated experimentally, and also analysed using a finite element method. Through the combination of the two approaches, the behaviour of the silver coating and mechanism through which it provides solid lubrication at the thread contacts has been understood. Following on from this a series of alternative coatings will now be investigated.

WEAR OF NEW COATED ABRASIVE BELT STRUCTURES IN AUTOMOTIVE CRANSHAFT MULTISCALE FINISHING

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ABSTRACT

Belt finishing is one of the abrasive machining processes, widely used in automotive industry, to improve surface texture and to increase wear resistance and fatigue life of journals crankshaft [1]. The coated abrasive grains morphology and material as well as the belt structure are the critical variables that affect the crankshaft surface quality in a wide range of scales [2].

Electrostatically deposited abrasive belts are commonly used to super-finish crankshaft's journals and pins (Figure 1-a). Recent study [3] shows that lapped deposition of coated abrasive grits allows achieve the functional surface morphology requirements by reducing significantly the asperities height without acting on the valley depth.

This paper is devoted to study the impact of the belt joint technology on the wear and service life duration of the abrasive belts. To this aims, experimental wear tests were occurred on four different deposition technologies of structured abrasive belts (Figure 1). The instrumented test rig allows to track in situ the evolution of friction and the power dissipated during the abrasive finishing process. The analysis of the experimental results is based on the characterization of the multiscale wear process signature of the abrasive belt using wavelets transform. Amounts of the evolved performances are then correlated separately by an energetic decomposition of the abrasive process to examine the evolution of the predominant activated mechanism.

Results show the dynamic evolution of the multiscale wear process signature for each belt deposition technology and suggest the existence of promising way for increasing the efficiency of belt abrasive technological processes.

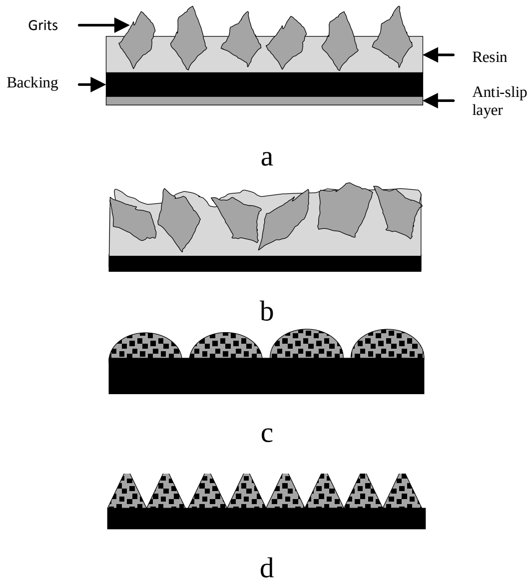

Figure 1: Four coated abrasive belts deposit, Electrostatic deposition (a), lapped deposition (b), micro-replicating deposition (c), pyramidal agglomerated grits (d).

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T4-2 Skin Tribology

MEASUREMENT OF THE FRICTION FORCE OF A PILLAR STRUCTURE ON A SMOOTH SURFACE

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INTRODUCTION

This paper focuses on the measurement of the dry friction of a single pillar and array of pillars dragging back and forth on the smooth surface. The pillars are made of soft polymer and the surface is a silicon wafer. Experimentally measured friction force is compared with the theoretical ones by using an energy equivalence of a single pillar.

MOTIVATION

Gecko has a unique fibrillar structure on the foot that allows to obtain high adhesion and friction force to almost any surface. The surface texturing of polymers to obtain synthetic fibrillar surfaces is a one way to mimic the Gecko's adhesive capability [1]. This phenomena provides an enormous application areas such as the climbing robots that uses only Van-der Waals force. While Gecko is climbing on a vertical wall, friction force balances the gravity force. Friction force between two surfaces in contact decreases as the relative velocity becomes higher, yet frictional dynamics of the fibrillar surfaces do not behave according to this condition. Gecko adhesion depends on the friction force occurring in the gripping direction, which leads to a directional frictional-adhesion model. In this model friction force plays an important role on the adhesion [2].

EXPERIMENTAL METHOD

The single and array of pillars with different diameters are made out of PDMS and manufactured by using a molding procedure. Custom-made experimental setup consists of two linear stages where precise motion is achieved in horizontal and vertical directions as seen in **Fig.1.**

RESULTS AND SUMMARY

The single pillar and the pillar array behave as a viscous friction at lower drag velocities. As the velocity becomes higher, friction force increases in the magnitude of 22 % for the single pillar and pillar array until friction force reaches to a saturation value. The friction force does not change when the pillar structure is dragged back and forth. Increasing the preload, which is less than the critical value of the buckling force, yields an increase on the friction force. The kinetic friction force of the single pillar and the pillar array are compared and a difference of 20 % is observed in the friction force. At lower drag velocities, stick-slip motion is observed for the single pillar. Energy based analytical modelling is applied to analyze the stick-slip motion and resulting relative

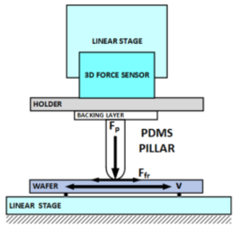

Figure 1 The illustration of the expérimental setup

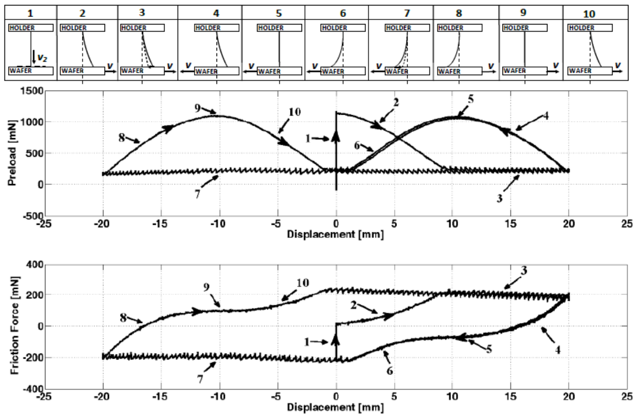

Figure 2 A sample of friction loop where the arrows represent the sequence of the motion.

error between experimental and theoretical results are less than 20 %.

ACKNOWLEDGMENTS

This work is supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under grant number 110M508.

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Multiscale Porous-Viscoelastic Model of the Skin and Subcutaneous Tissues: Preliminary Measurements on Pig Skin and Silicone Rubber

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ABSTRACT
This presentation includes a description of a porous-viscoelastic model of the skin’s dermis and may be extended to other subcutaneous tissues. The model is in contrast with currently used porous-elastic models and identifies the crack initiation and propagation in the tissue as a component to the pain feel during drug delivery. Multiscale Contact Mechanics is used to describe the crack initiation and propagation during a subcutaneous drug delivery injection. Although we discuss the potential wide range of application of the model on other physiological applications, we focused on the application to intradermal drug delivery. We have measured the crack propagation energy per unit surface area G (v,T) at different temperatures between 5 and 40 °C and crack tip velocity in both pig skin and silicone rubber slabs. The silicone rubber slabs were cross-linked to 0.5 and 2.5 MPa Young’s modulus. Values for the G (v,T) were obtained by tensile measurements at different speeds and temperatures. Additionally, using hyper-Differential Scanning Calorimetry (h-DSC) and Dynamical Modulus Analysis (DMA) we also identified phase transitions occurring in the pig dermis between 10 and 30 °C. The origin of such phase transitions is an ongoing research. The predictions of the MCM model were compared to experimental data from injections of saline solution at the dermis of pig skin and in the silicone rubber slabs.

ACKNOWLEDGMENTS
The authors Acknowledge the contributions of Paul Santos and Katherine Chew for the help with the experiments on crack propagations.

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FRICTION AND VIBRATION CRITERIA FOR TACTILE DISCRIMINATION OF PILE FABRICS

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ABSTRACT

The presented study is a part of the interdisciplinary project COSTaM on tactile disorders. The goal of this project is to develop tactile surfaces to identify tactile disorders and allow specific rehabilitation. This work is about the characterization of the touch of *fibrous* surfaces. The friction between the finger and the *fibrous* samples is investigated and two criteria which characterize the contact between finger and fabric have been identified.

INTRODUCTION

In the COSTaM project three kinds of real surfaces have been chosen, because they embody tactile descriptors identified as significant descriptors in perceptual space representation [1] and they should excite the different kinds of cutaneous mechanoreceptors [2]. The corresponding descriptors are: *relief* (smooth-rough), *braking* (slippery-sticky) and *fibrous* (without or with hairiness). Five intensity gradients of the *fibrous* descriptor, in terms of hair length, are investigated. The purpose is to study both the friction and the induced vibrations between the surfaces and the finger and to propose mechanical criteria which characterize the *fibrous* descriptor by a "tactile point of view".

EXPERIMENTAL

Investigated fibrous surfaces

Five artificial fur samples are investigated. They are similar except in their hair length: 1, 2, 3, 5 and 10 mm.

Tribometers

Two complementary experimental devices are used. The fabric sample moves under the finger at a nominal sliding speed of 20 mm/s. The individuals have to control their normal force to around 0.5 N. The TriboTouch set-up allows for moving the samples without parasitic vibration. During one test, the fabric moves along a single direction. The friction and normal forces are recorded by tri-axis force sensors. Moreover, the finger acceleration is obtained from an accelerometer positioned on the nail. With the LPMT's tactile tribometer, the fabric sample is affixed onto an oscillating motor-controlled table and a back and forth movement is imposed. The friction and normal forces are recorded by a tri-axis force plate. For both tribometers, the fingertip slides on the fabric. The individuals gave their informed consent and none suffered from physiological or cognitive deficits that might alter their tactile perception.

RESULTS

The coefficient of friction is proved to not be a pertinent criterion to discriminate fibrous fabrics as regarding hair length, in contradiction to [3]. Nevertheless, two interesting criteria which have a monotonic evolution with the hair length have been identified. A first criterion, is the RMS (Root Mean Square) of the acceleration of the finger in a direction perpendicular to the nail. The evolution of the RMS of the acceleration decreases, in both along and against pile main direction, when hair length increases. It can be supposed that the excitation of the cutaneous vibration mechanoreceptors, named Pacinian, is lower for long pile than for short pile. In another way, the mean adimensioned energy W_{adim} (in m^{-1}) dissipated during the change of finger direction, from along to against and against to along the pile main direction, lineary increases with the hair length:

$$W_{a\,dim} = \int \frac{F(x)}{W(x)} \cdot dx$$

where F(x) and W(x) are respectively the tangential and normal instantaneous forces and x the sliding displacement.

ACKNOWLEDGMENTS

The authors are grateful to all the volunteers who participated and gave their time freely. This work was supported by the DEFISENS program of the National Organization for Scientific Research (CNRS, France)/

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MODELLING THE INFLUENCE OF MOISTURE ON THE FRICTION OF HUMAN SKIN

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ABSTRACT

The friction of the human finger pad as a function of skin hydration was experimentally investigated and modelled on the basis of the adhesion friction model in order to analyse the moisture-dependence of parameters such as the real contact area and interfacial shear strength.

INTRODUCTION

The friction coefficient of human skin strongly depends on skin hydration and the presence of interfacial water films [1,2]. Previous studies reported evidence for a bell curve relationship between moisture degree and friction coefficient [3,4]. It is unclear how this behaviour can be explained within the adhesion friction model $F_{adh} = A \cdot \tau$ (where F_{adh} is the friction force, A the real contact area and τ the interfacial shear strength) which is commonly used to describe the friction of skin on the phenomenological level [5].

In this study we investigated the friction of the finger pad against different surfaces as a function of skin hydration. The objective was to observe and analyse different cases of bell-shaped relationships between friction coefficient and skin hydration, in order to gain new insights into the moisture-dependence of the parameters playing a role in the adhesion friction model.

METHODS

Finger friction measurement series against three surfaces (smooth and rough glass and aluminium with intermediate roughness) were carried out by one subject using a tri-axial force plate. The hydration level of the skin of the finger pad was varied by defined periods of occlusion and drying before friction experiments. Skin hydration was measured after each individual friction cycle using a Corneometer CM 825.

RESULTS AND DISCUSSION

The skin hydration states obtained by occlusion and drying processes were characterised by CM values between 40 and 120 (a.u.), representing normal to above-average skin hydration [6]. Within this range of hydration levels, the friction coefficients indicated bell-shaped curves for all investigated surfaces that could be approximated by quadratic functions (Fig. 1). The observed maximum friction coefficient depended on the roughness of the counter-surface and occured at different skin hydration states. The highest and lowest maximum friction coefficients of about 2.6 and 1.1 were found on smooth and rough glass for CM values of about 75 and 115, respectively. The results for aluminium lay in between (maximum friction coefficient of about 1.7 at a CM value around 100).

Qualitatively, the first, increasing part of the bell curve relationship between friction coefficient and hydration of human skin can mainly be associated with an increase of the real contact area due to hydration and softening of the stratum corneum, while the second, decreasing part is related to the effects of interfacial water [2]. Quadratic fit functions providing a good first approximation to the data shown in Fig.1 as well as alternative functions were used to model the bell curve behaviour analytically and to investigate which functional relationships between real contact area, interfacial shear strength and skin hydration are plausible implications within the framework of the adhesion friction model.

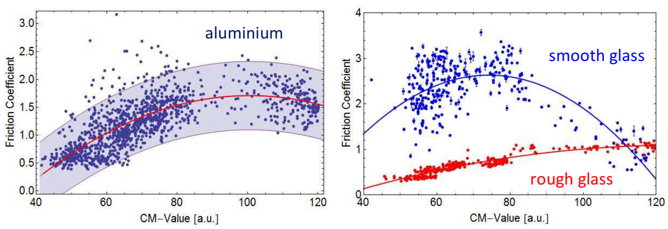

Fig.1: Relationship between friction coefficient and hydration of the finger pad on aluminium (left) and smooth and rough glass (right). The data were fitted by quadratic functions.

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T2-2 Tribochemistry and wet lubrication

MECHANISMS BEHIND THE PROMISING TRIBOLOGICAL PERFORMANCE OF A BORIC ACID BASED LUBRICANT ADDITIVE

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ABSTRACT

The tribological behavior of new Swedish boron containing lubricant products has been tested with the intention to understand the mechanism behind the remarkable fuel saving obtained in field tests. Chemical analyses of samples from lab tests as well as from field tests suggest that a thin layer of boric acid if formed and works as a solid lubricant.

INTRODUCTION

Lubricant additives are important to decrease friction and wear in vehicles and thereby save fuel and enhance the lifetime of components in engine and gearboxes. However, many additives used today are harmful for both environment and human health and should preferably be replaced. Additives containing boric acid constitute promising alternatives, which are relatively harmless [1], cheap and abundant in nature. The low friction properties of boric acid have been known since long [2]. However, their successful introduction has been hindered by problems with particle agglomeration [3]. A new Swedish product line with fuel enhancer and lubricants containing a boric acid based additive has existed on the market for some time and has exhibit promising results in field tests, but without the negative aspects associated to previous boric acid products. Remarkable average fuel savings in the range of 6 respectively 10 % were obtained with a fuel enhancer product added to the fuel in tests with cars and with diesel generators. This study aims towards understanding the mechanisms behind these positive results and thereby giving the scientific background that is necessary to enable a broader introduction to car and heavy-duty users.

METHOD

The friction and wear performance obtained with the boron containing products was compared with a number of reference oils in a reciprocating ball on disk equipment. A test series with strategic parameter variations was performed with the intention to map the parameter window and finding other requirements for beneficial effects.

To obtain further knowledge about the mechanisms behind the low friction, all surfaces were investigated in the scanning electron microscope, and the chemical composition of the wear marks and possible tribofilms was analyzed using energy dispersive X-ray spectroscopy, X-ray photo electron spectroscopy, auger electron spectroscopy and secondary ion mass spectrometry to obtain further knowledge about the mechanism behind the low friction. For comparison, the same analyses were performed on a piston ring from a motorcycle that was run with the product.

RESULTS AND DISCUSSION

A lower coefficient of friction was obtained in tests with the boron containing products compared to the reference tests. The performance was temperature dependent. Results from the chemical analyses showed that a low amount of boron bonded to oxygen was present in the wear tracks from experimental tests as well as on the piston ring from field. This suggests that a thin layer of boric acid is formed and works as a solid lubricant. The implications of these results as to the fuel savings obtained in the field tests will be thoroughly discussed.

ACKNOWLEDGMENTS

The support from the Swedish Foundation for Strategic Research (via the program Technical advancement through controlled tribofilms) is gratefully acknowledged. The authors are also grateful to Jonas Andersson for help with experimental work.

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TRIBOLOGICAL PROPERTIES OF DIALKYLPHOSPHONOACETIC ACID IN BIODEGRADABLE SYNTHETIC ESTERS

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INTRODUCTION

Demands for Bio-lubricants have been increasing, especially for applications in excavators, wind turbines, marine vessels and so on. Bio-lubricants often use natural or synthetic esters as environmentally adapted base stocks. However, their tribological properties cannot necessarily be improved by lubricating additives generally employed in mineral base oils. In this study, investigation was carried out to find out suitable phosphorus containing compounds for an ester base stock.

EXPERIMENT

The used phosphorus additives in this investigation are tricresyl phosphate (TCP), dialkyl phosphate (DAP) and dialkyl phosphonoacetic acid (DAPA); see Fig. 1.

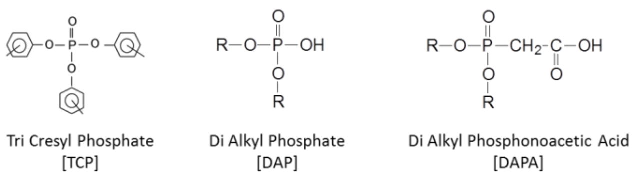

Fig. 1 Chemical structures of phosphorus additives

The selected ester base fluid is trimethylolpropane triolate (TMPO). TMPO is superior in biodegradability and has widely been used for bio-lubricants. Poly-α-olefin (PAO) is also used for a comparison. The viscosity of TMPO and PAO is in the ISO VG46 grade.

Lubricating properties were measured using the four-ball wear test and FZG (Forschungsstelle fur Zahnradar und Getriebebau) scuffing test.

RESULTS AND DISCUSSION

The antiwear properties of phosphorus additives in TMPO were evaluated by the four-ball wear test. The results of wear scar diameter are illustrated in Fig. 2. DAPA has shown the superior antiwear property to that of such conventional phosphorus containing additives as TCP and DAP.

The effectiveness of DAPA in TMPO was compared with that in PAO by FZG test. The results are shown in Fig. 3. In order to improve tribological properties, the addition of DAPA in PAO was not as effective as that in TMPO and provided a level equal to TCP in FZG test.

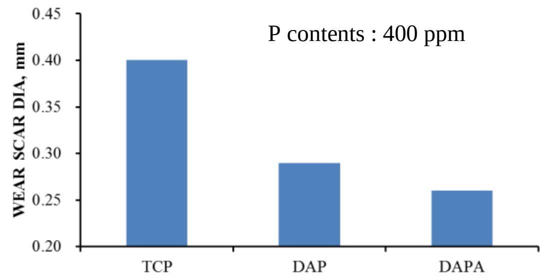

Fig. 2 Results of the four ball test with additives in TMPO
(Test conditions: 294 N, RT, 1200 min^{-1}, 30 min)

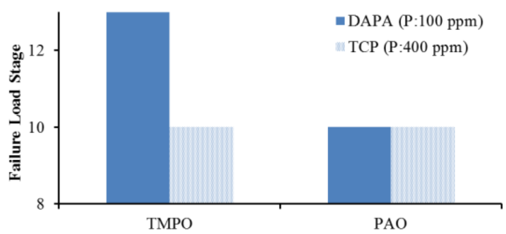

Fig. 3 Results of FZG scffing test with DAPA in TMPO and PAO
(Test conditions: 90 °C, 1450 min^{-1})

To clarify this different tribological behavior of additives between two types of base fluids, adsorption of DAPA onto iron surfaces was examined in TMPO and PAO. The results showed that the quantity of adsorption of DAPA was more in TMPO than in PAO, and this distinction in adsorption characteristics onto iron surfaces was considered to be in close connection with the tribological behavior of additives in different base fluids. Further, ^{31}P NMR results indicated that there was strong interaction by hydrogen bonds between DAPA molecules in PAO compared with weak one between them in TMPO, explaining that carboxylic acid of DAPA would easily adhere onto the iron surface in TMPO.

Stability of friction fade-out at PLC films slid by ZrO_2 pins under ethanol added hydrogen gas environment

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ABSTRACT

A clean hydrogen energy is expected as a promising future energy due to its high energy efficiency and small impact on the environment, and the hydrogen technology is considered one of the key technologies in the 21st century. In order to build hydrogen infrastructures taking into account the requirement of low energy cost, it is necessary to construct low-friction tribology systems against the high reduction power of hydrogen. On the other hand, tribological characteristics of diamond-like carbon (DLC) have been widely studied aiming various applications because DLC generally exhibits low friction, high wear resistance, high hardness and chemical inertness

We reported at the 41st Leeds-Lyon symposium on Tribology (2014) that polymer-like carbon (PLC) films slid by ZrO_2 pin exhibited exceptionally low friction coefficient [1], which we called friction fade-out (FFO) since the measured friction was the tribometer noise level as low as 1.0 mN when the applied load was 4.9 N under the hydrogen environment, corresponding to the friction coefficient of about 0.0002.

In this paper we will report that FFO occurs at significantly heavy applied load of 63.7 N, corresponding to the maximum Hertzian pressure of 2.3 GPa, that FFO occurrence is affected by the formation process and characteristics of tribofilms formed on ZrO_2 pin, and that the stable FFO can be reproducibly achieved when a mist of thin ethanol solution in water is added at the initial stage of the friction test to a dry hydrogen gas which is supplied to the test section. It is discussed by referring Raman spectroscopy measurements and SEM observations after the test that the tribofilm inviting stable FFO is formed by the process; initially ethanol and water molecules thrust into the clearance between ZrO_2 pin and PLC film and agglomerate at the clearance, then after the cease of ethanol mist supply, a solid hydrocarbon film like PLC is formed and at the same time some kind of gas is generated at the interface by the friction under a heavy applied load, where catalytic reaction of ZrO_2 plays very important roles.

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BOUNDARY LUBRICATION OF AQUEOUS COPOLYMER LUBRICANT: INFLUENCE OF COPOLYMER CONCENTRATION AND APPLIED PRESSURE

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ABSTRACT

Although there have been many experimental studies to investigate the lubrication of aqueous copolymer lubricant in boundary lubrication, a comprehensive theoretical investigation at atomistic level is still lacking. The aim of this work is to carry out a molecular dynamic (MD) simulation to investigate the tribological performance of polymer aqueous solution of polypropylene oxide – polyethylene oxide – polypropylene oxide (PPO–PEO–PPO) to support previous experimental observations. The empirical potentials using an explicit atom model were applied for the model system. An effective interfacial potential was derived from quantum chemistry calculations and applied for the interaction between the fluid and solid surfaces. The obtained results confirm that the friction force during shear and the wear between the two counter asperities decreased with an increase of copolymer concentration. In contrast, these quantities increased significantly with applied pressure.

INTRODUCTION

Put introduction text here. Please use the number-in-bracket [1] reference format throughout the paper.

NOMENCLATURE

Put nomenclature list here (if applicable). Sort by upper and lower case English, then upper and lower case Greek, etc.

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Main Body Sub-headings

Put body of the paper here. Please number all equations, and provide a Caption beneath all Figures and Tables.

ACKNOWLEDGMENTS

Put acknowledgments here (if applicable).

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IMPROVEMENT OF MICROPITTING, WEAR, AND FRICTION BEHAVIOUR UTILISING DIAMINE-BASED SURFACTANT AND ITS EFFECT ON TRIBOFILM FORMATION IN ROLLING-SLIDING CONDITION

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ABSTRACT

Effects of the diamine-based additive (DBA) on Stribeck friction curve and tribofilm thickness and micropitting occurrence have been investigated utilizing Mini Traction Machine (MTM-SLIM) and Micropitting rig (MPR) respectively. The X-ray Photoelectron Spectroscopy (XPS) analytical technique has been employed to investigate the effect of DBA on the chemical composition of the formed tribofilm.

INTRODUCTION

Micropitting is a prevailing surface feature occurring on gear and bearing contact surfaces. Previous research has shown that micropitting is prompted in the event of using anti-wear additives which can lead to premature failure [1].

In compliance with the micropitting concern for industry, the aim of this project is to optimize the performance of the bearing in terms of micropitting, wear, and friction in the presence of zinc dialkyldithiophosphate (ZDDP) utilising DBA. Friction modification and affinity of functional group of DBA to ZDDP, which brings about delay in ZDDP decomposition, were the rationales behind using DBA to diminish micropitting.

METHODOLOGY AND RESULTS

The both MTM and MPR tribological tests have been carried out considering four lubricants:

- Oil-A (base oil),
- Oil-B (base oil + ZDDP),
- Oil-C (Oil-B + DBA at Concentration of C),
- Oil-D (Oil-B + DBA at Concentration of C*[1]).

SEM, optical microscopy, and WLI disclosed that DBA effectively reduced micropitting appearance and micropitting volume as shown in ***Figure 1***.

MTM results showed that DBA added to Oil-C and Oil-D reduced the friction coefficient by approximately 10% and 20% respectively compared to Oil-B. The proposed mechanism of action of the diamine additive is thought to be the delaying effect on anti-wear tribofilm formation as it is implied in ***Figure 2***.

[1] C* = 2×C

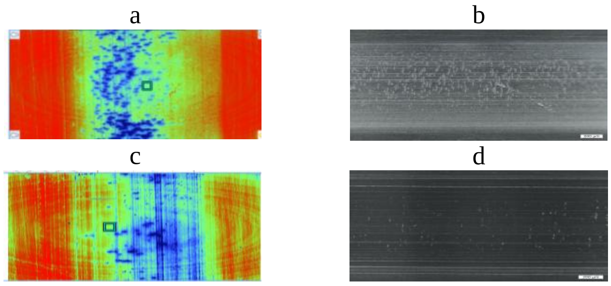

Figure 1: *a) WLI and b) Optical microscopy images of surface lubricated with Oil-B. c) WLI and d) Optical microscopy images of surface lubricated with Oil-D*

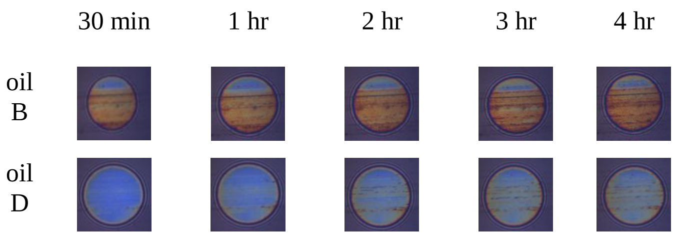

Figure 2 :*Tribofilm formation after specific rubbing times lubricated with Oil-B and Oil-D*

SUMMARY

In this paper micropitting volume and surface density, wear volume, friction coefficient, wear scar and tribofilm morphology, tribofilm thickness, and tribofilm chemical composition will be compared and discussed in detail considering lubricants with and without the presence of DBA and ZDDP. The employed characterization techniques are WLI, optical microscopy, SEM, and XPS.

ACKNOWLEDGEMENTS

This study was funded by the FP7 program through the Marie Curie Initial Training Network entitled “FUTURE-BET”.

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T3-3 Materials

THE EFFECT OF MARTENSITIC VOLUME FRACTION ON ABRASIVE WEAR AS DETERMINED IN A MULTI-PASS DUAL-INDENTER SCRATCH TEST

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1. INTRODUCTION

Dual phase steels (ferrite and martensite) with good strength and formability are potential engineering material system for automobile and other engineering applications. In DP steel microstructures, the ratio of the two phases is the most critical parameter in determining the final mechanical properties, including the abrasion resistance. Some early investigations have shown that the wear resistance continuously increases with the martensitic volume fraction, while more recent observations reported that the presence of a higher ferrite fraction may increase the abrasion resistance considerably compared to that of the full martensite due to the higher work hardenability. In the present work, dedicated experiments are carried out to create dual phase microstructures with different martensitic volume fractions, with a particular focus on steels with a high volume fraction of martensite, aiming to investigate the relation of the martensitic volume fraction and the abrasion resistance in DP steels. The abrasion resistance and failure mechanisms of resulting microstructures under different load conditions were evaluated using a multi-pass dual-indenter scratch test, which recently was shown to capture the key phenomena in abrasion wear [1].

2. EXPERIMENTAL PROCEDURES

2.1 HEAT TREATMENT AND SAMPLES PREPARATION

The composition of the Dual Phase steel in the current study is 0.22C-1.2Mn-0.25Si-0.2Cr. Two types of heat treatment cycles were performed: (a) fully austenitization followed by intercritical annealing at 625℃, 700℃, 725℃, 750℃, and 760℃ holding temperature for 1h respectively, and water quench, and (b) fully austenitization followed by water quench.

2.2 MULTI-PASS DUAL INDENTER SCRATCH TEST

The multi-pass dual indenter scratch test developed as a predictive tool for the abrasion resistance of steels consists of three steps: 1)Multi-pass (typically 10 passes) pre-scratching of the original surface with a large indenter (R=100µm, cone angle 120°) at various pre-loads (5 to 25 N), 2) Pre-scanning of the profile of the central region of the wear track formed using the small indenter (R=5µm, cone angle 60°) at a very low load of 0.03N not causing any further damage or deformation. 3) Scratching the central region of the wear track with a small indenter using a fixed load of 0.2 N in a single pass. The scratch depths to be reported refer to the penetration depth by the small indenter scratching only (i.e. the change in depth with respect to the depth produced in the prior scratching with the big indenter)

3. RESULTS AND DISCUSSION

The scratch depths as a function of volume fraction of martensite under different pre-loads are shown in Fig.1. A low scratch depth is indicative of a high abrasion resistance. An increase in scratch depth is indicative of local failure and onset of abrasive damage. It can be observed that under a low load of 5N, the scratch depths generally decrease with increasing martensite fraction up to 100%, which corresponds well with the indentation hardness. However, under a high load of 25N, the scratch depth decreases with increasing martensite fraction up to a critical fraction of 85% beyond which the scratch depths start to rise. Fig.2 shows the difference of scratch depth with increasing martensite fraction. For more ferritic DP steels, the increase in martensite fraction results in a significant decrease in scratch depth under high load but not under low load, while more martensitic DP steels show the opposite results.

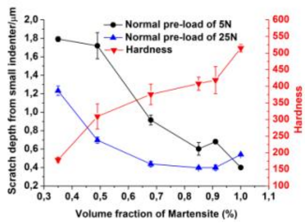

Fig.1 Variations of scratch depth by small indenter as a function of the martensitic volume fraction under different pre-loads

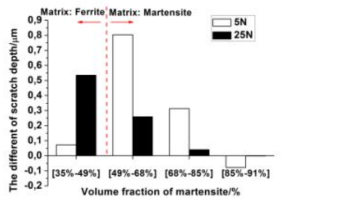

Fig.2 The difference of scratch depth with the martensitic volume fraction increase under pre-load of 5N and 25N for DP steels

4. CONCLUSION

For DP steels, the scratch depth decreases with increasing the volume fraction of martensite up to a critical volume fraction of martensite, and further increase in volume fraction does not improve the scratch resistance. The harder Full Martensite microstructure gives the best scratch resistance under low load, but not under high loads. The variations of the difference of scratch depth with increasing volume fraction depend on the pre-loading condition and the type of matrix of DP steels.

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DRY SLIDING PEEK AGAINST AISI 316 STAINLESS STEEL FOR SEVERE SERVICE

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ABSTRACT

The simulation and prediction of the tribological response of the interaction between a ball and seat is critical to the development of high performance ball valves for severe services energy applications. Simulating the contact conditions between a ball and seat, can be difficult given the non-linear relationship between loading, applied torque, friction control and sealing performance [1]. Simulations are further complicated when critical service conditions are also considered (such as large temperature differentials between the contact surfaces, pressures and contamination). At moderate temperatures, and depending on the required operating torque, polyetheretherketone (PEEK) may be used. The combination, when compared to other engineering polymers, of very good thermal and mechanical properties, low friction and good chemical resistance, particularly under severe service, make PEEK a very widely used material in valve components for energy applications in industries including petrochemical, nuclear [2], [3] and marine.

This paper presents a comprehensive analysis of the dry wear and friction of PEEK/ 316 bearing surfaces for a wide variety of simulated valve conditions. Tribological experiments were conducted using a Plint TE77 reciprocating tribometer under dry conditions for a range of temperatures (-30, ambient, 140 and 290°C). Contact conditions were designed to replicate real in-service pressures, with 3 (i.e. 0.5, 4, 7 MPa) used to derived appropriate test rig loads. Tests were conducted for a fixed number of cycles, simulating the accelerated durability requirements for typical ball valves. Throughout the experiments, friction and bulk specimen temperature were recorded, along with a visual record of the wear process. Specific tribological data was also acquired throughout the test using a high speed data acquisition unit.

Wear (measured gravimetrically) and surface topography was analysed post testing. An InfiniteFocus optical 3D micro coordinate system was used to assess surface morphology, as well as Scanning Electron Microscopy to map the development of wear.

Among the principal insights gained from this research was the mechanism of the activation of wear that was correlated against the increase in temperatures (particularly once the glass transition temperature of the material had been exceeded). The wear processes for selected seat materials were shown to be highly dependent on the surface morphology of the mating ball surface. Tribological data generated was then used to simulate the typical wear progression throughout valve operation, leading to the formation of an in-depth understanding of the formation and function the of transfer film, with these conditions.

When combined, the development of wear and friction on the mating surfaces are used to formulate a predictive tool for the performance and optimisation, in terms of material combinations, of soft-seated sealing contacts.

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PIN ON DISC TRIBOTESTS WITH THE ADDITION OF CU PARTICLES AS AN INTERFACIAL MEDIA: CHARACTERIZATION OF DISC TRIBOSURFACES USING SEM-FIB TECHNIQUES

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ABSTRACT

The general purpose of this investigation wasto investigate the effects of Cu particles as an interfacial media on the contact area of steel against steel during pin on discs tests. The present paper focuses on the effect of the Cu addition (400 μm, 20 μm and 50 nm) on the microstructure and topography of the steel discs. These resultswere compared with the condition without any particulate addition. Scanning electronicmicroscopy (SEM), focused ion beam (FIB) microscopy and X-ray mapping (XEDS) were used to characterize the chemical composition and themicrostructure of the debris, the tribofilmand the plastically deformed layer on the discs' tribosurfaces. The topographic characterization showedthe formation of third body by wear particles, the presence of *plateaus* with sliding wear marks and, for some conditions, the formation of oxide transfer layers.Morphological characterization of collected debris showed that Cu particleswere plastically deformedfor all investigated condition and that Cu particles of 20μm and 50 nm went through sintering during tribotest. The X-ray mapping characterization of the third body adhered to the tribosurfaces of the discs showed the presence of O associated with Fe for all conditions. Additionally, expressive adhesion of Cu particles on the disc tribosurface wasdetected via XEDS for the conditions with Cu particle size of 20 μm and 50 nm.The FIB cross-sections images revealed heterogeneous tribosurfaces, allowing the identification of the various stages of the tribofilm development: formation of superficial tribological transformation (STT) layers; nucleation and growth of sub-superficial crack; detachment of plastically deformed regions; and formationof debris. The depth of the STT layer did not vary with the Cu granulometry. The formation of a compact and continuous oxide layer on the discs´ tribosurface was only observed via FIB for the 400μm Cu condition and for the experimental setup without any Cu addition. For both samples comminution, oxidization and sintering of debris were observed, leading to the formation of a compact continuous oxide layers. Finally FIB technique combined with X ray mapping (XEDS) proved to be a powerful tool to investigate tribosurfaces.

INTRODUCTION

Put introduction text here. Please use the number-in-bracket [1] reference format throughout the paper.

NOMENCLATURE

Put nomenclature list here (if applicable). Sort by upper and lower case English, then upper and lower case Greek, etc.

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Put body of the paper here. Please number all equations, and provide a Caption beneath all Figures and Tables.

ACKNOWLEDGMENTS

Put acknowledgments here (if applicable).

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A TEST RIG FOR STUDYING THE FRICTIONAL BEHAVIOR OF STEELS WITH SULFUR POWDERS

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ABSTRACT

In order to study the friction behavior of steel with sulfur powders. A new test apparatus is designed and developed to reproduce the friction phenomena at lab scale, by exposing test specimens to normal load and rotating disk-on-thrust plate sliding contact in sulfur powder environment. The test rig can represent the friction behavior, a series of experiment has been carried on the test rig to study the friction ignition mechanism of sulfur powders.

INTRODUCTION

In the process of sulfur production and transportation, many transmission components are exposed to sulfur powder environment. Sometimes the friction of the steel transmission components with sulfur powders leads to fire and may bring serious results [1]. There are no test apparatus or methodologies described in the literature for studying the mechanisms of producing fire by the friction of steel components with sulfur powders and performance of such complex friction scenarios.

THE TEST RIG

A new test rig is built up. The core of the test rig is illustrated in Fig.1.

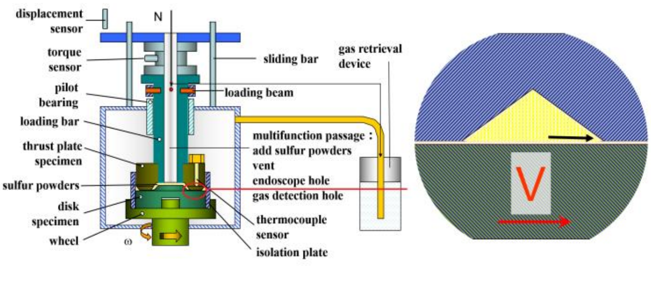

Fig.1 Diagram of the key parts of the test rig

In the test rig, the structures of test specimens are designed specially to ensure plenty of fine sulfur powders entering the contact surfaces and enough frictional heat building up as soon as possible in the process of friction. The stationary thrust plate specimen with a central hole as sulfur entrance is mounted on the rotating disk specimen which is driven by a servo motor to generate sliding friction. A set of lever mechanism is placed on a shaft fixed with the thrust plate to provide the normal load. A thermocouple sensor is located next to the contact surface of the thrust plate to measure temperature meanwhile a torque sensor is linked with the plate to detect friction on line.

THE TEST RESULTS

Initial tests of the 1045 steel specimens with sulfur containing 2% water show that the friction of steels with sulfur powders can result in formation of ferrous sulfide under certain conditions and enough frictional heat building up in the process can further activate the ferrous sulfide's self-heating reaction which leads to fire near the contact surfaces even at a low temperature less than 70ºC. The test result is illustrated in Fig.2.

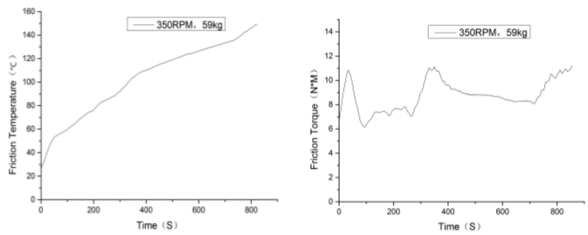

Fig.2 Friction temperature and friction torque of the test

CONCLUSIONS

Test results obtaining by the developed test machine present the change rule curve of fritiontemperature and frition torque which change along with variation of time in the frition process. The test rig supply a powerful tool to realize the the friction ignition mechanism of steel components in sulfur production and transportation system.

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EXPERIMENTAL STUDY ON IGNITION MECHANISMS OF SULFUR CAUSED BY FRICTION

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ABSTRACT

In order to study the ignition mechanisms of sulfur caused by friction, a series of experiments have been performed. Test results showed that: under a high load, the sulfur powders was ignited by the friction produced high temperature; Under a low load, the complex physical-chemistry reaction in the friction progress produce ferrous sulfide's, and the ambition temperature can activate the ferrous sulfide's self-heating reaction, so it could ignite sulfur at a low temperature below 70 ℃.

INTRODUCTION

In the process of sulfur production and transportation, many transmission components are exposed to sulfur powder environment. Sometimes the friction of the steel transmission components with sulfur powder leads to fire and may cause severe accidents [1]. When considering sliding contacts, the studies show that 95% of the mechanical energy is transformed into heat [2]. The poor cooling conditions will lead to a rise in temperature. When the temperature rise of 270 ℃ the sulfur will be ignited. But in the actual production process when the temperature is below 70 ℃ sulfur burning phenomenon will always appear. There are no methodologies to explain it in the literature for studying the mechanisms of producing fire by the friction of steel components with sulfur powders.

TEST MACHINE AND TEST SETUP

The core of the test machine is illustrated in Fig.1.

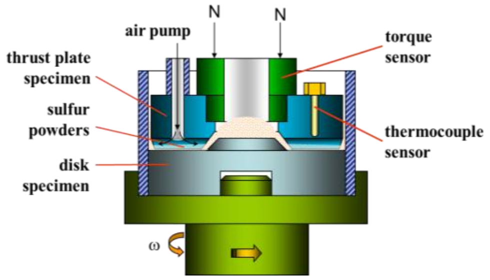

Fig.1 Diagram of the key parts of the test machine

The friction temperature near friction surface and the friction torques can measured on line in the homemade test machine.

TEST SETUP

The detail of the test set-up illustrated in Tab.1, the friction medium is sulfur powders, its water content is 2% and its diameter is below 0.25mm.

Tab.1 The material of tested specimens and other setup of test

Normal Load(kg)		20,30,40,50,60,70,80
Rotational Speed		300rpm
Specimens Material	thrust plate	1045 steel ,316L,Q235
	disk	1045 steel
Ambient emperature		16℃

TEST RESULTS AND DISCUSSION

Part of the experiments has been done, the temperature of near friction surface vs time curve is shown in Fig.2.

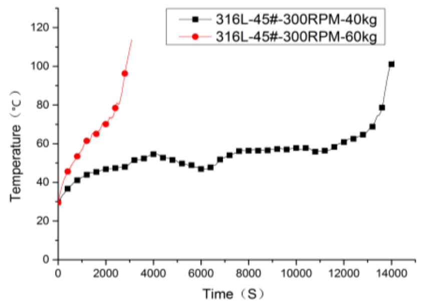

Fig.2 Temperature curve of 316L-1045steel under different load at 300 RPM rotational speed

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T5-2 Rough Elastomers

General theory of frictional heating with application to rubber friction

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The energy dissipation in the contact regions between solids in sliding contact can result in high local temperatures which may strongly effect friction and wear. This is the case for rubber sliding on road surfaces at speeds above 1mm/s. We derive equations which describe the frictional heating for solids with arbitrary thermal properties.

The theory is applied to rubber friction on road surfaces, and we take into account that the frictional energy is partly produced inside the rubber due to the internal friction of rubber, and in a thin (nanometer) interfacial layer at the rubber-road contact region. The heat transfer between the rubber and the road surface is described by a heat transfer coefficient which depends on the sliding speed. Numerical results are presented and compared to experimental data.

We find that frictional heating results in a kinetic friction force which depends on the orientation of the sliding block, thus violating one of the two basic Leonardo da Vinci “laws”of friction.

PERCOLATION OF CONTACT AND NON-CONTACT: FROM SINGLE-WAVELENGTH ROUGHNESS TO SELF-AFFINE SURFACES

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ABSTRACT

The 1966 Greenwood-Williamson paper pioneered research in tribology by linking the contact mechanics of microscopic single-asperities to that of macroscopic, nominally flat surfaces. One important finding of their work was that the functional dependence of contact area on load at the macroscopic scale can differ qualitatively from that at the microscopic scale.

In our paper we also study the contrast between contact mechanics at macroscopic and microscopic scale, however, with an emphasis on the contact mechanics of saddle points, with and without adhesion. Specifically, we study how open channels – allowing a fluid to flow through an interface – close with increasing load. To this end we first study how a single open channel closes and gets blocked when the local pressure increases (or the strength of the adhesive interaction, which has a similar effect). Blockage essentially happens when two previously isolated contact patches coalesce to a single patch. Interestingly, the contact mechanics of saddle points shares much similarity to that of Hertzian contacts. In a second step, we rationalize the closing of open fluid channels in contacts of macroscopic, nominally flat self-affine surfaces in terms of the insight gained at the microscopic scale.

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BI-SINUSOIDAL ROUGHNESS MODELING FOR SOFT MICRO-ELASTOHYDRODYNAMIC ASPERITY LUBRICATION IN ROUGH CONFORMAL CONTACTS

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Conformal surfaces in parallel sliding lack a macroscopic hydrodynamic pressure and fluid film formation mechanism. However, such a mechanism still exists on a microscopic level due to roughness. In a recent paper [1], the authors had presented a soft (iso-viscous elastic) micro-elastohydrodynamic asperity lubrication approach with application to an elastomeric radial lip seal in lubricated sliding contact with a smooth rigid counterface. In contrast to commonly applied flow factor approaches, the rough elastomer seal lip surface is directly modeled as a bi-sinusoidal wavy surface. The finite element based fluid structure interaction model comprises elastic deformations of the elastomer surface asperities, inter-asperity cavitation and coupling of frictional heating, lubricant film temperature and lubricant viscosity. As long as the *first-order* hydrodynamic pressure generation within the drag flow over the rough surface alone is not sufficient to balance the external load, the flattened and tangentially deformed asperities are sliding on a thin *second-order* soft µ-EHL oil film. The thickness of this oil film is determined applying the soft-EHL central film thickness formula developed by *Chittenden* et al. [2], which had been previously implemented by *Gabelli* [3]. The computed friction agrees well with experimental results obtained with a virtually new radial lip seal. Even at the lowest sliding speeds, when the hydrodynamic lifting force is negligibly small, the soft micro-elastohydrodynamic asperity lubrication mechanism is obviously capable of giving a physically sound explanation of both low-speed lubricant film formation as well as the frictional characteristics of the lubricated sealing contact.

In the present paper the above methodology has been further validated with experimental results which had been previously obtained with a run-in radial lip seal of the same type [4].

BI-SINUSOIDAL ROUGHNESS MODEL

The seal lip is characterized using optical interference surface profilometry. From the according topography the root mean square (r.m.s.) height S_q and r.m.s. slopes $\Delta_{r.m.s.,x/y}$ are computed.

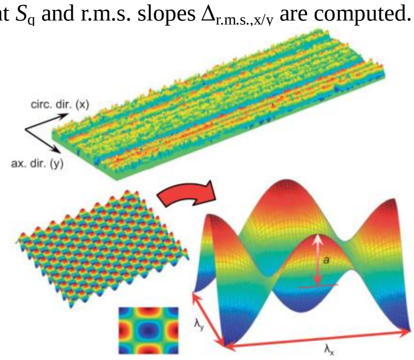

Figure 1: Bi-sinusoidal roughness model [1]

Using these parameters, a sinusoidal roughness model according to figure 1 is set up with amplitude *a*, effective wavelengths $\lambda_{r.m.s.,x}$ and $\lambda_{r.m.s.,y}$ and radii of curvatures R_x and R_y in circumferential and axial direction, respectively (table 1). It is worth noting that the r.m.s. wavelength $\lambda_{r.m.s}$ – as a hybrid roughness parameter – combines amplitude and spacing information. It is a weighted average and considers a profile as a series of harmonics in which the amplitudes are weighted in proportion to their frequencies.

Table 1: Parameters of the roughness model

amplitude:	$a = \sqrt{2}\, S_q$	(1)
eff. wavelengths:	$\lambda_{r.m.s.\,x/y} = 2\pi \frac{S_q}{\Delta_{r.m.s.\,x/y}}$	(2)
radii of curvatures:	$R_{x/y} = \frac{1}{\sqrt{2}\, S_q} \cdot \left(\frac{\lambda_{r.m.s.,x/y}}{2\pi}\right)^2$	(3)

MAIN FINDINGS

Due to the run-in process, both the r.m.s height and the r.m.s. wavelengths of the elastomer seal lip surface roughness are significantly reduced. Still, the computed seal friction agrees well with the experimental results. Therefore, the proposed roughness representation obviously allows sufficiently accurate modeling of those roughness components that govern the physical behavior of the contact.

Both the increased asperity density (i.e. reduced normal load per asperity contact) as well as the actual geometry of the model asperity facilitates *first-order* hydrodynamic lift and *second-order* µ-EHL film formation, which is in agreement with previous lubricant film thickness measurements [4].

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Proceedings of the 42nd Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France
leeds-lyon - Room 3 - Monday, September 7, 2015 - 17:20/17:40 (20min)

ROLE OF SURFACE ROUGHNESS IN RADIAL SHAFT SEALS

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ABSTRACT

This paper describes overview and a recent theoretical study on the dependence of fluid transportation of lip surface roughness in radial shaft seals. It is widely recognized that surface roughness on rubber lips works to generate hydrodynamic pressure as well as to cause fluid flow perpendicular to the direction of motion. Deterministic and semi-stochastic models of surface roughness are used in numerical analysis. The analysis demonstrates that, not only size of the wavelength of surface asperities, their height and spatial distribution affect fluid flow. Experiments with actual surface roughness are conducted and axial flow is predicted by the rate of transportation of gas dissolved in the sealed oil.

SLIDING OF AN ELASTOMERIC/GLASS CONTACT: OPTICAL STUDY OF THE TRUE CONTACT AREA

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ABSTRACT

We develop a non-invasive optical method to measure the real contact area at the interface between an elastomeric surface and a glass slider. We apply it to study the incipient tangential loading of a rubber sphere on a glass substrate. We show that the true contact area decreases significantly under shear and compare with models from the literature. We the use these results to better understand the behavior of sheared multicontact interfaces.

INTRODUCTION

The study of the shear rupture mechanisms of contact interfaces is difficult because these confined interfaces are usually not directly accessible to measurement. To overcome this difficulty, we developed a non-invasive optical method to observe the transparent contact interface between an elastomeric slider and a glass surface [1]. We performed a study of the optimization of the image acquisition procedure for proper monitoring of the true contact area. Here, we apply our insights to a system of interest in tribology: the sliding of the interface between a polydimethilsiloxane (PDMS) sphere and a smooth glass plane.

RESULTS

We first show how the area of a single sphere-on-plane contact decreases, by up to 20%, as the tangential force is increased. The circular shape of the contact is also modified to a pseudo-elliptical shape as the area decreases. We compared our measurements with existing models from the literature [2, 3] and found that they cannot capture all of the observed behavior.

We then show that the true area also decreases in the case of a multi-contact between a rough rubber slab and the same smooth glass plate (fig. 1). This system is more complex than the previous sphere-on-plane contact, with the area of an individual micro-contact being not only controlled by the random height of its asperity, but also by the (unknown) shear force applied on it. We propose an interpretation of the data with a statistical model involving many micro-contacts behaving like single sphere-on-plane contacts.

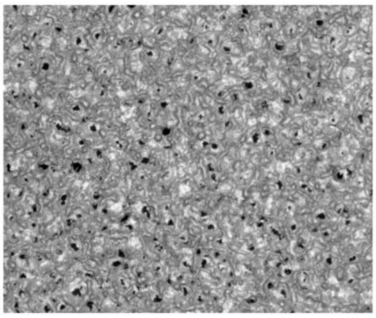

Figure 1 : Image of the interface between a rough PMDs slab and a smooth glass plate. The black points are the microcontacts.

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T1-1 Lubricated rough contacts I

ROUGHNESS IN SOFT EHL CONTACTS – THE COMPLEMENTARY WAVE RE-ASSESSED

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ABSTRACT

Soft EHL contacts are becoming of increasing importance in engineering with the greater use of oil lubricated polymers. For example PEEK moulded gears are now widely used as replacements for steel components. Although they are larger than the steel equivalents they are far cheaper and can incorporate complex additional functions at little extra cost. Although pressure-viscosity effects produce some minor increase in viscosity the very high viscosities found in steel components are absent.

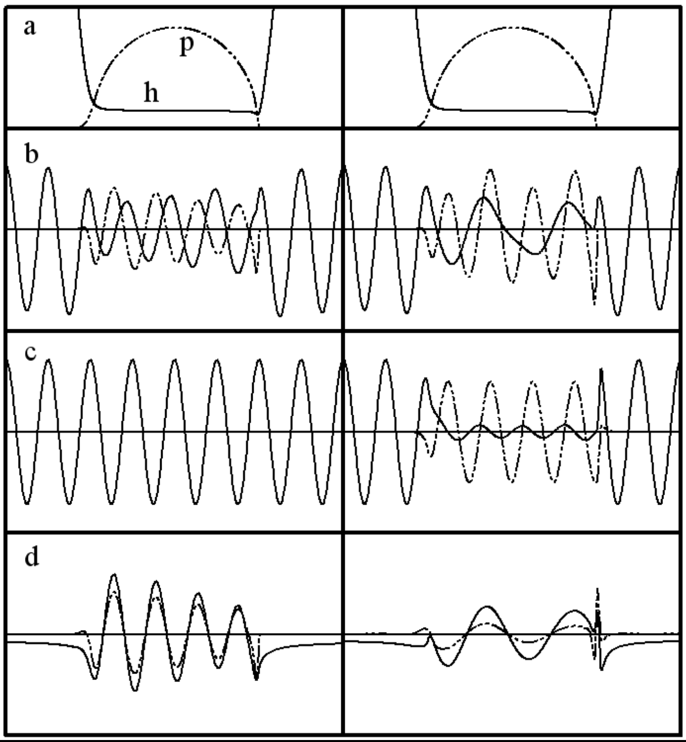
The behaviour of surface roughness in rolling, hard EHL conjunctions is well established with an apparent attenuation of the roughness inside the contact (behaviour under rolling-sliding conditions is less well defined with thermal effects and the fluid shear characteristics complicating the behaviour). However, that of soft EHL conjunctions is less well defined.

Behaviour in these contacts is complex even under pure rolling conditions with a complementary wave being formed in the inlet and decaying in amplitude as it passes through the conjunction. This modifies the original surface profile resulting in varying residual roughness through the contact. Under sliding conditions the behaviour is further complicated by roughness attenuation due to the relative motion of the surfaces. However, thermal effects and the fluid shear characteristics become of secondary significance.

As examples, Fig. 1 compares the pressures and clearances in rolling and rolling-sliding PEEK contacts with a transverse, sinusoidal roughness. The upper curves show the pressures and clearances without any roughness. The second curves the changes produced by a sinusoidal roughness of unit amplitude. To find the behaviour of low amplitude roughness a small multiple of this needs to be added to the pressures and clearances in the upper figures. The third curves show the effect of the relative sliding alone while the lowest curves give the complementary waves. These two curves combine to produce the variations shown in curves b.

With pure rolling there is no attenuation due to sliding and it is the complementary wave alone that is responsible for the reduction in the roughness amplitude inside the contact and for the associated pressure ripple. With the rolling-sliding conjunction the original roughness is very largely eliminated by the relative motion of the surfaces. However, the inlet generates a complementary wave with a wavelength twice that of the roughness and it is the combination of the attenuated profile and the complementary wave that creates the final clearance profile and generates the associated pressure ripples.

It may be seen that the complementary wave is of critical importance in both cases.



Rolling	Rough surface velocity = 0.5u

Fig 1 Pressures and clearances in a PEEK contact with transverse, sinusoidal roughness.
a) Smooth surface
b) pressure and clearance perturbations
c) Attenuation due to sliding
d) Complementary wave

The aim is to explore the role of the complementary wave in soft contacts and to show how the operating conditions affect the way it is generated and how it decays across the conjunction.

THE EFFECT OF ROUGHNESS FEATURES ON LUBRICANT FLOW INSIDE EHL CONTACT

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ABSTRACT

Lubricant rapidly changes its rheological properties during the passage through elastohydrodynamically lubricated (EHL) contactdue to high pressure and high shear rates. In some cases lubricant can go through glass state transition. The behavior of lubricants under such conditions remains a challenging problem. Information about lubricant flow inside highly loaded zone can contribute to knowledge about involved processes significantly.

Standard solution of classic Reynolds equation for central zone predicts linear though-film speed profile. However, the existence of shear bands, wall slips or shear localizations were observed several times by various researchers. Recently, the results of transient film thickness variations were used to obtain information about through-film speed profile. It was shown, by considering flow continuity, that results can be explained by highly irregular speed profile – called plug-flow [1].

In this study transiently induced effects in contact inlet are observed by optical tribometer during its transportation through EHL contact. Variations of entrained film are related to the lubricant flow. The effects of various roughness features and sliding conditions on lubricant flow are presented. Results show changeover from one kind of behavior to the other.

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Proceedings of the 42[th] Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France
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EFFECTS OF THE THERMAL CONDUCTIVITY ON POINT EHL CONTACTS WITH RIDGE AND GROOVE

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ABSTRACT
The EHL tribo-characteristics are influenced very much by the thermal conductivity of contact materials. The effects of a transversely oriented bump and dent in ceramics (Si_3N_4 and ZrO_2) and steel circular contacts on the film thickness and pressure are described through non-Newtonian thermal EHL analysis. Over a wide range of slide-roll ratio, defined as SRR = $2(u_{ceramic} - u_{steel})/(u_{ceramic} + u_{steel})$, if the absolute values of SRR are the same, the film thickness at central region of the contact is smaller when the velocity of steel material is higher. Consequently, the pressure produced by the bump becomes larger when the velocity of steel material is higher. It has also been found that the deformation of the ridge and groove under rather small film thickness is largely influenced by the sign of SRR and the surface where the irregularity exists. The formation rate of the complementary wave, which passes through the EHL conjunction at the entrainment velocity, produced by the surface irregularity is also influenced by the sign of SRR and the surface where the irregularity exists. In particular, the complementary wave produced by the groove brings about a higher pressure at the ridge position depending on the relative position between the groove and the ridge.

Proceedings of the 42th Leeds-Lyon Symposium on Tribology
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A UNIFIED APPROACH FOR CHARACTERIZING MULTIPLE LUBRICATION REGIMES INVOLVING MULTISCALE PLASTIC DEFORMATION

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ABSTRACT

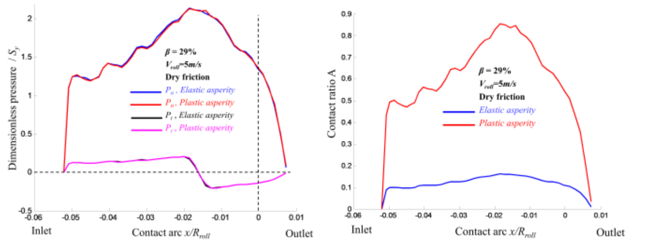
This paper presents a method for characterizing the hydrodynamic, mixed and boundary lubrication regimes in cold metal rolling. The analysis involves random surface asperities and multi-scale plastic deformation of both the asperities and workpiece. This enables us to investigate the asperity plastic deformation effect on the surface topography evolution. The modelling is based on a concept of equivalent interface layer between lubricated surfaces in contact sliding.

INTRODUCTION

Engineering surfaces are microscopically rough; thus the real interface contact of two surfaces is between surface asperities. In cold metal rolling, the surface asperities carry very large contact stresses to bring about the bulk plastic deformation of a metal strip, which inevitably makes the asperities deform plastically. Such microscopic asperity deformation has a significant influence on the interface contact, leads to the variation of a strip surface topography, and eventually determines the rolling performance and surface finish of the strip. Extensive studies have been carried out; but a comprehensive understanding of the asperity plastic deformation effect on roll-strip interaction involving lubricant is not yet available. Because of the random asperity contacts, a statistical characterisation is required to estimate the real contact area, asperity contact stress and influence of lubricant. From the inlet to the outlet of a rolling bite, hydrodynamic, mixed and boundary lubrication regimes will all appear, governed by the coupled effect of solid-solid (asperity-asperity) contact and solid-liquid (asperity-lubricant) contact. To analyze such problems, the micro-scale plastic deformation of surface asperities at the roll-strip interface, the solid-lubricant interaction and the macroscopic bulk strip deformation must be taken into account simultaneously. This is the aims of the present investigation.

MODELLING AND RESULTS

The unified approach for the interface lubrication and friction was established based on the multi-scale method developed by the authors [1]. An equivalent interface layer (EIL) was introduced to integrate the average Reynolds equation with the plastic deformation of randomly distributed surface asperities. In the EIL, a statistical characterization [2] was performed to give the microscopic real contact area. A finite element analysis was coupled external to the EIL to predict the macroscopic bulk strip deformation. Figure 1 shows typical pressure and friction distributions across a rolling bite.



(a) Normal pressure and friction (b) Contact ratio

Fig.1 Typical calculated results

CONLUSIONS

This work has developed a unified approach for the interface lubrication in cold strip rolling, integrating the coupled plastic deformation effect of both the microscopic asperities and macroscopic strip. The method has characterized different lubrication regimes in a single step. It is expected that the method can be applied to other contact sliding processes involving complex lubrication and plastic asperity deformation.

ACKNOWLEDGMENTS

This research was supported by a BAJC project, BA12003. C. H. Wu is financially supported by CSC and UNSW scholarships.

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T5-3 Rough Contact 1

Proceedings of the 42th Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France
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ELASTIC CONTACT BETWEEN REPRESENTATIVE ROUGH SURFACES

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INTRODUCTION

Roughness plays a primordial role in many surface and interfacial phenomena: fluid flow, light dispersion, friction, lubrication, wear, mass and energy transport through the contact interface. Consequently, it is important to take the roughness into consideration in many tribological applications including sealing of metal-to-metal contacts, fretting in disk-blade aeronautical systems, tire cohesion with the road, electric contacts, noise generation of brake systems and hydraulic fracturing for gas and oil extraction. Particularly, it is important to link the characteristics of the surface with its mechanical and physical contact behaviour.

We perform a series of numerical simulations on contact between artificially generated randomly rough surfaces and analyse the evolution of the global parameters, such as the contact area and the approaching. We also study local properties, such as morphology of contact clusters and probability density of contact pressure, which are of a great importance for many applications.

METHODS

To generate artificial random rough surfaces we use a filtering technique in Fourier space [1], which enables us to control precisely surface characteristics: lower and upper cutoff frequencies in the spectral content, fractal dimension or Hurst exponent and root mean squared roughness or root mean squared gradient. The Nayak parameter [2], which controls the breadth of the surface spectrum is also controlled via a simple equation, which links it to other surface parameters [3]. For every study 50 statistically similar surfaces were generated.

To solve the mechanical boundary value problem for an elastic half-space with periodic roughness and frictionless non-adhesive contact constraints, we use a spectral boundary element method [5], enabling us to solve this problem using fine spatial discretisation (4096x4096) within a reasonable CPU time.

RESULTS

First, we will discuss the roughness characteristics and how to approach an idealised roughness [2]. Among other things, we will demonstrate how the lower cutoff frequency controls the Gaussianity of the surface [3,4] and how the average roughness characteristics correspond to actual measurements. Second, we analyse the asymptotic behaviour of the real contact area close to zero contact and full contact. Comparison with analytical models is also provided. Non-linearity of the contact area evolution and heuristic equations, which describe this evolution are suggested. Third, we discuss the ways to characterise contact clusters, their geometrical characteristics, their evolution and coalescence.

Finally, two applications are demonstrated: static contact seal and electric contact. These problems imply a coupling between mechanical contact and viscous fluid flow analysis or electrostatic analysis.

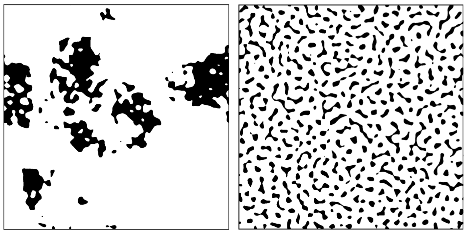

Fig. 1. Example of contact area distribution for surfaces with different lower cutoff frequency in surface spectra

ACKNOWLEDGMENTS

GA and JFM greatly acknowledge the financial support from the European Research Council (ERCstg UFO-240332).

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1

TOPOLOGICAL CHARACTERIZATION AND SIMULATION OF TEXTURED ROUGH SURFACES

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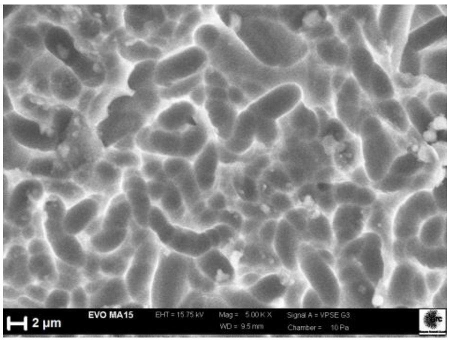
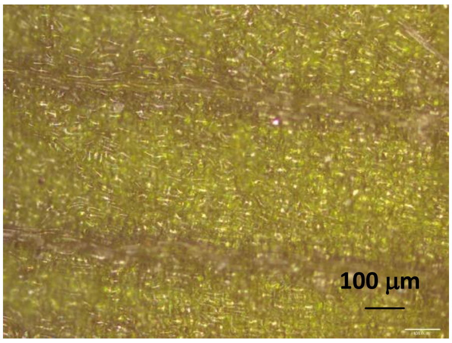
ABSTRACT

The random process theory (RPT) has been widely applied to predict the joint probability distribution functions (PDFs) of asperity heights and curvatures of rough surfaces [1-3]. However, a check of the predictions of RPT against the actual statistics of numerically generated random fractal surfaces and of real rough surfaces has been only partially undertaken [4]. The present experimental and numerical study provides a deep critical comparison on this matter, providing some insight into the capabilities and limitations in applying RPT and fractal modeling to antireflective and hydrophobic rough surfaces, two important types of textured surfaces.

A multi-resolution experimental campaign by using a confocal profilometer with different magnifications is carried out and a comprehensive software for the statistical description of rough surfaces is developed. It is found that the topology of the analyzed textured surfaces cannot be fully described according to RPT and fractal modeling. The following complexities emerge: (*i*) the presence of cut-offs or bi-fractality in the power-law power-spectral density (PSD) functions; (*ii*) a more pronounced shift of the PSD by changing resolution as compared to what expected from fractal modeling; (*iii*) inaccuracy of the RPT in describing the joint PDFs of asperity heights and curvatures of textured surfaces; (*iv*) lack of resolution-invariance of joint PDFs of textured surfaces in case of special surface treatments, not accounted by fractal modeling. A numerical method for the realization of synthetic surfaces with statistical and spectral characteristics consistent with the experimentally observed ones is finally proposed.



(a) Antireflective coating of solar cells



(b) Hydrophopic rough surface of Ginkgo Biloba

Fig. 1: two images of textured rough surfaces.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007–2013)/ERC Grant Agreement No. 306622 (ERC Starting Grant "Multi-field and Multiscale Computational Approach to Design and Durability of PhotoVoltaic Modules" - CA2PVM).

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EXPERIMENTAL INVESTIGATION OF PLASTIC CONTACT OF ROUGH STEEL SURFACE AGAINST A HARD FLAT

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INTRODUCTION

An correct characterization of contact between rough surfaces is substantial for analyzing tribological problems, like friction, wear and contact resistance. The contact of rough surfaces have been studied by many researchers. The pioneering contribution was made by Greenwood and Williamson (GW) [1] who developed a basic elastic contact model. Supplementing the GW model, elastic-plastic asperity contact models have been devised [2-4]. Contact models usually considered surfaces with Gaussian ordinate distribution. Relatively little attention has been paid to study of contact of stratified surfaces. Very few experimental research of contacting rough surfaces have been reported and usually contact behavior of surfaces of symmetric height distribution has been studied.

EXPERIMENTAL DETAILS

Experiments were performed on modified hardness tester. The hard flat specimen from sintered carbide was used. It co-acted with 42CrMo4 steel flat surface of 2.15 GPa hardness and different surface topography after vapour blasting and/or lapping. Nine kinds of one-process surfaces were created on steel samples, the height standard deviation (the Sq parameter) was in the following range: 0.3-6 µm. Six types two-process textures were characterized by the Sq parameter: 1.5-3.1 µm; their plateau height standard deviation Spq was in the following range: 0.5-1.8 µm. Before tests, steel samples were cleaned in alcohol and dried in air. The normal load in compression test was 150 N, 550 N and 950 N. The number of repetitions for each load was five. Before and after compression, steel samples were measured using white light interferometer Talysurf CCI Lite. The special relocation procedure was elaborated to analyze surfaces in the same place before and after loading. On the basis of profile analysis before and after loading, plastic deformations were obtained (see Figure 1).

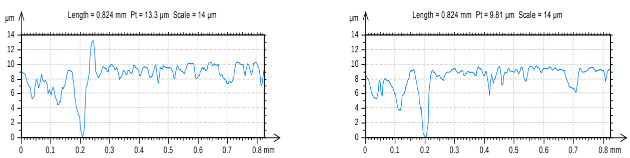

Fig. 1. Profile of two-process surface before (left) and after compression (right)

Plastic deformation was compared with that obtained using JG model [4] for various sampling intervals.

RESULTS

For each applied loading plastic deformation was proportional to the Sq parameter of one-process surface and the Spq parameter of two-process texture, which proves that plateau part of stratified surface decides about contact. Plastic deformation was a little smaller than calculated elastic-plastic deformation using the JG model for sampling interval about 12 µm. Figure 2 presents the relation between Sq (Spq) parameter and plastic deformation as well as calculated elastic-plastic deformation (for sampling interval of 12 µm) using JG model.

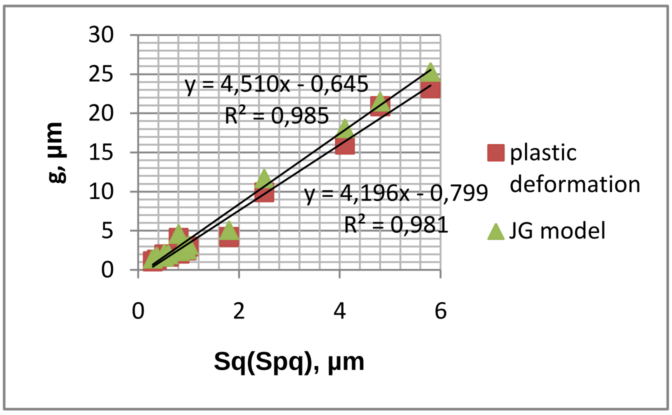

Fig. 1. The effect of Sq(Sqp) parameter on measured plastic deformation and elastic-plastic deformation for normal load of 950 N

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Implementation of FFT Algorithms to Contact Analyses of Engineering Surfaces

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ABSTRACT

The Greenwood-Williamson theory [1], together with the Greenwood-Tripp solutions, inspired an era of modelling contacts of engineering surfaces. Stimulated by the success of statistical analyses of engineered rough surfaces, numerical contact modelling views digitized rough surfaces deterministically and solves the integral elastic contact equations via the influence coefficient approach. Unlike the statistical approach that makes assumptions of asperities and processes to categorize the statistical parameters prior to the contact analyses, the deterministic approach directly analyzes the digitized surface topography and applies regression to the results of the contact analysis. However, a considerable amount of computation is involved in the numerical processes, which demands fast and accurate methods to provide analyses with realistic times. This issue becomes more severe if heat treatment, coatings, and inhomogeneous materials are involved and if plastic deformation is also a concern. The fast Fourier transform (FFT) [2] was suggested to transfer space-domain problems to the frequency domain and convert convolutions to multiplications, which significantly eased the computational burden. Discrete convolution and fast Fourier transform (DC-FFT) and additional FFT algorithms [3-5], together with the conjugate-gradient method (CGM) [6] and parallel computing [7], enable more efficient simulations of complex problems of contacts of engineering materials [8-11]. The theoretical basis of these FFT algorithms and solutions approaches are reviewed, and recent anayses of the contacts of engineered rough surfaces, multi-layered material systems, heat-treated and functionally graded surfaces, and inhomogeneous materials are summarized.

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T3-4 Nano

Proceedings of the 42th Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France
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TRIBOLOGICAL BEHAVIOUR AND ADHESION OF CARBON NANOTUBES GRAFTED ON CARBON FIBRES

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ABSTRACT

Carbon nanotubes (CNTs) grafted on fibres are widely used to reinforced composites and improved the fibre/matrix interface. This study concerned the tribological and adhesion properties of CNTs grafted on carbon fibres by the flame method. Reciprocating friction and adhesion tests were performed to examine the resistance of the CNTs on the fibres. The results showed that under a normal load higher than 1 N, CNTs are removed after 2000 cycles of friction. Moreover, CNTs are quite resistant to tack tests.

INTRODUCTION

With their excellent properties, CNTs are ideal candidates to reinforce composite materials. One technique is to graft CNTs on the fibres in order to enhance the fibre/matrix interface. A study highlighted the behaviour of CNTs grafted on carbon fibres (CFs) [1], and showed that CNTs formed a transfer film and are finally removed from the contact. In this study, we determine the resistance of the fibre/CNTs interface under friction and the adhesion between CNTs and fibres.

The raw material is a plate woven fabric, composed of carbon multifilament 6K in warp and glass E in weft. The raw material is treated by acid sulphuric to eliminate the sizing. Then multi-walled CNTs are produced directly on the surface by the flame method, using a metallic catalyst [2]. Two different catalysts were used in order to determine their influence on the interface resistance. The conditions of fabrication are optimized in order to obtain homogeneous CNTs.

Friction tests are realized on a linear reciprocating tribometer, with a cylindrical slider (stainless steel, with a diameter of 20 mm), in order to approach a rolling on a metallic piece. The normal load is applied by means of dead weights and the tests were performed under a normal load in range of 0.5 N, 1 N, 1.5 N, 2 N, 2.5 N, with a contact surface between 10 - 30 mm^2, at a sliding speed of 20 mm/s and a sliding distance of 20 mm. The tests were carried on virgin CFs, desized CFs, CFs passed only at the flame and CNTs grafted CFs with catalyst no.1 and catalyst no.2. SEM observations were conducted in order to see the evolution of the surface.

Friction results shows a decrease of the coefficient of friction (COF) due to the transfer film created by the CNTs, and then a stabilization around 0.2 (value of virgin carbon) that show that the CNTs are removed, for high normal load. For a normal load of 0.5 N, CNTs are still on the surface.

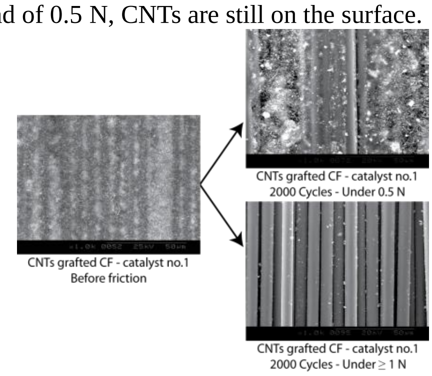

Figure 1: Evolution of CNTs grafted CFs – catalyst no.1 under friction stress under different normal load.

Adhesion tests were performed on a rheometer used as indenter, with a loading and unloading at a constant speed in order in reach a fixed load, with a indenter covered with a scotch tape. The results allow determining the adhesion energy, related to the quantity of residues. Observations showed a quantity of residues higher for catalyst no.2.

ACKNOWLEDGMENTS

The authors want to thank SATT Conectus Alsace for financial support and Dr. H. Oulanti, T. Le Huu and F. Laurent, from the Laboratoire de Physique et Mécanique Textiles in Mulhouse (France) for providing the CNTs grafted fabrics.

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FRICTION OF CARBON TOWS AND FIBRES

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ABSTRACT

This experimental study of the perpendicular friction between carbon tows and carbon single fibres is presented. The friction phenomena are studied from evolution of friction and normal forces and from the coefficient of friction that can be computed.

INTRODUCTION

Nowadays lots of mechanical composite parts are reinforced by carbon weaving material. During the process damaged occurred on carbon fibres that are due to friction phenomena and particularly fibre-to-fibre friction [1]. The aim is to focus on the friction phenomena between two carbon tows which are located perpendicularly. These friction can occur between warp and weft yarn during weaving. The study is also conducted on single fibres which constitute the carbon tows.

EXPERIMENT

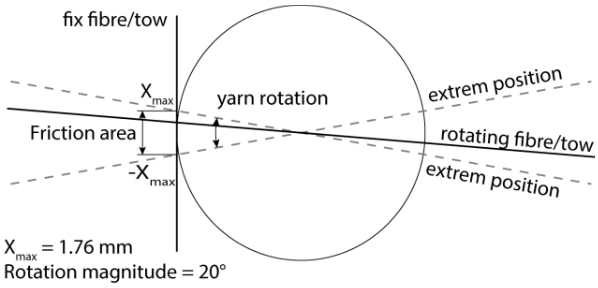

Figure 1: Schematic of friction experiment.

Material

The study is realized on 3K carbon yarn manufactured by Toho Tenax Europe GmbH whose yield is 200 tex. That means there are 3000 filaments of carbon, whose diameter is 7 µm, in the tow section.

Experimental device and measurements

Friction measurements are performed by means of a NTR2 nanotribometer (CSM Instrument Company, Peseux, Switzerland). This device is originally a pine-on-disk tribometer with reciprocating movement allowed. Specific experimental sample carriers have been developed in order to position the carbon tows or fibres.

According to the low friction angle relative to the diameter of the rotation the move between the two friction samples can be considered as perpendicular (magnitude of friction displacement of 3.4 mm for a lateral move of 0.15mm) (Fig. 1). Measurements are realized at a constant friction altitude.

The experimental device allows to acquire friction and normal forces during the test. The coefficient of friction can then be computed.

RESULTS

Firstly, it is interesting to note that, after an initial decrease, the normal load tends toward a constant value during the friction test. This decrease is more important for fibre-to-fibre friction than for tow-to-tow.

In Fig 2 the typical average coefficient of friction curves is plotted versus displacement. These curves represent the tow-to-tow and fibre-to-fibre friction. The shapes are symmetrical between the two friction directions of the cycle.

The coefficient of friction is smoother and slightly higher with the tow.

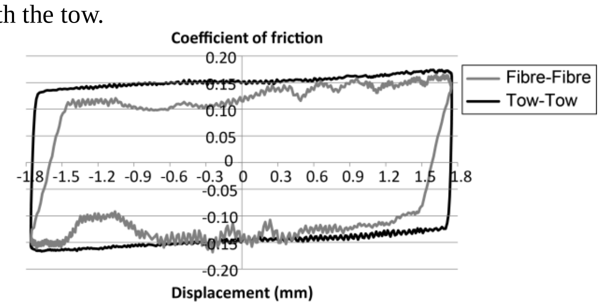

Figure 2: Average friction cycle in term of coefficient of friction for tows and fibres friction.

ACKNOWLEDGMENTS

The authors want to thank Toho Tenax Europe GmbH for providing carbon filament yarns.

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Proceedings of the 42nd Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France

A NEW METHODOLOGY FOR MEASURING SIMULTANEOUSLY THE FRICTION, WEAR, AND PLASTIC DEFORMATION OF CARBON-BASED MATERIALS AT THE MICRO- AND NANO-SCALE

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ABSTRACT

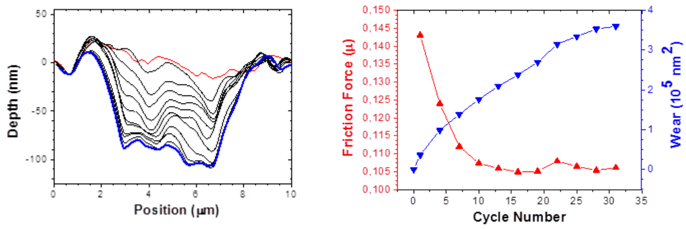
We present a new methodology to measure simultaneously the friction, wear, and plastic deformation of a carbon-base material at the micro- and nanoscale. We have designed an experiment to obtain topographic information at the nanometer scale while force lateral sensors register simultaneously the friction force variations at the microNewton scale. A special software output gives the resulting friction coefficient, track roughness, wear rate, thermal drift, and plastic deformation as a function of the running cycles of the probe. The new method builds a novel bridge to relate tribological mechanisms at different scales.

INTRODUCTION

Nowadays there is an increased need to know the nanotribological properties of novel carbon-based coatings to be used in part devices operating under nano- and micro-contact situations, e.g. hard disk drives, magnetic heads, micro-electromechanical systems (MEMS) and microsensors, etc. Therefore there is a demand for instruments and methods testing friction and wear at the nano- and micro-scales [1]. Atomic force microscopy has demonstrated to be an important tool for performing not only the topography imaging at the nanoscale but also single-asperity contact tests in the range from few nN to mN loads. Also, the developing of electrostatic force transducer systems during the last decade has given place to new instruments allowing the precise nanoscale determination of vertical loads, lateral forces, and displacements. However, all these instruments use imprecise measurement methods because they ignore the random nature of the thermal drift. Furthermore, their approaches don't take into consideration the plastic deformation or material densification during the tribotests. In this work we present a new methodology to measure simultaneously the friction, wear, and plastic deformation of a carbon-based material.

EXPERIMENTAL DESIGN AND RESULTS

We have designed an experiment where the probe is permanently scanning a 10 µm track in a reciprocal movement. Different loads are applied in order to obtain the topographic information while force lateral sensors register simultaneously the friction force variations. The experimental input data are information vectors that contain: load (µN), friction force (µN), vertical Z displacement (nm), lateral X displacement (nm) and time (s). The data is processed using a simple program running in MathLab®. The software output gives the resulting friction coefficient, track roughness, wear rate, thermal drift, and plastic deformation as a function of the running cycles of the probe. All tribological experiments have been done using a Triboindenter TI-950 from Hysitron. A conical diamond tip of 5 µm end diameter was used for the tests. The figure shows an example of the wear profile evolution (left), and friction and wear ratio of the material as a function of the cycle number during the nanotribological characterization of an amorphous carbon sample lubricated with distillated water under a load of 1 mN. The repetition of the experiment under different loads (from 3 µN to 12 mN), different probe diameters, and different environments (dry or lubricated) can be used to understand the tribomechanical and tribochemical behavior of the carbon materials at the micro- and nano-scale.



Wear profile evolution (left) and friction coefficient µ (▲) and wear rate (▼) for carbon under water lubrication.

ACKNOWLEDGMENTS

The authors acknowledge the support from the Swedish Government Strategic Research Area Grant in Materials Science at Linköping University (SFO-Mat-LiU) on Advanced Functional Materials. F.J. Flores-Ruiz also acknowledges the support from CONACyT project CB-2012-01#179304 and LIDRA Project 123630.

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T1-2 EHL modelling

Central film thickness in EHL Point Contacts under Pure Impact Revisited

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Abstract

Impacting EHL problems have been studied both for dry and lubricated (pure squeeze) contact in the past by various authors, e.g. see [1], [2]. In a recent paper the authors have made quantitative predictons of the film thickness in a line-contact problem [3]. In this paper the circular contact problem is considered. The objective is to elucidate the scaling behaviour of the minimum and central film thickness. For clarity the elastic-isoviscous case (soft lubrication) has been studied first. Figure 1 shows the central film thickness as a function of time for different values of the single non-dimensional parameter M governing the problem. Also shown in this figure are the same results but scaled using $H/\sqrt{\lambda}$ with $\lambda \propto M^{-4/3}$. It can clearly be seen that the scaling unites all curves. In the paper this behaviour is explained, as well as the behaviour of the minimum film thickness as a function of time. Next the piezoviscous problem is considered. Also for this problem detailed results are presented and discussed.

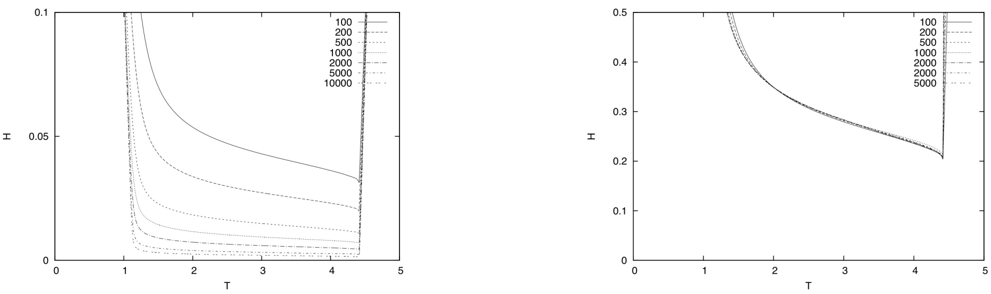

Figure 1: (Dimensionless) Central film thickness as a function of time for $M = 100, 200, \cdots, 10000$.

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Proceedings of the 42th Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France

INFLUENCE OF THERMAL AND MECHANICAL PROPERTIES OF COATINGS ON FRICTION IN ELASTOHYDRODYNAMIC CONTACTS

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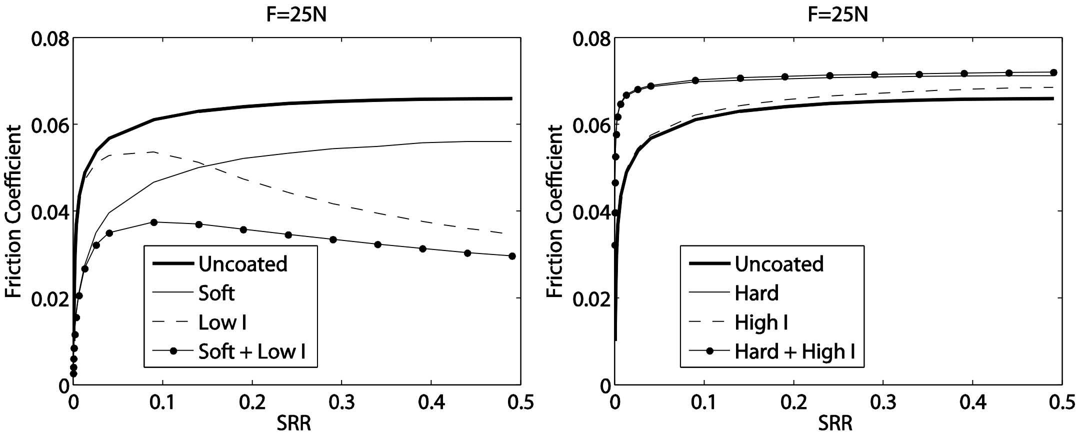

Figure 1: Effect of coating's thermo-mechanical properties on friction in coated circular TEHD contacts

ABSTRACT

This paper presents a numerical investigation of the influence of thermo-mechanical properties of coatings on friction in elastohydrodynamic lubricated (EHL) contacts. In recent works by the author [1-3] friction was found to increase with the thermal inertia of coatings under high sliding speeds. In the current work, mechanical properties of coatings are also shown to have a significant impact on friction. Friction actually exhibits an increase with the rigidity of the coating. Furthermore, a combination of soft coatings with low thermal inertia is shown to maximize friction reduction while hard coatings with high thermal inertia maximize friction increase. These effects are found to increase with the coating thickness.

INTRODUCTION

The influence of surface coatings on the performance of EHL contacts has been a subject of interest for the tribological community over the last few decades. From the earliest works on the topic, the focus was on the effect of mechanical properties of coatings on pressure, film thickness and stress distribution within the solid components of these contacts. In the current work the focus is on the influence of themo-mechanical properties of coatings on friction in EHL contacts. Seven different coating configurations are used:

- "Uncoated": No coating is used
- "Soft": Soft coating
- "Hard": Hard coating
- "Low I": Low thermal inertia coating
- "High I": High thermal inertia coating
- "Soft + Low I": Soft coating with low thermal inertia
- "Hard + High I": Hard coating with high thermal inertia

RESULTS AND DISCUSSION

Figure 1 suggests that soft coatings and low thermal inertia coatings reduce friction while hard coatings and high thermal inertia coatings increase it. It also shows that a coating with a combination of soft and low thermal inertia material maximizes friction reduction while the combination of hard and high thermal inertia maximizes friction increase. The influence of thermal inertia of coatings on friction was shown in [2] to be a purely thermal phenomenon. For low thermal inertia coatings, heat is trapped within the central area of the contact, reducing lubricant viscosity and as a consequence friction. The opposite effect is observed with high thermal inertia coatings. As for the influence of mechanical properties, it is shown that soft coatings lead to reduced vicosity and a decrease in friction. However, the viscosity decrease is now a consequence of a contact pressure drop. The exact opposite effect is observed for hard coatings. In all cases, film thickness is not affected and the reported effects are observed to increase with coating thickness.

CONCLUSION

Friction in EHL contacts may be controlled by a suitable choice of surface coatings based on their thermo-mechanical properties without affecting lubricant film thickness.

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Proceedings of the 42th Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France

LOW DEGREE OF FREEDOM ELASTOHYDRODYNAMIC FRICTION PREDICTION: THROUGH THE FAST ESTIMATION

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ABSTRACT
A semi-analytical model for rapid estimation of the friction coefficient in elastohydrodynamically lubricated contact, is developed and compared with the experiment.

INTRODUCTION
It is of interest to determine the friction and the risk of failure in different contact types in various applications. One example is friction in elastohydrodynamically lubricated concentrated contacts found in rolling element bearings, gears and cam mechanisms.

A fast and reliable estimation for EHL contact has been under the spotlight as industrial concern step forward. This should have ability to reduce the processing time and fully compatible with multi body dynamic software. Although a fully deterministic approach is more accurate than simplified model, it takes longer to obtain results. As an engineering tool it is important that the calculations can be performed in reasonable time frames and captures the realistic behaviour of lubricant, i.e. temperature distribution, proper rheology.

Therefore, a semi-analytical model is proposed where we estimate the average temperature and the friction in the EHL contact within much less computational time compared to a fully deterministic model. Ball on disk tests for two different highly loaded cases are carried out in order to justify the Semi-analytical model.

MODEL DESCRIPTION

The Hertzian pressure solution is assumed to be a proper estimation of EHL pressure distribution. The influence of pressure and shear rate on viscosity are obtained by mathematical expression such as Carreau, Vogel like equations. The relative density of the lubricant is expressed by Tait EOS [1]. In order to obtain the average temperature across the film thickness theory of hot spot for the circular contact is implemented [2]. The film thickness is estimated by Hamrock-Dowson formula which corrected for shear thinning effects for EHL contacts [3]. Friction measurements are performed with a ball on disc test device, i.e., a Wedeven Associates Machine. In each test, the entrainment speed and contact pressure are kept constant while the slide to roll ratio is varied [1].

<u>Friction coefficient: Prediction vs. Measurements</u>

Comparison between predicted friction and measurement under different operating conditions is obtained. Effects of thermal conductivity, film thickness and limiting low shear viscosity are survived. This approach leads to the proper agreement between experiment and proposed model. Effect of limiting low shear viscosity in Carreau equation will be discussed.

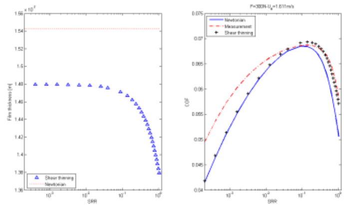

Fig1.Film thickness [left] and Friction coefficient [right]

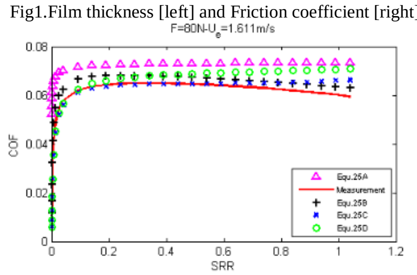

Fig2. Effect of limiting low shear viscosity on friction

ACKNOWLEDGEMENTS

The authors wish to thank Scania, Bosch and Hägglunds Drives (Bosch Rexroth) for financial support.

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MODEL ORDER REDUCTION FOR EHD CONTACTS CONSIDERING STRUCTURAL DYNAMICS

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ABSTRACT

In some applications, e.g. valve-seat/valve-needle contact, due to the part geometry and boundary conditions the deformation of the contacting bodies cannot appropriately be modeled through half-space theory. Additionally, the dynamic behavior of the structure can influence the elastohydrodynamic (EHD) contact such that considering dynamics through rigid body motion does not suffice. Consequently, structural dynamics need to be incorporated into the model. This, however, makes computation more costly. To decrease computation time Model Order Reduction techniques [1] and adaptive step-size time integration can be used. The aim of this study is to investigate a method for fast computation of dynamic EHD contacts accounting for the dynamics of the adjacent structures.

To this end, an existing approach for Model Order Reduction of EHD contacts [2, 3] is extended to consider structural dynamic behavior of real geometries. In order to allow for modeling of real geometries, Finite Element discretization is applied instead of the typical approach, i.e. using half-space theory. Reynolds equation is used to describe the fluid behavior. Finally, time integration is carried out using Diagonally-Implicit Runge-Kutta (DIRK) methods. The Reynolds equation and the equation of motion of the structure are solved simultaneously, i.e. the equations are coupled monolithically. The nonlinear equation system is solved using the Newton-Raphson method. As in [2, 3] the reduction procedure is carried out on the discretized Reynolds equation as well as on the discretized equation of motion.

Differences between modeling the bodies with Finite Element Method and half-space theory will be studied for selected geometries. Furthermore, the dynamic EHD contact behavior will be compared for the case of rigid body motion and structural modeling via Finite Element Method. Moreover, by comparing the accuracy and efficiency of the reduced model with the full model the effectiveness of the applied Model Order Reduction techniques will be investigated. Finally, the suitability of DIRK time integration schemes for this dynamic nonlinear coupled problem will be studied.

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T5-4 Lubricated Rough Contacts II

INFLUENCE OF SURFACE WAVINESS ON PREDICTIONS OF FRICTION BETWEEN CYLINDER LINER AND OIL CONTROL RING

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ABSTRACT

It is of a vital importance for automotive industry to reduce the frictional losses in internal combustion engines and hence their fuel consumption and CO_2 emissions. The major contributors to this are the oil control ring (OCR) and cylinder liner interactions. These interactions are of complex multi-physics and multi-scale nature and many attempts have been made to improve the modelling and understanding of the phenomena involved. Even though continuous improvements have been made (see for ex. [1-3]), the form, waviness and roughness variation of real engineering surfaces still cause a large scatter in the results. The most of the models include measured liner surfaces, which are then filtered to capture the micro-effects of the roughness scale. However, by doing this, the contact conditions change (asperity contact distributes more evenly, see Fig. 1) such that the part of the boundary friction reduces and the part of the hydrodynamic friction increases accordingly for a given engine speed. This study focuses on one of these multi-scale problems, namely on how the 3D measurement type/size and filtering affects the predictions of friction between cylinder liner and OCR of truck engines. Two types of 3D liner surface measurements were investigated: (i) interference (with an objective of 2.5x, size of 2.5x3.3mm) and (ii) 4x8mm stylus measurement. The form was removed by fitting and subtracting a 2nd order polynomial and the waviness was filtered out by using a robust Gaussian filter with three different cutoffs: 2.5mm, 0.8mm and 0.25mm. The friction behaviours (i.e. the Friction Mean Effective Pressure-FMEP) between the primary/ filtered liner surfaces and a perfectly flat ring surface were then simulated for different engine speeds. The relative errors of the OCR's FMEPs with respect to the primary surface were evaluated and results discussed.

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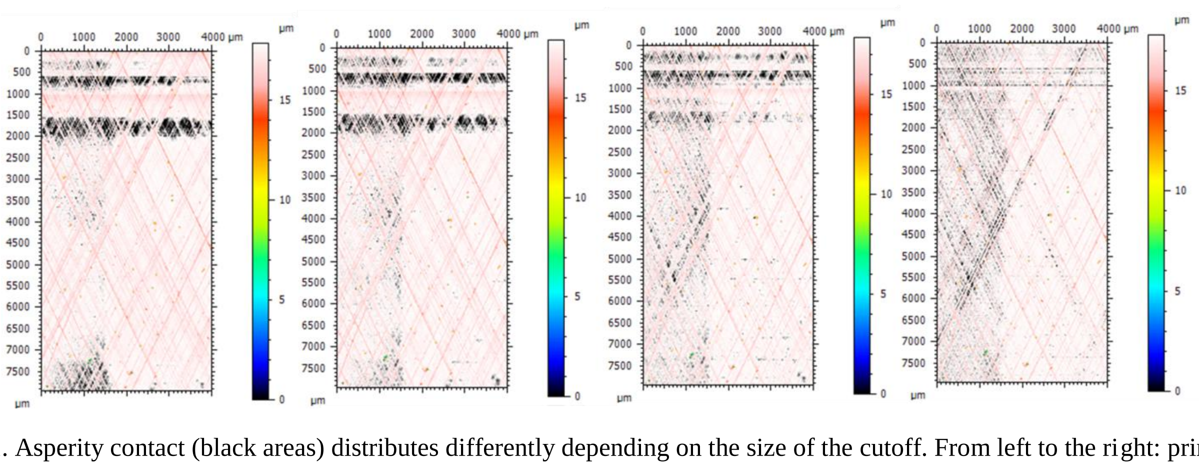

Figure. 1. Asperity contact (black areas) distributes differently depending on the size of the cutoff. From left to the right: primary surface, roughness surfaces after filtering with 2.5mm, 0.8mm, and 0.25mm cutoff (robust Gaussian filter used).

1

AN AVERAGED APPROACH TO ASPERITY CONTACT INTERACTIONS FOR NON-GAUSSIAN LUBRICATED SURFACES

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ABSTRACT

The contiguous surfaces of tribological contacts are often subjected to a period of embedding during the initial stages of operation commonly referred to as the running-in period.Asperity interactionsand increased frictional losses are often prevalent during this period. After the transience of the surface roughness during the initial running-in phase,the resultant surfacecontributes to thetribologicalbehaviour of the contact throughout the majority of its remaining usable life.

The analysis of the surface roughness as a number of spherical Hertzian contacts was provided by the work of Greenwood and Williamsons[1]. Later Greenwood and Tripp[2,3]adapted the model provided for the probability of asperity interaction between two surfaces. The aforementioned asperity contact models are adapted in the current study to model the asperity interactions throughout a contact's running-in phase. The adapted model considers non-Gaussian surface roughness distributions and account for the significant change of geometry of the highest summits by considering the mean asperity radius of curvature as a function of the peak height.

A mixed regime of lubrication model is developed in which the Patir and Cheng[4, 5]Average Reynolds model accounts for the surface roughness effect on the generated hydrodynamic pressure. The model relies on the use of statistical sampling assuming that the surface topographical regions are repeatable in nature in a similar way to Greenwood and Williamson[1].The asperity interactions are considered using the modified Greenwood and Tripp model described previously.

The frictional losses predicted by the numerical model are compared with theexperimental results. The tests areconducted under such conditions that the contact resides in the mixed regime of lubrication and experiences wear during the early stages of running. The surface is periodically measured using an Infinite Focus Microscope until such point as the surface roughness sufficiently stabilises (signifying the end of the running-in process). The measured roughness data is used as the input data for the numerical model.

The paper presents an adapted asperity contact model capable of considering the effect of roughness interactions on frictional losses during the formative embedding process. The numerical results are compared with experimental test results. The combined numerical and experimental approach allows for an improved understanding of the frictional losses during the running-in.

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Adhesion of rough contacts with bounded distribution of heigths with Bradley-DMT model

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Abstract

Theories for adhesion of rough surfaces so far have been either based on asperities and Gaussian distribution of heights, or have assumed Gaussian processes and quite sophisticated calculations. Here, we look at rough surfaces for which we can reasonably assume there is a highest "point", or, more precisely, the distribution of heights is bounded from one end. We develop a "Bradley-DMT" model for a rough surface, as we neglect the elastic deformations due to compressive loads, assuming they are negligible at pull-off, because of the truncation. Hence, we can concentrate instead on observing the effect of the distribution of heigths, which most often are neglected in the Literature even for the pure mechanical contact case, with no good reasons since many manufacturing processes, polishing, abrasion, and even the very processes of plasticity and wear (if surfaces are sliding) tend to flatten the surfaces and make the distribution of height look indeed "truncated" and "non gaussian". Analytical simple results are obtained for Weibull distributions for large roughness, showing the decay depends on the Weibull exponent a, being faster for larger a.

The results of the present model, using a simplified form of the full Lennard-Jones potential (with not significant effect on the results), are extremely simple for any distribution like Rayleigh, Weibull, Truncated Gaussian, and show, contrary to the mentioned existing theories of adhesion of rough bodies, no dependence on the details of the roughness spectrum, radii of the asperities, fractal dimensions and so on. The results are much easier to interpret in the "fractal limit", with respect to existing theories.

Taking the case of truncated Gaussian distribution, it is seen that if we truncated at 1 standard deviation (and consider the surface has been squashed to that level by some process), then adhesion decays less strongly

Preprint submitted to journal *February 23, 2015*

than in any other distribution as can be clearly expected by the assumption made. This could be understood for example in application to a wearing surface, which is predicted by this model to observe two competing effects – on the one hand, the rms amplitude decreases during wear, and hence adhesion should increase; further, the truncation level goes higher and therefore the pull-off decays faster with rms amplitude.

Taking the limit when the truncation goes to a large number of standard deviations, the results seem to converge towards the Weibull decay for exponent $\alpha = 1$, a result which seems of some interest and should in principle give a very simple strong theoretical comparison for the numerical DMT theory for adhesion of Persson and Scaraggi. A comparison with Fuller and Tabor with Weibull distribution of asperity heigths but the JKR model, shows instead that adhesion decays brutally to zero and therefore is qualitatively different.

Key words:
Roughness, Adhesion, Rigid body, Bradley's theory

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MECHANICAL INTEGRITY OF 3D ROUGH SURFACES DURING CONTACT

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INTRODUCTION

Rough surfaces are locally in contact through their roughness peaks. At local scale, the contact pressure can be much larger than the macroscopic pressure. In many practical cases, roughness adopts a random morphology (Fig. 1a). Therefore, any mechanical indicator built on the surface becomes itself a random variable. Any random variable associated with the surface properties is described by a Probability Density Function (PDF) and obviously depends on the morphological structure of the surface. The knowledge of the contact pressure PDF is one of importance since, for example, it provides the probability to ruin and erase the surface in a pure plastic deformation..

MATERIALS AND METHODS

To model this PDF, we use a particular density probability function, the generalized Lambda distributions (GLD), who are generic and polymorphic by approaching a large number of known distributions (Weibull, normal, lognormal). These last ones were successfully used to model damages in materials. To compute the contact pressure we use an semi-analytical model of elastic contact by integrating the morphology of the real surface (Fig. 1b). At first, we use surfaces simulated by Weierstrass functions that presents a set of real surfaces similar with a wide range of surfaces met in tribology. We then evaluate the relevance the lambda distributions to model the contact pressure (Fig. 1c).

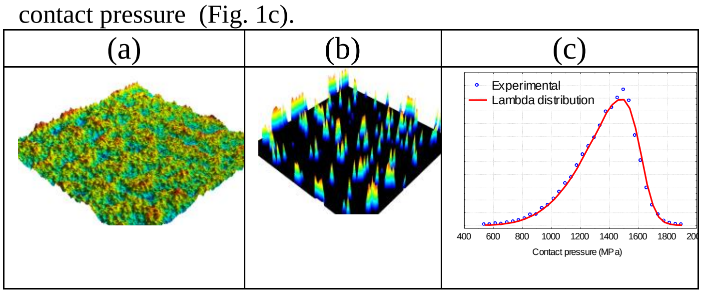

Figure 1. a) Simulated surface with 1024x1024 resolution b) Pressure computation on the surface c) Modeling of the probability density function of the pressure

RESULTS AND INTERPRETATION

By means of these statistical distribution estimates, a probabilistic argument can be set-up to predict the PDF of the maximal pressure. This density can also modeled by a GLD itself. It is then possible to determine the contact pressure PDF concomitant with possible plastic deformation (Fig. 2a). We also study finite size sampling influence on the variation of this PDF, using statistical technique based on resampling called the bootstrap. Also, it is possible to provide a superior bound to the maximal pressure, in order to predict in which case the pressure will never exceed a given value so that surface integrity of the surface shall be preserved (Fig. 2b).

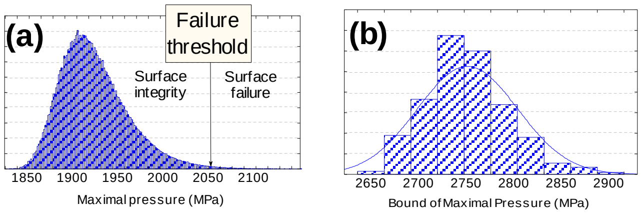

Figure 2. a) PDF of the maximal contact pressure, b) PDF of the safety bound of the maximal contact pressure.

CONCLUSION

A statistical protocol allows us to extract t the maximal pressure PDF of a rough surface. This density is well described by a GLD density function. It is then possible to determine the contact pressure PDF so as to generate plastic deformation. However, the influence of finite sampling effects on this PDF still remains to be done. Doing so should provide sensible estimate of the failure PDF at scales much larger than a given scanned sample. However, the measure uncertainties must be integrated into the picture to build a reliable failure PDF. The larger the scanned surface, the better the prediction. Conversely, if the number of scanned surfaces is too small, then, the elastic limit of the material must be increased to guarantee, with a fixed probability, the integrity of the structure to plastic deformation. The choice of the number of surfaces to be measured then becomes a tradeoff between measure cost, over-quality cost and failure cost.

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T3-5 Wear

Proceedings of the 42th Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France
leeds-lyon - Room 3 - Tuesday, September 8, 2015 - 11:00/11:20 (20min)

ROLLS WEAR CHARACTERIZATION IN HOT ROLLING PROCESSES

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INTRODUCTION

Hot rolling is a conventional manufacturing process of steel industry that allows obtaining a flat or long semi-product from a slab or a billet. After melting shop, the goal of this process step is to transform the slab into a thin sheet (2–4 mm) in successive reduction rate occurring at high temperatures, between 1300°C and 500°C. Improving life of rolls in hot rolling processes is of main concern for metal forming industries as their grinding, replacement and early breaking represent 25% of the production costs. So, mastering their damage and more specifically their wear becomes of major importance. The aim of this study is to characterize the evolution of the topography of the rolls in order to quantify their damage. For this purpose, a recently developed generic method [1] is used to analyse wear during hot rolling.

MATERIALS AND METHODOLOGY

Our study focuses on the finishing mill that is the second reduction step on hot strip mill line. The finishing mill is a quarto-tandem mill that means that each stand is composed of two working rolls that are in direct contact with the product and two backup rolls that are used to support severe stress by reducing deflection. Three to seven stands can be used for the rolling. Two stainless steels are concerned with this study: austenitic and ferritic grades. Because of their large dimensions (from 680 mm to 760 mm in diameter and 2.5 m long), replicas have been performed onto the surface of the work rolls (11 replicas on each generatrix with 6 generatrix per roll). A white light interferometer (NewView 7300, Zygo), with a Mirau x50 type objective (zoom 0.5), is used to characterize and to quantify surface roughness onto the replicas. A total of 640 replicas have been analysed. Finally, an expert system, developed in the authors' laboratory, is used in order to get a multi-scale decomposition of the surfaces and finally select the relevant parameters able to characterize wear.

RESULTS AND INTERPRETATION

The topography evolution on backup rolls, for the ferritic grade, from one stand to another is presented on figure 1, figure 2 and figure 3. We can first observe that the roughness doesn't evolve at the ends of the rolls and is the same as the one observed before rolling, which could show that the backup roll doesn't influence the roughness of the working roll. Secondly, the roughest parts are observed at the centre of the cylinders and an increase of this roughness is observed from one stand to another, which is representative of the increasing wear of the rolls.

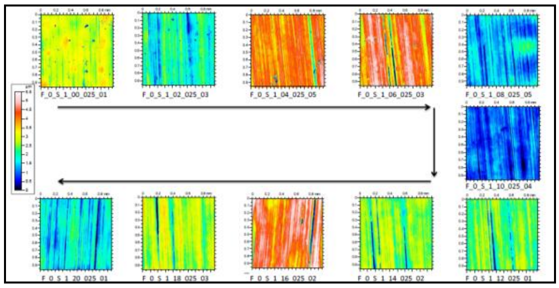

Figure 1: Topography on backup roll on ferritic grade-stand 1

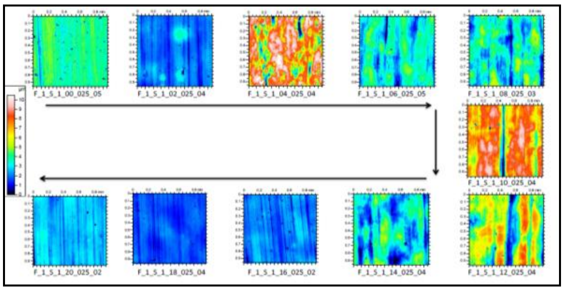

Figure 2: Topography on backup roll on ferritic grade-stand 2

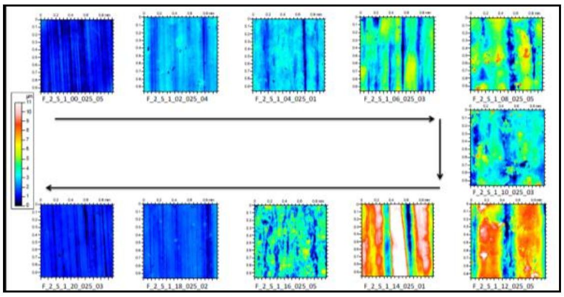

Figure 3: Topography on backup roll on ferritic grade-stand 3

CONCLUSION

These very promising results show the availability of the expert system in characterizing the topography evolution during rolling processes despite the wide dimensions of the rolls.

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HIGH TEMPERATURE SLIDING WEAR MECHANISMS UNDER VARIATION OF LOADING CONDITIONS

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INTRODUCTION

High temperature (HT) sliding contacts are typically found in many industrial applications. During hot rolling of steel, sheet metal is kept aligned using wear plates. The selection of cost-efficient HT wear resistant materials for wear plates is crucial in order to decrease maintenance costs [1]. Material selection using lab-scale tests requires a careful design, since process conditions, such as sheet metal thickness or contact forces applied during the alignment process vary widely, leading to different contact conditions at the interface. Additionally, the formation of wear grooves leads to increasingly conformal contacts and hence lower contact stresses.

The aim of this study is to investigate the influence of normal load on the HT wear rate of technologically relevant Fe-based alloys. To this end, HT sliding tests were performed using prospective wear plate materials and the corresponding wear mechanisms were studied in detail.

METHODS

HT sliding tests were performed on a modified ASTM G65 test rig allowing for inductive heating of plate samples and high sliding speeds [1]. Wear volumes were measured using 3D optical profilometry for improved accuracy. The corresponding wear rates were normalised dividing by the total sliding distance and normal load. A wheel made from a representative sheet metal grade was used as a counter body and pressed against the plate samples with normal loads of 45 and 130 N at room temperature (RT), 500°C and 700°C. Three different plate materials were chosen for testing: (i) a low-alloyed steel grade currently in use, (ii) a martensitic hardfacing featuring fine V-carbides, and (iii) a hypereutectic, Cr-carbide-rich hardfacing.

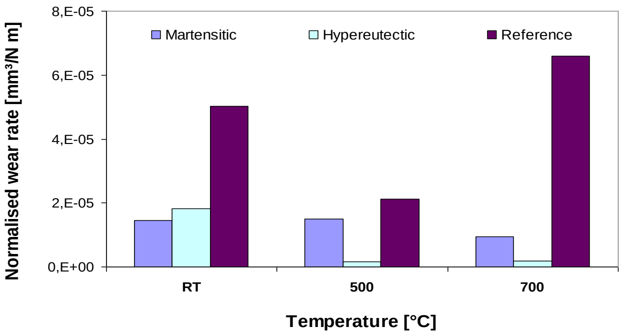

Fig. 1: Normalised wear rates at 45 N for: a) reference material, b) martensitic hardfacing and c) hypereutectic hardfacing

RESULTS

The hardfacings showed significantly lower wear rates under all testing conditions, when compared to the reference material. The hypereutectic hardfacing had the highest wear resistance at HT, as summarised in **Fig. 1** for 45 N normal load. A strong influence of temperature on wear rate was found for all tested materials, especially at 45 N. At 130 N the differences between the calculated wear rates were less significant. Lower wear rates at HT were attributed to the formation of protective mechanically mixed layers (MML) due to the agglomeration of oxidised wear debris, as shown in **Fig. 2**. This entailed superior wear resistance for the hypereutectic hardfacing at temperatures ≥ 500°C. Significant MML formation was also observed for the martensitic hardfacing at 700°C. As for the reference material, MML formed already at 500°C, but wear resistance was observed to decrease at 700°C due to pronounced material softening.

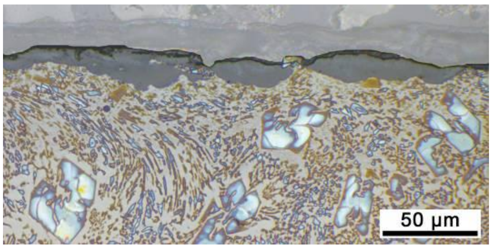

Fig. 2: Longitudinal section of a hypereutectic hardfacing sample after testing at 500°C

The results suggest that contact stresses and the degree of conformity between wear plates and sheet metal can play a significant role in damage evolution during hot rolling and have to be considered during material selection.

ACKNOWLEDGMENTS

This work was funded by the Austrian COMET Program (governmental funding programme for pre-competitive research, project XTribology, no. 824187) and has been carried out within the “Austrian Center of Competence for Tribology” (AC2T research GmbH).

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Proceedings of the 42th Leeds-Lyon Symposium on Tribology
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WEAR TESTING OF AEROSPACE SELF-LUBRICATING BEARING LINER MATERIALS

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INTRODUCTION

The paper describes a novel method for testing the wear rates of liner materials for self-lubricating bearings. The apparatus differs from similar machines in that it is designed for reciprocating contact, to simulate motions encountered in helicopter main rotor pitch link bearings, and is designed to test up to 4 samples at the same time, reducing the effect of variability in environmental conditions. This paper describes key aspects of the test rig along with initial results.

Self-lubricating bearings have been in widespread use since the mid-1950s, predominantly in the aerospace industry where they have the advantage of being low maintenance components. They usually consist of a spherical bearing with the inner and outer elements separated by a composite glass fibre / PTFE resin-bonded textile liner. Previous work [1] found that the wear of typical composite liners has three distinct phases – initial wear in, steady-state wear phase, final wear-out, and that humidity and environmental temperature can have a strong influence [2,3]. Typical bearing-scale tests are long duration, and so a method of accounting for environmental factors and allowing the rapid screening of materials and test conditions is described here as an aid to technology development.

WEAR TESTING RIG & INITIAL RESULTS

The rig tests four separate samples of bearing liner material held stationary and loaded against oscillating counterfaces mounted on a common drive shaft oscillating ±10° at 5 Hz in order to mimic bearing kinematics to SAE 81819 standard. Figure 1 is a section through the rig, showing one of the four loading arms. Simultaneous testing of four samples allows tests on the effects of operating parameters to be conducted under the same environmental conditions. In addition, four simultaneous tests allows a rapid programme of testing to be carried out. The vertical displacement of each arm is monitored, to indicate wear, together with temperatures. Furthermore, Acoustic Emission (AE) sensors are fitted to each sample holder, to allow monitoring of the wear processes within each sample. AE signals measured over one oscillation (from -10° to +10°) are shown in Figure 2, for the initial and steady state wear phases.

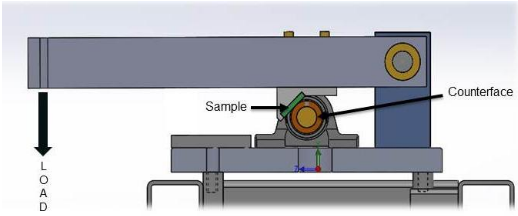

Figure 1: Test Rig arrangement

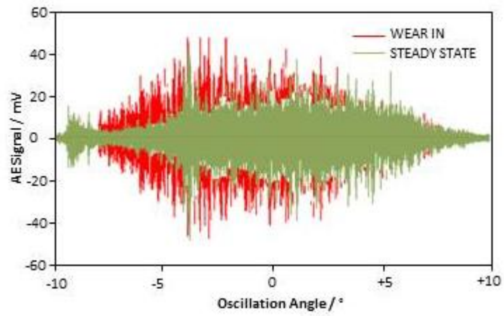

Figure 2: AE signals during initial and steady state wear

CONCLUSIONS

A suitable method for accelerating the wear testing of composite bearing liner materials for aerospace applications has been developed. The method reduces the influence of environmental conditions, and initial results show promise as a method for rapid comparative testing for technology development.

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Proceedings of the 42nd Leeds-Lyon Symposium on Tribology
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THE LINEAR WEAR RATE OF A COATED CONTACT BETWEEN A SPHERE AND A FLAT SURFACE

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ABSTRACT

A theoretical model is introduced for the computing of the linear wear of a coated contact between a sphere and a flat surface. Both the theoretical model and the experimental data show that the period of time until wear through increases disproportionately with the increasing thickness of of the coating in a coated contact between a sphere and a flat surface.

INTRODUCTION

The functionality of a coated surface is often determined by the lifespan of the coating layer. If the coating undergoes sliding motion, the period of time until wear through is subsequently the decisive parameter. According to Archard [1], the specific wear coefficient is defined as the quantity of worn material per unit sliding distance and per unit of normal load. The wear volume h is therefore propotional to sliding distance s. For coating layers the linear wear displacement h is more convenient than V. It can, for example, forecast the sliding distance or operating time before wear through of the coating occurs. The relationship between h and s is somewhat complicated in the case of a contact between a sphere and a flat surface due to the increasing contact area with the progress of wear. This geometrical combination is a widely used design for various technical components such as electrical contacts in connectors, switches and relays. The linear wear rate cannot be a constant and must decrease with the progress of wear. We have used a simple model to describe the relationship between the wear displacement and the sliding distance and verified the model by means of wear tests.

THEORETICAL MODEL

The initial contact area A_0 is first determined with an FEA computation. The radius of the contact area r_0 and the measure b_0 can as a result be easily calculated. According to Archard, if the other parameters do not change, the wear volume is linear proportional to the sliding distance. Therefore the instant linear wear displacement h at the given distance b can be calculated with the geometrical relationship shown in Fig. 1.

EXPERIMENTAL

In the experiments the implemented contact samples had a sphere on a flat setup, in which the radius of sphere was 4.5mm. The base material of the samples was bronze (CuSn4). The samples were electrochemically galvanized with silver coating. The thicknesses was 6 µm in sphere and planar respectively. A fretting wear test rig was used for the tests. In the current measurements the parameters are were defined as follows: the amplitude 200 µm, the contact force 3 N, frequency 1 Hz and room temperature. During the experiments the wear, normal force, friction force and friction coefficient were recorded continually along with the measuring cycles. In order to verify the wear curves, the tests were terminated at different cycles, and then the silver thickness was measured using an X-ray fluorescence device. Fig. 2 shows the computed and measured wear rate curves as a function of sliding distance. A very good correlation between both of the curves can be observed, with the curves showing a clearly digressive development of fretting wear displacement, which means that the period of time until the wear through increases disproportionately with the increasing thickness of the coating.

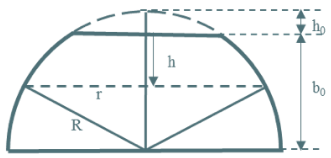

Fig. 1: Spherical contact point

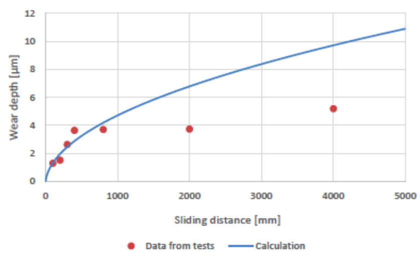

Fig. 2 : Comparison between calculated curve and the results from tests

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T3-6 Coatings

MULTI-SCALE STUDY OF INITIAL TOOL WEAR ON TEXTURED ALUMINA COATING, AND THE EFFECT OF INCLUSIONS IN LOW ALLOYED STEEL

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ABSTRACT

Innovative textured alumina coatings have been engineered recently for boosting cutting tool lifetime. However, there is a lack of complete understanding in the tribology aspect when machining with different textured coating. In this study, the focus is on the initial tool wear of a textured alumina coating and the relation to the workpiece's inclusion types.

When turning low alloyed steel with hard inclusions, scores and grooves have been observed in the wear of the alumina coating in CVD coated cutting tools. Multiple basic studies of inclusions in steel and tool wear have been done before. In this work a multi-scale approach has been implemented for an enhanced understanding of the behavior and effect of the inclusion types and shapes on the related flank wear of the textured alumina coating.

For the chip formation studies, a quick stop device with a high speed camera has been used. The analysis included different areas of the quick stop sample, where a high difference in strain magnitude exists. Following this, one can observe the different strain levels in the frozen chip sample and its effect on different inclusion types.

To study the wear due to the inclusion particles on the surface of the CVD coating, white light interferometry was used. A 3D surface was generated, and topography analysis was performed in the Micro and Nano scale. For an in depth study of the wear on the tool surface at an even smaller scale, Transmission Electron Microscopy (TEM) was used. This allowed the study of the coating texture and the subsequent effect of the initial wear on the coating's crystalline structure. More TEM Nano-scale observations showed traces of embedment for workpiece material into the coating surface layer. Using the above described multi-scale analysis, the mechanism behind this initial tool wear was analyzed and discussed.

EFFECT OF SILVER MOLYBDATE ON TRIBOLOGICAL PERFORMANCE OF NICKEL-BASED COMPOSITE COATINGS

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ABSTRACT

Silver molybdate powders were prepared by the sol-gel method. Then the Ag_2MoO_4 containing nickel based composite coatings were prepared by electro co-deposition method. The effects of Ag_2MoO_4 addition amount on tribological performance of composite coating were investigated. The friction coefficient of composite coatings decreased with the increase of Ag_2MoO_4 addition amount until the amount of Ag_2MoO_4 reaches 0.05g/L.

INTRODUCTION

The Ag_2MoO_4 can be formed on the frictional surface of silver and molybdenum containing coatings [1,2], which plays the role of lubrication at moderate temperature and endow the coatings lubricating properties over a wide temperature range. Ag_2MoO_4 decomposes at about 500℃, which influences its lubricating effect. Liu[3] prepared the silver molybdate containing nickel composite by powder metallurgy method and found the compound oxides decompose into silver and molybdenum oxides during hot pressing. The Ag_2MoO_4 containing composite coatings were electro deposited under low temperature, so their intrinsic properties can be evaluated.

EXPERIMENTAL DETAILS

Ag_2MoO_4 powders were prepared by sol-gel method. Ni-based composite coatings were prepared by electrodeposition method. The addition amounts of Ag_2MoO_4 in solution were 0.01g/L, 0.02g/L, 0.05g/L and 0.1g/L. The tribological performances of composite coating were tested by ball-on-disk tribometer with the Si_3N_4 ball as counterface from RT to 600℃.

RESULTS AND DISCUSSIONS

Fig.1(a) shows the morphology of Ag_2MoO_4 powders prepared by reaction of ammonium molybdate and silver nitrate. The particles show rod-like features with the length of 1-5 μm and the diameter of 1-2 μm. The Ag_2MoO_4 can be detected by EDS in the nickel based coating (Fig.1(b)) .

Fig.2 (a) shows the friction coefficient of coating with different Ag_2MoO_4 addition amount varied with sliding time. The friction coefficient decreases with the increase of addition amount of Ag_2MoO_4 until it reaches 0.1g/L. The friction coefficient of composite coating with 0.05g/L is the lowest (0.5). The wear rate of Ni-Ag_2MoO_4 increase with the increase of temperature due to decompose of Ag_2MoO_4 (Fig.2(b)). The samples gain mass due to the oxidization at 600℃.

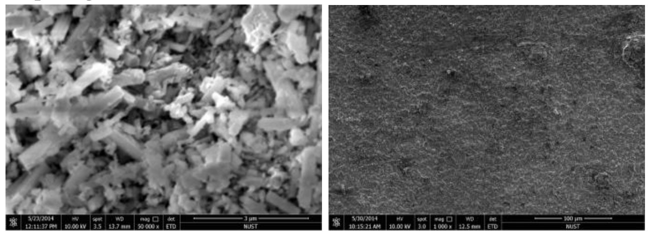

Fig.1 SEM morphology of Ag_2MoO_4 powders (a) and Ni based composites(b)

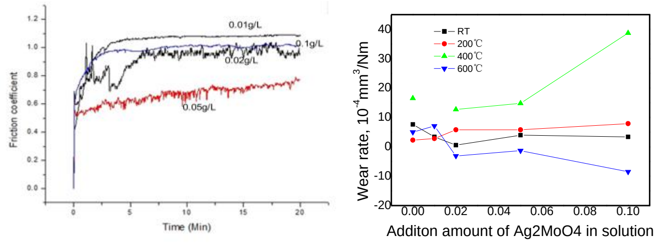

Fig.2 Friction coefficient (a) and wear rate (b) of Ni-Ag_2MoO_4 at different temperature

CONCLUSIONS

The lower friction coefficient can be obtained by adding optimal amount of Ag_2MoO_4 in coatings. The wear rates increase with temperature due to decompose of Ag_2MoO_4.

ACKNOWLEDGMENTS

This project is supported by China Postdoctoral Science Foundation (No. 2013M540450, 2014T70520).

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TRIBOLOGY BEHAVIOR OF CU-MOS_2 COMPOSITES DURING DRY SLIDING

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ABSTRACT

A Cu-MoS_2 composite coating was fabricated by cold spray and its tribology performance was studied within dry air. It was demonstrated that a small amount of solid lubricant (1.8 ± 0.99 wt.%) could significantly decrease coefficient of friction (CoF) from around 0.7 (pure Cu coating) to 0.15. MoS_2 patches in the wear track were identified as low CoF zones, and the main velocity accommodation mechanism was interfacial sliding between MoS_2 debris. Even though the coating worn heavily in the early sliding (0.88 nm/cycle in penetration depth during the first 100 cycles), extremely slow wear (0.0014 nm/cycle) over the following sliding helped achieve a high coating endurance. The MoS_2 patches in the wear track and ejected wear debris on the ball produced reservoirs to replenish MoS_2 at the contact, and became depleted with sliding up to approximately 2250 cycles. The dynamics of the process, material buildup and loss in the wear track and on the ball, was examined using energy dispersive X-ray spectroscopy (EDX) and Raman spectroscopy. Subsurface microstructure revealed by electron chanelling contrast imaging (ECCI) technique showed a layer of sliding-induced microstructure, 3-5 µm thick in Cu-MoS_2 coating, while 10-30 µm in Cu coating.

INTRODUCTION

Cold spray has been demonstrated as a promising coating method for heat sensitive materials such as solid lubricant as it intrinsically minimizes or eliminates thermally induced chemical changes [1]. Also, it is well known that MoS_2 produces low friction coefficient and long sliding life of withstanding hundreds of thousands sliding cycles [2]. However, a few studies devoted to explore tribological behavior of cold-sprayed metal-MoS_2 composites. In the present study, therefore, it was aiming to understand better how MoS_2 behaves with cold-sprayed Cu during dry sliding, and thus influences sliding life of the coating.

RESULTS AND DISCUSSION

As shown in Fig. 1, Cu-MoS_2 coating showed much lower overall CoF compared to the Cu coating. After a short run-in stage where CoF dropped, CoF then increased and eventually became relatively constant between 0.14 and 0.15, followed by a continuously increase after around 2250 cycles (see the inset). However, Cu coating showed a consistent increase until reached the steady-state value of 0.65-0.70. After 1000 cycles, it increased gradually up to approximately 0.95. If failure was arbitrarily defined as the number of sliding cycles the coating survived before the average CoF increased beyond the steady-state value, shown as the rectangles in Fig. 1, Cu-MoS_2 coating was able to endure up to around the 2250th cycle, whereas the Cu coating only stayed stable for approximately 1000 cycles before CoF started climbing. It indicated that Cu-MoS_2 coating was able to withstand much more sliding cycles and therefore enhanced the sliding life.

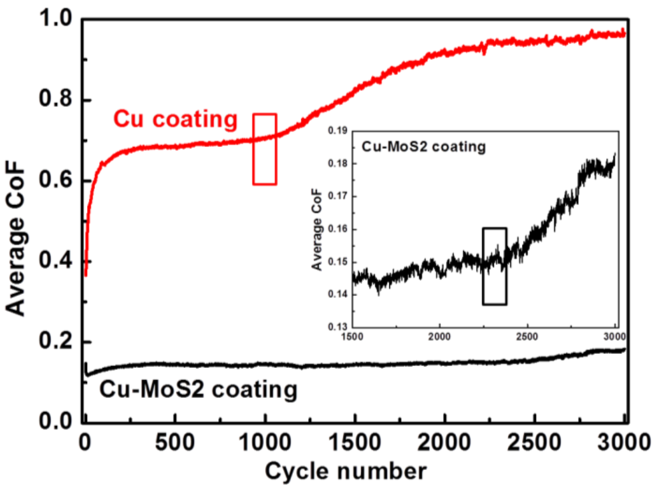

Fig. 1. Average coefficient of friction versus cycle number on cold-sprayed Cu-MoS_2 and Cu coatings. Rectangles indicate the cycle numbers where CoFs go beyond steady-state values.

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MECHANICAL PROPERTIES OF ^{13}C DLC FILMS DEPOSITED BY PBII&D

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ABSTRACT

Diamond-like carbon (DLC) films have extraordinary properties [1] and have already applied to a lot of products. Their unique properties are surely affected by the structural nature of the films, especially the amounts of sp^3/sp^2 hybridization which strongly concern the properties of the films are most important factor. TEM/EELS, NEXAFS, ultraviolet Raman spectroscopy, XPS and so on are often used to evaluate the ratio quantitatively, however, it will be so hard to decide the typical procedure because each procedures have the academic and/or industrial problems. On the other hands, solid-state nuclear magnetic resonance (solid-state NMR) is the most quantitative procedure to evaluate the ratio because of the sensitive detection for ^{13}C structures, however, sample pretreatments, i.e., preparation of sample powders should be the big problem. In this study, ^{13}C DLC are deposited on pure iron and pure aluminum sheet and the DLC powders are gathered by dissolution process of the sheet. The change in structure of before and after the process and the mechanical properties of the films are discussed in this study.

INTRODUCTION

Recently, DLC (diamond-like carbon) films have attracted interesting for their extraordinary mechanical and tribological performances such as high hardness, low friction, high wear resistance. These performances of DLC films are remarkably affected by the structural nature of the films, i.e., sp^3/sp^2 hybridization, hydrogen contents, density and so on. Especially the amount of sp^3/sp^2 hybridization and hydrogen contents are most important factors to decide the performances. On the other hands, ^{13}C solid NMR measurement is one of the strong tool in order to evaluate sp^3/sp^2 ratio quantitatively, however, effects of pre-treatment procedure on the change in structure of the films have been unclear. The effects are discussed in this study.

NOMENCLATURE

DLC films are grown on Si(100) wafers, pure aluminum sheet (99% fineness) by using PBII&D (Plasma Based Ion Implantation and Deposition) system. In this study, regular methane gas (CH_4) and only ^{13}C applied methane gas ($^{13}CH_4$) are used as precursor.

After the deposition the films deposited on iron and aluminum sheet are immerged into 6 mol/L HCl solutions at 75 ℃ each other until the substrates are completely dissolved. In this study, not only solid NMR measurement but also several analytical procedures such as Raman, XPS, ERDA are accomplished.

Fig.1 shows the results of Raman spectroscopy of $CH_4/^{13}CH_4$ DLC films which are deposited under the same conditions. Each Raman peaks indicate the typical DLC peaks, however, the center position of each G peaks is different. In addition, there is a little shoulder at around 1200-1300 cm^{-1} in case of $^{13}CH_4$ film. These results indicate that there are some change in structure of the films in spite of the same deposition conditions. These will be caused by the difference in one neutron between C and ^{13}C. More details will be discussed in presentation.

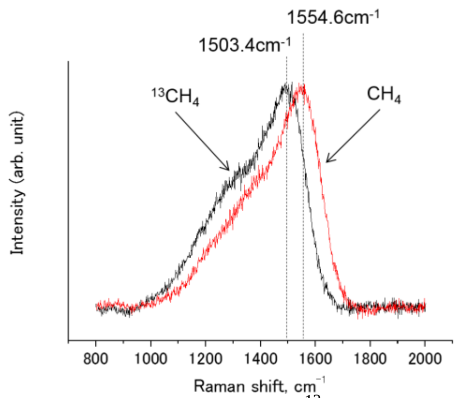

Figure 1 Raman results of $CH_4/^{13}CH_4$ DLC films

ACKNOWLEDGMENTS

This work was supported by JSPS Grant-in-Aid for Young Scientists (B) Number 26820037.

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T2-3 Damage, RCF and surfaces

THE EFFECT OF COATINGS AND OIL ADDITIVES ON THE EVOLUTION OF SURFACE TOPOGRAPHY, WEAR AND FRICTION DURING RUNNING-IN

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ABSTRACT

The ongoing research on improving the efficiency of automotive engines is mainly focused on finding new environmentally friendly additives, new materials, and on using new types of components in classical applications. For example, using rolling element bearings instead of plain ones in crankshafts can reduce the friction in boundary/mixed lubrication regime.

One of the key phenomena having a high impact on the life of machine elements is running-in which is defined as the simultaneous transitional process involving variations in roughness, wear, and friction, occurring within the interface.

DLC coatings, though exhibiting low friction, mostly do not interact with additives [1]. Another type of coating, which has not been deeply studied yet, is the Fe_3O_4 coating. Ito et al. [2] showed that for pure sliding motion, this type of coating, together with an anti-wear additive (e.g. ZDDP) can work as a friction modifier, reducing the friction in the contact. Moreover, the iron oxide works as sacrificial layer during running-in period, reducing friction and avoiding the wear on the steel surface [3].

The main purpose of the present work is to investigate experimentally the effect of additives and coatings on the evolution of wear, friction and roughness with steel and coated samples (DLC and Iron Oxide) during running-in period.

The experiments were done on a micropitting test rig using a small roller in a rolling/sliding contact with three larger rings, under mixed lubrication, in order to simulate the operating conditions typical for Rolling Element Bearings.

The non-coated rings were made of steel (AISI 52100) while the rollers were coated with three different coatings: Highly Hydrogenated DLC, Si-doped DLC and Black Oxide. The first two coatings have a high hardness compared to the steel while the Black Oxide coating is softer.

Mineral Base oil (Group III) was used as a model base oil. For tests with additives, the base oil was mixed with 1 wt.% of ZDDP (antiwear additive) and MoDTC (friction modifier additive).

The chemical composition analysis was made by using XPS for all the samples, FT-IR for ZDDP-derived layers and Raman for MoDTC lubricated contacts.

Roughness results for the roller shows always an initial decrease of its value followed by an increase of roughness. This behavior can be assigned to two main processes, namely flattening of asperities in contact (due to plastic deformation) and mild wear [4]. The same processes have been found to take place when coatings are used. With harder coatings, plastic deformation of asperities is the dominant process, while with softer coatings the main process driving the evolution of topography is the abrasive wear.

When additives are present, the processes acting on the surface are physico-chemical (formation and removal of tribolayer) and mechanical (changes in surface roughness, friction and wear).

ACKNOWLEDGMENTS

This study was funded by the FP7 program through the Marie Curie Initial Training Network (MC-ITN) entitled “**ENTICE** - Engineering Tribochemistry and Interfaces with a Focus on the Internal Combustion Engine” [290077]

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Proceedings of the 42th Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France
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IMPACT OF LUBRICANT FORMULATION ON PITTING OF MANUAL TRANSMISSION GEARS

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INTRODUCTION

Pitting and micropitting, resulting damages of rolling contact fatigue, are caused by cracks initiation and propagation under gears tooth surface. The literature underlines the complexity in studying this phenomenon due to the number of factors involved such as rolling to sliding ratio, residual stresses, surface roughness, metallurgy of gears and bearings and environment influence. Recent works on pitting have shown that initiation of micrometric cracks occurs on gears tooth at early stage of gears life (running-in) [Olv05]. Mechanism and rate of propagation of contact fatigue crack are thus of great importance to the overall life. Among all factors having an effect on contact fatigue crack propagation, the role played by the lubricant has taken a lot of interest last fifteen years. However literature focuses mainly on the lubricant's mechanical role on crack propagation. Only few studies investigated the impact of lubricant chemistry on crack propagation and more specifically the role of lubricant's additives [Meh10].

MATERIAL AND METHODS

In this study, expertise of gears tested on full scale transmission stand with different lubricant formulations has been performed. Optical and Scanning Electronic Microscopy (SEM) and Electron Backscatter Diffraction technique (EBSD) have been used to characterize cracks size, morphology and metallurgical transformations associated with contact fatigue. For some formulations, foils containing fatigue cracks have been prepared by Focused Ion Beam technique (FIB) for Transmission Electronic Microscopy (TEM) observations and Energy-dispersive X-ray Spectroscopy (EDS) analysis. Complementary to these observations, steel samples have been submitted to lubricants exposure at different temperature and linear reciprocating tribotests to better understand lubricant additives interaction with gears steel. Nature and chemical composition of reactive film and tribofilms formed during these tests have been performed using X-ray Photoelectron Spectrometry (XPS) and SEM observations.

RESULTS

After full scale transmission test numerous fatigue cracks have been found on geartooth whatever is the lubricant formulation tested. All cracks were surface initiated. EDS analysis reveals the presence of oxides together with chemical elements emanating from lubricant's additives on cracks faces and tip demonstrating the lubricant penetration into cracks. MET observations of FIB preparations reveals that chemical elements detected are present as films formed on crack faces and crack tip. Films formed on crack faces are chemically and morphologically different from film found at crack tip. Moreover films chemistry and thickness depend on lubricants formulation.

CONCLUSION

According to tribotests and lubricant exposure results hypotheses concerning films formation can be developed:

- Films present on crack faces can be identified as tribofilms
- Chemical reaction of extreme pressure additive with native steel surfaces could explains film present at crack tip.

Additives may thus affect crack propagation in several ways. Formation of tribofilms may lower the friction coefficient between cracks faces thus increase the crack propagation rate. Reaction of additives molecules on crack tip fresh surfaces could involve mechanisms close to those known in stress corrosion cracking.

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COMBINED FRICTION MEASUREMENTS OF THRUST BEARING WASHERS (DISKS) - FROM MACRO TO MICRO SCALE

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ABSTRACT

The interaction of lubricant and bearing influences friction as well as bearing life. Oil additives forming boundary layers on the bearing surface may influence both effects. Typically FE-8 test rigs are used for characterization of rolling element bearings in combination with specific lubricants. Additionally the influence of the lubricant can be investigated on a two-disk test rig. This test allows measurement of friction during full and boundary lubrication. To examine the friction on the surface of the bearing components after test in a macro scale test rig, a micro pin–on-disk tester is used. Disks from prior FE-8 tests and unused disks were measured. The resulting friction behavior is compared to friction measured in the twin disk machine as well as the results from the FE8 tests. It could be shown, that boundary layers achieved in the FE8 tests can be detected in the micro pin-on-disk setup.

INTRODUCTION

The investigation of the occurring boundary layers on bearings is complicated due to the thickness in the range of a few nm. For additivated greases Wiendl et al. investigated the correlation of chemical processes and surface layers [1]. Nanoindentional studies on bearings and ToF-SIMS measurements were executed on used rolling bearings. It was found that antioxidants reduce the oxidation of the grease and influence surface layers. Gatzen et al. analyzed the effects of polymer additivated greases on surface layers [2]. The tests on rolling bearings were performed applying nanoindentational tests and ToF-SIMS. Formed surface layers could be shown and effects on surface roughness and hardness were detected. Common to these tests is the measurement in the nm range. Applying a micro pin-on-disk tester allows to evaluate the friction properties of the boundary layer in the micro scale and to conclude on its influence to the macro scale.

EXPERIMENT

Each of the thrust bearings subjected to the life test was lubricated with an specific oil and mounted in the FE-8 test rig. The test is specified in the standard DIN 51819 for the mechanical-dynamic measurement of rolling element bearing lubricants. The traction behavior of the lubricant was measured on a two-disk test rig. For the micro-pin-on-disk tests, a modified spin-stand was used. The test stand was originally developed to investigate the head-to-disk interface of a hard disk drive (HDD). Figure 1 depicts the micro-pin-on-disk tester.

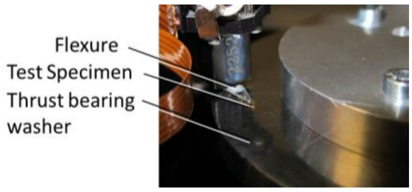

Figure 1: Micro pin-on-disk test stand

As test specimen, a 100Cr6 ball with a diameter of 500 µm was attached to the slider of a HDD recording head (head gimbal assembly – HGA) using adhesive, which was mounted on the testers arm. The tests were performed without lubrication at a rotational velocity of 1 min^{-1}, the load was approx. 30 mN. It could be shown, that for the thrust bearing used with specific oils, a significantly lower COF (coefficient of friction), compared to other oils, could be detected. In case of an unused thrust bearing, a reduction of the COF by the formation of a boundary layer could be shown.

CONCLUSION

By applying the micro pin-on-disk tester with its sensitive measurement capabilities, differences in the dry friction of tested axial bearing washers could be shown, which are assumed to be caused by different boundary layers. The COF attained in two-disk tests shows analog trends to the measurements in the micro pin-on-disk tester. The presented setup allows to measure the influence of boundary films on the micro scale and to use these data for understanding the tribological properties in macroscopic test rigs.

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Influence of subsurface plastic deformation on the running-in behavior of an AlSi alloy

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ABSTRACT

The subsurface microstructure of tribological contacts is subjected to plastic deformation and shear. The present publication focusses on the influence of the initial microstructure preset by final machining on the wear behavior of a hypoeutectic AlSi9Cu3 alloy. Aluminum disks were tested with a steel pin on a pin-on-disk tribometer under consideration of running-in phenomena. As the systems were tested in the ultra-low wear regime, pin wear was measured by radionuclide-technique. The microstructures of the samples were characterized by nanoindentation, x-ray photoelectron spectroscopy and focussed ion beam microscopy. The visualization of subsurface shear by markers in the disks shows a clear correlation of subsurface deformation and wear. With the experiments, the relationship between final machining and tribological behavior was clearly demonstrated.

T1-3 Lubrication applications I

Squeeze film tilt effects in microsystems

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ABSTRACT

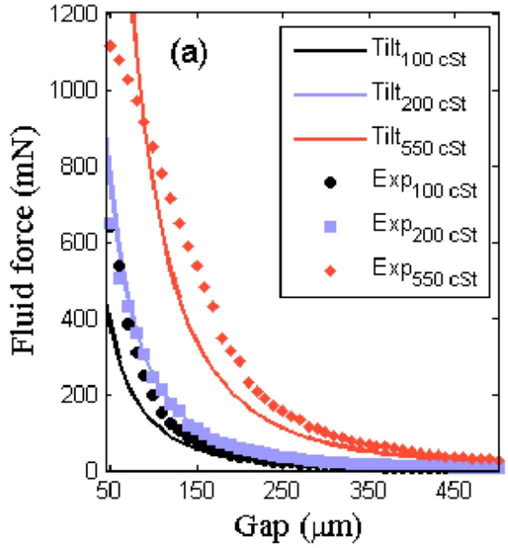
The evaluation of fluid squeeze film damping is crucial to the design of microsystems. In a MEMS device, such as a torsional mirror, the sensing or activating element undergoes motion normal to a fixed substrate with respect to a nearby surface, generating hydrodynamic lubrication-like forces. In the design process, complex dynamic MEMS structures must be modeled. Generally, these hydrodynamic forces are not used to lubricate or separate surfaces, but arise incidentally. However, they often comprise the largest applied forces to the system, and the largest source of parasitic losses. Useful, trusted, and verified formulas for damping are not available to those who model dynamic MEMS systems.

INTRODUCTION

Previous experimental measurements of squeeze film damping forces in the MEMS field indicated a fundamental discrepancy from classical lubrication theory [1, 2]. This paper presents an explanation for the dis-crepancy reporting on past experiments presenting a new numerical and theoretical approach. In the past, analysis of experimental data assumed parallel surfaces, although a non-uniform fluid film thickness due to plate tilting may occur in practice. Small inclinations and misalignments are usually overlooked in theoretical treatment, however, this study finds they could have a dramatic impact on the observed forces. To investigate this effect, a compact linear solution for hydrodynamic squeeze film damping forces was developed via a perturbation method assuming an incompressible fluid bounded by tilted plates undergoing small normal vibrations.

The results show that the inclination causes asymmetric pressure distribution and decreased fluid force. In fact, almost immeasurably small angular tilt can cause significant change in the fluid force. The theoretical predictions employing the tilt model are found to agree well with the experimental measurements.

The present study augments previous work [3-5] by including the effects of fluid inertia and viscoelasticity in slightly non-parallel films undergoing rapid normal oscillations.



Experimental forces (dots) and predictions (lines) as function of smallest static gap in the tilted plate system (ΔH = 80 μm) for actuation frequency of (a) 200 Hz. Data for 100 cSt (black), 200 cSt (blue) and 550 cSt (red).

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Proceedings of the 42th Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France
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A FULLY-COUPLED ELASTO-HYDRODYNAMIC MODEL FOR AIR FOIL THRUST BEARINGS

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INTRODUCTION

In the last decades air foil bearings (AFBs) have become an interesting alternative for rotating machinery applications. Replacing classical hydrodynamic oil bearings by AFBs yields less system complexity, an omission of the oil supply system and helps to fulfill continuously increasing emission standards.

In spite of their numerous advantages, AFBs still have not become a standard, widely used bearing technology. The main reason for that is – despite of a lot of research effort in the past – a lack of predictive models for AFBs.

Next to temperature considerations, especially the elastic structure is a challenging feature of AFBs. It has the implication that the shape of the fluid film becomes a function of load which is not the case in rigid oil bearings. As a consequence of this, pressure generation and the elastic deformation of structural components are fully coupled and have to be solved simultaneously.

Figure 1 shows schematically a widely used configuration of the elastic elements of air foil bearings.

A bump foil strip acts as the elastic support of a top foil, which forms in conjunction with the moving part the hydrodynamic wedge for the pressure build up.

The bump foil strip itself consists of arc-shaped bumps that are connected by bridges.

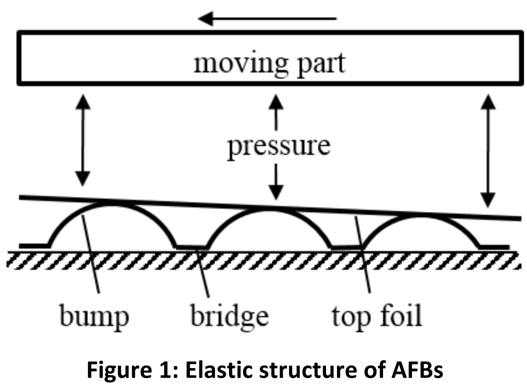

Figure 1: Elastic structure of AFBs

A common approach in literature is to model the structure as a plate with an elastic foundation. The main uncertainty in this case stems from the estimation of the spring constant for the elastic foundation. Up to date it is determined by measurements [1] or by a finite element calculation for one individual bump.

FULLY-COUPLED MODEL

The authors present a structural model which eliminates the need for an estimation of the spring constant for the elastic foundation. This is achieved by applying the Reissner-Mindlin shell equations to the top foil as well as to the bump foil strip. A penalty contact including coulomb friction is formulated between the base and the bump foil strip as well as between the bump foil strip and the top foil. The structural model is coupled with the compressible Reynolds equation and a finite element method is used in order to solve the nonlinear fully-coupled system of equations.

The results of the detailed fully-coupled model are compared to elastic foundation type [2] and other reduced [3] models.

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NUMERICAL ANALYSIS OF DRAG TORQUE OF A GROOVED SURFACE IN MULTI-DISK CLUTCHES

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ABSTRACT

According to the state of the art, a multitude of studies exist that deal with the influence of groove pattern and its geometry on drag losses in the disengaged wet multi-disk clutch. Thereby mainly conventional groove geometries such as the radial groove pattern are examined. Until now, only empirical investigations were achieved and delivered mainly a qualitative characterization of the drag torque phenomena in lubricated clutches. These tests were ran in different operating conditions and issued on many optimized designs. Nevertheless, the groove patterns are still optimized by cost intensive experimental studies for the specific application. Therefore, specific variations of the groove geometry in the context of parametric studies are experimentally combined with a high effort.

In the numerical simulation, it is in principle possible to carry out a systematic variation of the influencing parameters particular of the geometry of groove pattern. However, in the field of numerical modeling, there are few publications. Aphale et al. [1] compared the results obtained from the analytical solutions, experiments and numerical simulation. Thereby a radial groove and the variation of the groove depth are considered. In [2], the investigations were continued with the focus on the number of radial grooves and other groove patterns. Huang et al. [3] considered a radial groove as well and varied the number of grooves and the groove depth and compared the results with the experimental investigations.

The main challenges in the modeling of the system are the multi-phase flow and the complex geometry of groove pattern. Rudloff et al. [4] presents a simulation model to describe the two-phase flow and modeled the oil properties depending on the pressure, the temperature and the shear rate as well as a model of cavitation. As a groove pattern a bucket groove and a waffle groove pattern is considered.

The modeling of complex groove geometries particular production influences was barely considered in the simulation of drag torque up to simple groove geometries.

A simulation model is presented based on ANSYS CFX for calculating the flow conditions and drag torques of grooved surface of a single friction plate. Three conventional groove patterns, the radial, the waffle and the group-parallel groove pattern are modeled and the drag torque and the pressure distribution are calculated.

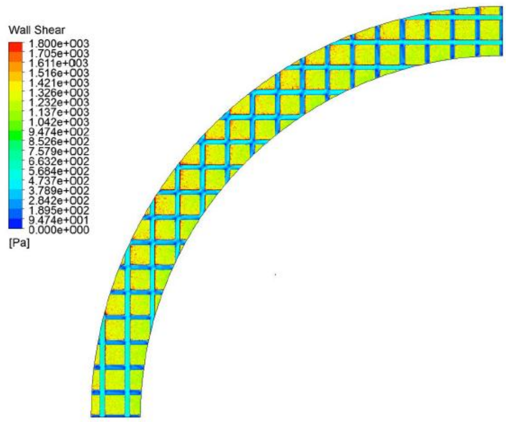

Figure 1: Wall Shear distribution on a waffle groove pattern

Depending on the groove geometry different approaches to mesh generation of the groove geometries are performed. The results are verified by experimental studies.

Based on the created numerical model a parametric study of the geometrical properties of the radial groove pattern is carried out.

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WEAR OF BEARING BUSHES ON RUN-IN SURFACES

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INTRODUCTION

The running-in process is commonly said to involve a topographical adaptation of the contacting surfaces of a tribosystem, among other effects [1]. During this phase of the wear process, high local pressures lead to flattening of asperities and general smoothing of the surface, and subsequently a larger microscopic contact area bearing the load.

Wear models [2] attempting to connect wear with, e.g., surface roughness therefore have to carefully differentiate between running-in steady-state wear regimes, as the topographical changes during running-in must be accounted for. In the present paper, the effect of surface topography on both running-in and steady state wear is investigated separately for different lubrication regimes.

METHOD

Tribological testing was done on a bearing test rig with unidirectional sliding. CuZn25Al5 bearing bushes were run against 100Cr6 counterparts (pins). The shaft diameter and a slight convexity in the axial direction were specifically designed to achieve the desired contact pressures in the tribotests and avoid issues with edge-running effects. Both friction and wear was measured continuously during the tests.

All experimental results are analysed by fitting an exponential function to the observed wear, quantifying the amount of running-in wear, duration of running-in and steady-state wear rate [3, 4].

Sliding contacts involving a component with softer material often lead to wear behaviour which can be correlated with the "*pv*-factor", i.e. with the contact pressure and sliding speed, as long as the coefficient of friction remain constant. In this case the generation of heat in the contact is an indicator for the wear [5]. Therefore the temperatures of the sample and the lubricant are also continuously monitored.

RESULTS

Pre-tests (without wear measurement) were performed in order to measure the Stribeck curve for this particular tribosystem. In the Stribeck curve the transition between boundary and hydrodynamic regime is visible. After running-in tests (with parameters chosen according to the Stribeck curve), the already run-in surfaces were subjected to the main tribotests for which loading conditions corresponding to the three lubrications regimes – boundary, mixed and hydrodynamic – were chosen. The wear occurring during these experiments was then analysed to see whether further running-in was observed, to make sure to determine the pure steady-state wear rate depending on the lubrication regime and depending on the nature of the run-in surface. Additionally, the topographic/roughness changes induced by the main tribotests were analyzed. The wear results are compared to numerical results from existing wear models, such as Archard's wear model and the *pv*-factor model.

A separation of the hydrodynamic and asperity contact is needed for classification of the mixed lubrication conditions, as only the asperity contact part is responsible for wear. A simulation model of the tribometer was made, and numerical calculations using EHD were performed to investigate the mixed lubrication regime depending on test parameters.

ACKNOWLEDGMENTS

This work was funded by the Austrian COMET Program (Project K2 XTribology, no. 824187) and carried out at the "Excellence Centre of Tribology" and in cooperation with AVL List GmbH.

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T3-7 Fretting

EXPERIMENTAL STUDY OF THE FRETTING WEAR BEHAVIOR OF INCOLOY 800 ALLOY AT HIGH TEMPERATURE

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ABSTRACT

The fretting wear behavior of the nuclear power material Incoloy 800 was investigated in this study. A PLINT high-temperature fretting tester was used on an Incoloy 800 cylinder against a 304SS cylinder at vertical cross contact under different temperatures (25 °C, 300 °C, and 400 °C). During testing, a normal load of 80 N was applied, and the displacement amplitudes ranged from 2–40 µm. The fretting-wear mechanism at high temperatures and the kinetic character of the materials of the Incoloy 800 steam generator tube were analyzed. Results showed that the fretting running regimes varied little with the increasing temperature, and some microcracks were observed in both the mixed fretting regime (MFR) and the partial slip regime (PSR) at high temperatures. Slight abrasive wear and microcracks were the main wear mechanisms of the Incoloy 800 alloy in PSR, whereas those in the MFR and the gross slip regime were oxidative wear, abrasive wear, and delamination.

INTRODUCTION

Fretting is a wear phenomenon that occurs when two contact surfaces are subjected to slight oscillatory movements in amplitude. This phenomenon can accelerate the crack nucleation of the working components, thus resulting in premature catastrophic failures [1–2]. Fretting is a major cause of failures in the tight and clearance fit assembly of nuclear power systems. Numerous fretting damages [3] are incurred at various parts of such systems, such as in reactor fuel assembly, control rod assembly, the reactor component, the steam generator, the pressure vessel, the main pump, and the coolant pump. The steam generator is a significant piece of equipment in nuclear power systems, and the heat exchanger tube is a key component of this generator. Thus, fretting damage is among the main reasons [4–6] for its component failure. Incoloy 800 alloy is widely used in nuclear power and aerospace fields given its high thermal strength, good corrosion resistance, and antioxidation capability. It is currently one of three main materials used in nuclear steam generator tubes. The effects of working conditions, organizational structures [6], and other factors [7–16] on the friction and wear properties of Incoloy 800 and Inconel 690 alloys have been researched using micro-analysis equipment. However, relatively less work has been conducted on fretting damage and its mechanism under high-temperature conditions. In the current study, the fretting running behaviors and fretting-wear mechanisms of Incoloy 800 alloy are investigated in air at high temperatures. Therefore, this research can provide helpful information and guide actual applications of Incoloy 800 alloy.

ADD MAIN BODY HEADINGS HERE

1 Experimental details

Fig.1 Fretting wear test rig

2 Results and discussions

2.1 Characteristics of the fretting running regime

Fig.2 Fretting logs of Incoloy 800 alloy under a normal load of 80 N given different temperatures and displacement amplitudes

2.2 Friction coefficient

Fig.3 Evolution of the friction coefficient with the number of fretting cycles in different fretting running regimes

2.3 Wear volume

Fig.4 Maximum wear depth vs. temperature under a normal load of 80 N in three running regimes

2.4 Analyses of the morphologies of fretting scars

Fig.5 Surface morphologies and EDX analysis of the wear scars in PSR at room temperature

3 Conclusions

ACKNOWLEDGMENTS

The authors express their gratitude for the kind support provided by the National Natural Science Foundation of China (Contract number 51375407, 51305364), the 2014 Scientific and Technological Innovation Funds of the Central Universities.

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Investigation on fretting wear behavior of Inconel 690 tube in water

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ABSTRACT

In this paper, a study was conducted on Inconel 690 alloy tubes against 405 stainless steel plates in different water temperature environment, and the results were compared with dry condition. After the tests, the worn surfaces and cross-section morphologies were observed through scanning electron microscopy (SEM), energy dispersive X-ray (EDX) and electron probe microanalysis (EPMA). Moreover, a particular debris cleaning method was used to remove wear particles of worn Inconel 690 alloy effectively in order to estimate exact wear volume. In water environment, the friction coefficient and wear volume increased with the increasing temperature. The worn surfaces were smoother than that in air, where it were found delamination cracks. Due to water acted as lubricant, the wear particles were ejected resulting in "U" shape profile along the fretting direction in water, while "W" shape in air. Overall, the damage of specimens in water were slight than that in air.

INTRODUCTION

Fretting wear and impact wear occur at the mating surfaces of steam generator tubes and their supports (or anti-vibration bars) due to flow-induced vibration. Once the integrity of tube destroyed, it would cause the leakage of radioactive substances[1]. Hence, researchers have paid much more attention to fretting wear experimental and simulation work of steam generator tubes. Literatures indicated that displacement, load, temperature and environment were critical variables impacting on fretting resistance of tubes. Chung *et al* has shown that the formation of glaze oxide layer at high temperature or a liquid film in water acted as solid or liquid lubricant to reduce friction coefficient and wear volume [2-4]. Otherwise, the most of experiments were carried out under cross-contact, additionally the wear volume was not exact for wear particles covered on the worn surfaces.

This work was to explore the damage mechanisms of Inconel 690 alloy in different water temperature environment under tube/plate contact. A particular cleaning method was used to remove wear particles of worn Inconel 690 alloy effectively in order to estimate exact wear volume.

NOMENCLATURE

ADD MAIN BODY HEADINGS HERE

1. Experiment details
2. Results
3. Discussion
4. Conclusion

ACKNOWLEDGMENTS

This study was supported by National Science Foundation of China (51025519, 51375407), and Large-scale advanced PWR major projects (2010Zx06004-18).

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ROLE OF WS2, WS2+CRC AND BONDED COATINGS ON DAMAGE AND FRICTION OF INCONEL 718 FLAT ROUGH SURFACES AT HIGH TEMPERATURE

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ABSTRACT

Inconel 718 flat rough surfaces were tested under fretting solicitations at ambient and high temperature. Analyses were focused on friction coefficient, damage and fretting loops. Several coatings were tested, and showed significant differences of behavior above a temperature threshold.

INTRODUCTION

Fretting is a critical tribological phenomenon occurring in mechanical assemblies subjected to vibrations which can lead to wear or cracking dominated damage. The response of the assemblies subjected to complex normal and tangential loading depends on numerous parameters: materials, environment and notably temperature [1]. The industrial frame for this study is a self-locking endoscope stopper located near the engines, and thus exposed to severe thermo-mechanical solicitations. This stopper owes its self-locking function to interlocking teeth maintained by a spring. During the flight phases the contact is subjected to small tangential oscillations at high temperature (600°C). Different coatings and surface treatments were tested in order to limit the fretting damage, and thus preserve the functionality (manual unplugging of the endoscope stopper).

EXPERIMENTAL SETUP AND PROTOCOL

Materials and coatings

The bulk material used is a molded Inconel 718 alloy, resulting in highly rough nominally flat contacting surfaces of the teeth. The thermal constraints limit the coatings and surfaces treatments options. The uncoated contact behavior was compared to a bonded coating (already implemented in the industrial product) and to WS_2 solid lubricant deposited by ionic implantation on the raw substrate or on a CrC underlayer.

Test rig and conditions

The tests were carried out on a newly designed high temperature fretting tribometer [2]. Its specific instrumentation allows a free displacement piloting protocol based on the direct monitoring of the load delivered by an electromagnetic exciter. The tests combine low frequency (10Hz)/reciprocal sliding phases at ambient temperature (simulating the unplugging phase) and high temperature phases with fretting solicitations at 50Hz for overall 400 000 cycles duration. The nominal contact pressure ranges between 1 and 20 MPa.

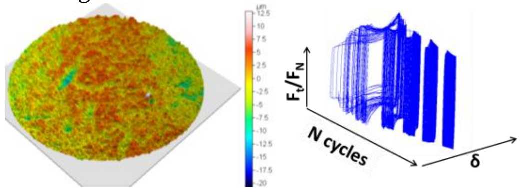

Fig.1: typical initial sample surface (left) and fretting logs (right)

RESULTS

Uncoated contact show signs of severe seizure during both fretting and unplugging phases. The bonded coating has the lowest friction at ambient temperature, but doesn't prevent sticking during the fretting phases. The WS_2 and WS_2+CrC solutions show a significant drop of the friction coefficient above a certain temperature threshold. The friction evolution also depends on the normal load.

Competition between debris generating wear and adhesion phenomena is responsible for the surfaces response. The high roughness, as well as waviness and shape defects results in widely variable local contact pressure. The damage is concentrated on localized areas.

ACKNOWLEDGMENTS

This study has been sustained by Pole Astech – Paris region (financed by FUI9) in close collaboration with companies JPB Système and ACM.

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Cyclic crystal plasticity modelling of fatigue with application to fretting

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INTRODUCTION

Fretting-induced relative slip is typically in the range 5 to 100 µm, for macroscale applications such as splined couplings taper-lock joints and bolted connections. This length-scale is directly comparable to key microstructural dimensions (e.g grain size) of commonly-used metallic alloys. Relative slip is well known to play a key role in determining fretting fatigue life [1]. Fretting crack nucleation is typically also at the same length-scales. Previous work has shown that grain orientation can have a significant effect on predicted fretting fatigue life [2]. It is therefore necessary to assess the effect of key microstructure characteristics to accurately and reliably predict crack initiation in fretting and hence design materials and surfaces against fretting. Applications where fretting crack nucleation, leading to fatigue failure or wear, depending on the competitive interaction between short crack nucleation and growth and material ablation effects due to wear, is critical, include artificial hip joints, gas turbine couplings and flexible marine risers (Figure 1). This work investigates a microstructure-sensitive crystal plasticity modelling approach for fretting, applicable to the latter applications.

METHODOLOGY

A finite element crystal plasticity frictional contact modelling methodology is developed to simulate the role of statistical size effects on crack initiation in fretting. Statistical size effects arise in fretting due to micro-scale contact widths and relative slips, where fatigue crack initiation is governed by the orientation or plastic behaviour of a small number of grains.

Monotonic and cyclic plasticity tests on a biomedical-grade cobalt-chromium alloy are employed to facilitate calibration of crystal plasticity model which incorporates both monotonic and cyclic hardening behaviour, including isotropic and kinematic hardening. Representative volume element models of the material microstructure are generated, based on measured distributions of grain size and orientation, to identify the constitutive parameters through calibration with experimental results. Fretting models are developed to incorporate microstructure geometries and crystal plasticity material models at the contact zones. Realistic microstructure morphologies implemented in the finite element model via automated Voronoi tessellation applied to voxel meshes.

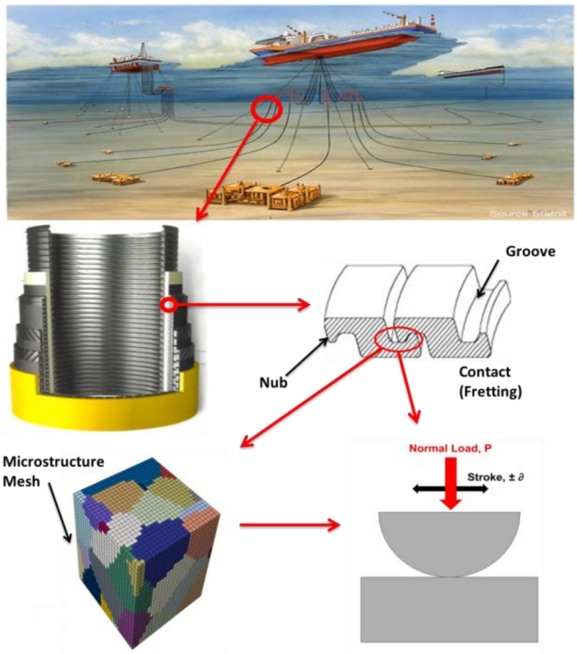

Figure 1: Fretting modelling of flexible marine risers

Some key non-dimensional parameters analysed include contact width to grain size and relative slip to grain size ratios. A key challenge in this work is the establishment of a scale-consistent failure parameter for crack initiation, N_i, under fretting conditions, leading to either fatigue cracking or wear, dependent on sliding regime. One parameter investigated here is cyclic crystallographic slip [3].

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MODELLING OF FRETTING IN THE PRESSURE ARMOUR LAYER OF FLEXIBLE MARINE RISERS

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INTRODUCTION

Fretting is a surface damage mechanism that occurs in the contact region between two materials under combined normal load and micro-scale cyclic relative tangential motion. These conditions are present, for example, in the nub and groove valley regions (see Figure 2) of the pressure armour wires in flexible marine risers under in-service loading. Flexible risers are a key component in the delivery of offshore hydrocarbons from the seabed to sea level, typically to a floating structure, such as a platform or vessel and are comprised of a large number of layers (see Figure 1) with different functions. The primary function of the helically wound interlocked metallic pressure armour layer is to contain the internal pressure due to conducted hydrocarbons, primarily by hoop stress resistance. However, the riser itself will also be subjected to significant large bending and torsional deformations, as well as axial tensile forces, due to the combined effects of vessel motion, buoyancy and hydrodynamic loading, for example. Fretting wear and fretting fatigue can cause local cracking and damage of the pressure armour layer, thus reducing the service life of the riser.

This paper will present a computational methodology for frictional contact mechanics of the pressure armour layer in flexible risers. This will allow, for the first time, quantification of key fretting variables, such as contact pressure, slip and sub-surface stresses [1], in this complex geometry, under representative loading conditions. It is also intended that this will facilitate representative fretting wear and fretting fatigue testing of pressure armour layer material.

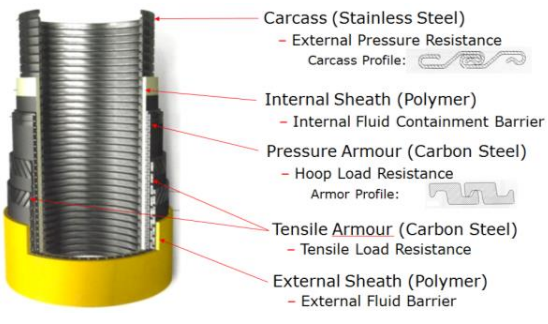

Figure 1. Cross-section of a flexible marine riser.

METHODOLOGY

A simplified, axisymmetric model of a riser cross-section has been developed (see Figure 2), incorporating, in particular, frictional contact of the nub and groove regions of the pressure armour layer, based on the simplifying assumption of a negligibly small helix angle (typically less than 5°). The finite element frictional contact methodology is validated against an analytical solution for Hertzian contact, based on the theory of elasticity, for gross and partial slip. The riser cross-section model has been subsequently applied to investigate the effects of combined internal pressure and cyclic relative (axial) displacement on the primary macroscopic fretting variables of contact tractions and relative slip, as well sub-surface multiaxial stresses. The effects of evolving coefficient of friction, e.g. due to fretting, and plasticity are also investigated.

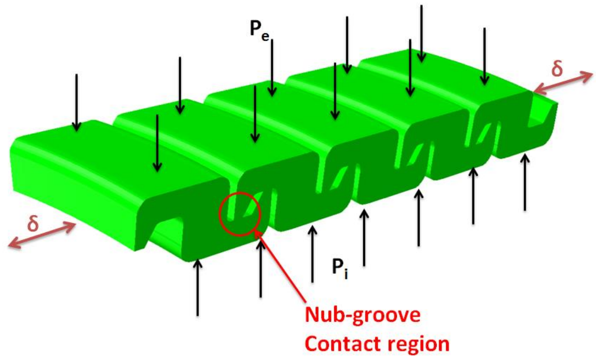

Figure 2: Schematic of the loading conditions on the pressure armour layer.

In order to quantify the effects of the simulated frictional contact (fretting) on fatigue life, based on the riser contact model, a critical-plane, multiaxial fatigue methodology is implemented, incorporating the effects of high (elastic) and low (plastic) cycle fatigue and mean stress.

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T5-5 Adhesion and Cracks

ADHESIVE DEVELOPMENT AND CRACK PROPAGATION IN BARNACLE INTERFACES

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ABSTRACT

Acorn barnacles like *Balanus amphitrite* develop protective shells around their soft tissues consisting of a base plate, multiple interlocked side (parietal) plates and movable plates covering the top opening (operculum). Adult acorn barnacles adhere to surfaces by secreting proteins which "cure" underwater to form a thin adhesive plaque or cement between their calcareous baseplate and whatever substrate they are living on. Prior work has shown that the nature of the barnacle base plate and adhesive may impact release characteristics [1,2]. Furthermore, the adhesion process occurs in cyclic stages as the barnacle expands its periphery [3] and is compositionally non-uniform in a regular, concentric pattern in the interface. How the overall shape and shell microstructure and topography, as well as the variation in adhesive chemistry and composition, contribute to adhesion and release processes is part of ongoing research in this field.

In this work, we report on a series of experiments designed to investigate the nature of the barnacle-substrate interface by (1) monitoring the development of the interfacial films between the barnacle and substrate using surface plasmon resonance imaging (SPRi) and (2) measuring where cracks initiate, and how they propagate, with high speed videography. For the SPRi measurements, we monitor growth and development of barnacle interfaces on glass slides coated with a thin film of gold. Over a period of days to weeks, intensity changes in the SPR signals observed reveal secretory activity and variation in refractive index across the interface. For the latter experiments, we have settled and grown adult barnacles on plastic bars and tested them in four-point bending in order to propagate a crack in between the base plate and the substrate. We have used high speed videography to capture the crack nucleation and propagation events, and use image analysis to determine debonding area versus time, in order to calculate the strain energy release rate. Ceramic rods and hollow forms have been tested as controls. We will discuss how these approaches allow insights into the adhesive processes of barnacles, and how the adhesive and shell structure contributes to resisting debonding from substrates.

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ADHESIVE CONTACT OF ROUGH SURFACES

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ABSTRACT

Macroscopic objects rarely stick together, yet the van der Waals interactions between surface atoms produce attractive pressures that are orders of magnitude larger than atmospheric pressure. This "adhesion paradox" has been linked to surface roughness, which reduces the area of intimate atomic contact to summits on the rough landscape. Using large-scale contact calculations we show that for nominally flat surfaces there is a crossover to from zero to finite pull-off force where surfaces become sticky. We present a parameter-free theory that captures the interplay between elasticity, interatomic attraction, and surface roughness. The theory also describes the contact of rough spheres at intermediate loads. At lowest and highest loads, spheres show Hertzian behavior that is due to contact of the first asperity and the macroscopic spherical geometry, respectively.

BRIEF RESULTS & DISCUSSION

Van-der Waals interactions operate between all surfaces and are strong enough to hold 1000kg per square centimeter. Yet, few surfaces are adhesive. This discrepancy between atomic and macroscopic forces is due to roughness and has been dubbed the adhesion paradox.

To quantify this behavior, we carried out molecular statics and continuum simulations of the contact area, stiffness and adhesion between rigid, randomly rough surfaces and elastic substrates [1]. The surfaces are self-affine with Hurst exponent 0.3 to 0.8 and different short and long wavelength cutoffs. The rms surface slope and the range and strength of the adhesive potential are also varied. For parameters typical of most solids, the effect of adhesion decreases as the ratio of long to short wavelength cutoff increases. In particular, the pull-off force decreases to zero and the area of contact A becomes linear in the applied load L. A simple scaling argument is developed that describes the increase in the ratio A/L with increasing adhesion and a corresponding increase in the contact stiffness [2]. The argument predicts a crossover to finite contact area at zero load when surfaces are exceptionally smooth or the ratio of surface tension to bulk modulus is unusually large, as for elastomers.

We also studied the contact of rough surfaces with a nominally spherical geometry. For large spheres, our results show an A proportional to L regime identical to the one obtained for nominally flat surfaces at intermediate loads. The lowest loads are determined by the contact of the first asperity that can be described by Hertz's expression in the nonadhesive case and a JKR/DMT [3,4] model in the adhesive case. At the highest loads, surfaces are pushed into conformity, the contact area becomes compact and A versus L follows Hertz's expression. We provide a simple expression that fits our numerical data throughout the three scaling regimes over more than ten orders of magnitude in applied load.

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ADHESION OF AN AXISYMMETRIC ASPERITY

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ABSTRACT

The contact and adhesion of asperities as well as of micro- and nano-scale bodies is of significant importance in the function of many small-scale systems. Traditional models of elastic contact and adhesion approximate the asperity as a paraboloid of revolution. Recent efforts have used higher-order monomial shapes to approximate an originally parabolic shape which has been partially flattened by wear. In this work the transition from the 2^{nd}-order to higher-order models is investigated. It is found that the appropriate model depends not only on the shape of the asperity but also on a dimensionless parameter involving the work of adhesion, the composite modulus, and the radius of curvature of the asperity.

INTRODUCTION

The adhesion of a spherical asperity (approximated by a paraboloid of revolution) can be modelled with the JKR [1], DMT [2], or Maugis [3] theories. It has been shown that the JKR model is valid for large values of the Tabor parameter ($\mu > 3$), whereas the DMT model is applicable for small values of this parameter ($\mu < 0.1$). Furthermore the Maugis model spans the range for small, intermediate, and large values of μ.

Recently there has been interest in the contact and adhesion of higher order monomial shapes using either the JKR style model of Carpick *et al.* [4] or the Maugis type of model of Zheng and Yu [5]. Such shapes are relevant to, for example, an AFM tip which has been partially flattened due to wear.

An axisymmetric shape of an asperity obtained from experimental data can be fit to either a 2^{nd}-order or to a higher-order monomial shape. However a best-fit to the geometry may require a two-term approximation with the aforementioned shapes representing limiting cases. Two questions then arise which will be addressed in this work. Is the appropriate adhesion theory for the 2^{nd}-order or higher-order shape related to the best-fit of the geometry? In particular does the choice of theory depend upon a material parameter as well as on the geometry? A two-term approximation of the shape is used in order to explore these limits. In a wide range two terms are needed to properly model the adhesion and pull-off force.

DESCRIPTION

Consider an axisymmetric asperity shape given by

$$w(r) = \frac{r^2}{2R}\left(1 + \alpha\left(\frac{r}{R}\right)^2\right) \tag{1}$$

where R is the radius of curvature, r is the radial coordinate, and α is a dimensionless parameter which describes the deviation from a 2^{nd}-order shape. It is noted that because $r<<R$ the 4^{th}-order term will be equal to the 2^{nd}-order term at $r = 0.1R$ if $\alpha = 100$.

From a physical point-of-view it is desirable to think in terms of a prescribed applied force and to then determine the corresponding penetration (δ) and the contact radius (a). However it is more convenient mathematically to specify the contact radius "a" and to calculate the contact force by properly combining the results given by Steuermann which are summarized by Johnson [6].

CONCLUSIONS

The results show that the deviation from the JKR theory depends not only on the geometric parameter α but also on the ratio of the work of adhesion w to the product of R and the composite modulus E^*. In particular for $w/E^*R = 10^{-4}$, and $\alpha = 100$, the pull-off force is reduced by about 30%. Larger values of w/E^*R correspond to greater deviations from the JKR theory.

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HYSTERISIS BEHAVIOUR IN CONTACT OF ROUGH METALLIC SURFACES

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ABSTRACT
This paper describes exploratory study to understand energy dissipation in the contact of rough metallic surfaces. Ball-on-cylinder contact tests were conducted with AISI 440C in air, inert gas and in vacuum. The hysterisis behaviour was found in the contact tests. In addition, a simple analysis of asperity contact was made in order to understand the energy dissipation.

INTRODUCTION
A friction damper is used in cryogenic rotating machine [1], and it is assumed that a main factor of damping is friction. However, the energy dissipation should happen in elastic contact without the friction, for example, plastic deformation of asperites. A contact theory of rough surfaces was developed by Greenwood and Williamson[2], and Chang[3] studied the effect of the surface energy on the rough surface contact with the improved DMT model.

When the roughness of the surfaces in contact is not negligible, fresh surface is formed by plastic deformation, and the surface energy becomes higher. In such a case, the actual displacement-load curve should be different from those predicted by the Chang model. The purpose of this study is to understand the effect of the change in the surface energy.

CONTACT TEST
A simple indentation test with a ball and a cylinder made of AISI 440C stainless steel was conducted. Table 1 shows a test conditions. In this test, the cylinder was clamped with jig, and the ball was displaced by an actuator. Load and displacement were measured with a load cell and eddy current displacement sensor. The contact tests were conducted with several different roughness of the cylinder. In the each test, the load was applied 4 times, and the ball contacted on same point of the cylinder. Figure1 shows one of the test results. It can be seen that loading and unloading curves are different suggesting that there is hysteresis. There is a small displacement at 0N caused by plastic deformation in the 100 N test, this implies that the hysteresis is not caused by the plastic deformation in the 100 N test. It may be possible that the adhesion force induced by the plastic deformation of surface asperities worked during the contact.

Table 1 Test conditions

Ball	Material	AISI440C
	Roughness	0.013-0.050μmRa
Cylinder	Material	AISI440C
	Roughness	(1) 0.01μmRa (2) 0.38μmRa (3) 0.44μmRa (4) 0.52μmRa
Applied load		50N, 100N, 150N, 200N
Cycle time		15s (200N)
Environment gas		Air
Temperature		10-22 °C

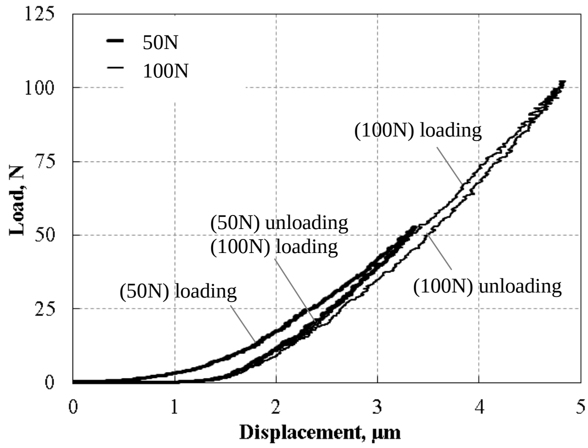

Fig.1 Test result with the cylinder (4)

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Proceedingsofthe 42^th Leeds-Lyon Symposium on Tribology
September 7-9, 2015,Lyon, France

MICROSCALEANALYSIS OF ADHESIVE CONTACT BETWEEN ROUGH DUCTILE METALS

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ABSTRACT

Many engineering applications share the interest in the basic phenomena ruling the mechanics of contact between metallic surfaces. In the frame of the technological research for a space mission, this topic found an interesting development, in which the contact between engineering gold-coated surfaces is studied as it could affect the performance and functionality of a space mechanism [1].

In the LISA Pathfinder spacecraft a gold-coated proof mass must be caged and released to free-fall by a mechanism with a minimal residual velocity [2].Due to the high vacuum conditions, low contamination, high surface energy and ductility of gold [3], the proof mass – caging mechanism contacting surfaces develop adhesive bonds which may become critical at the separation phase.

The behaviour of the mating surfaces is determined by the mechanics of contact between the roughness summits at the micro-scale, where the actual contact takes place [4][5]. The surfaces involved in the in-flight operation are tested on ground [2] and are here analysed by means of a laser profilometer in order to characterize their morphology both before and after the contact.

These measurements make it possible to develop a multi-asperity model of the mechanics of the adhesive contact, which allows us to predict adhesion forces, contact areas and curvatures at the micro-scale. The comparison between the surfaces before and after the contact makes it possible to show that plastic deformation occurs at the micro-scale, even if not predicted at the macroscopic level. The results of this research activity are here presented and discussed, highlighting their relevance on the development of the space mission.

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T2-4 Boundary regime in ICE

Analytical Study of Tribofilm Formation and Removal Generated by Zinc Dialkyl Dithiophosphate

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ABSTRACT

A modelling framework was recently developed [1] for boundary lubrication that includes an analytical model for the growth of the tribofilm on contacting asperities. The model implements tribofilm formation and removal into deterministic contact mechanics simulation for rough surfaces. Most of the models developed in this concept, were only dealing with formation of the tribofilm. But distinguishing between formation and removal can be good in two ways. Firstly, the removal of the tribofilm can help to better understand the wear mechanisms in boundary lubricated contacts in steady-state. Secondly, the formation of the tribofilm can give information about the energy needs for induction of tribochemical reactions. A set of experiments were designed to support the model and a comprehensive analytical study of tribofilm formation and removal was carried out.

METHODOLOGY

A tribochemical growth model for the tribofilm was developed based on the thermodynamics of interfaces. This tribochemical model was then implemented into a deterministic contact mechanics simulation of rough surfaces taking into account the elastic and plastic deformations. The effect of different contact parameters was responsible for the inhomogeneous growth of the tribofilm on contacting asperities due to surface roughness.

RESULTS

The outputs of the model are prediction of inhomogeneous tribofilm formed on the asperities and local wear in respect to the tribofilm growth. The removal of the tribofilm shows a significant effect on the wear behavior of the system. It has been shown that load and temperature show a significant effect on the removal process and chemical and mechanical characteristics of the tribofilm.

ACKNOWLEDGMENTS

This study was funded by the FP7 program through the Marie Curie Initial Training Network (MC-ITN) entitled “ENTICE - Engineering Tribochemistry and Interfaces with a Focus on the Internal Combustion Engine” [290077] and was carried out at University of Leeds and SKF Engineering and Research centre. The authors would like to thank to all ENTICE partners whom had kind discussions on the topic and the methodology.

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Proceedings of the 42nd Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France
leeds-lyon - Room 3 - Tuesday, September 8, 2015 - 16:40/17:00 (20min)

INFLUENCE OF COEXISTING FUNCTIONALIZED POLYALKYLMETHACRYLATES ON THE FORMATION OF ZNDTP-DERIVED TRIBOFILM

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ABSTRACT

The effect of polar compounds on the tribofilm formation of ZnDTP was studied. Several kinds of functionalized PMAs were used with ZnDTP, and their effect on the tribofilm formation of ZnDTP was discussed.

INTRODUCTION

Zinc dialkyldithiophosphate (ZnDTP) has been well-known to show supreme antiwear performances by forming thick polyphosphate-based tribofilm on the friction surface. However, it has been also pointed out that the performance of ZnDTP suffered interference from coexisting dispersant [1,2]. In order to keep the good antiwear performance of ZnDTP when it is used together with coexisting polar compounds, the effect of the polar compounds on the tribofilm formation of ZnDTP should be clarified. In addition to this, recent demand for minimizing energy consumption requires the use of lower viscosity oils to reduce a viscous drag. In this case, a good temperature-viscosity characteristic of the oil is highly required and formulation of viscosity index improvers (VIIs) has a key for developing the energy-saving lubricating oils. In this study, several kinds of functionalized PMAs were used with ZnDTP, and their effect on the tribofilm formation of ZnDTP was discussed.

EXPERIMENTAL

Tribometer

A ball-on-disk type rolling-sliding tribometer was used. The applied load, entrainment speed, slide-roll ratio, and oil temperature were 63.4 N (P_{mean} = 667 MPa), 80 mm/s, 100% and 100 °C, respectively.

Sample Oils

PAO (3.88 mm^2/s @100 °C) formulated with prim-C8 ZnDTP was used as sample oil. Three kinds of functionalized polyalkylmethacrylates having amino group (PMA-N), hydroxyl group (PMA-OH) and carboxyl group (PMA-COOH), and non-functionalized polyalkylmethacrylate (PMA 0) were used. Polyamino polyisobutenylsuccinimides (dispersant) was also used as a reference.

Surface Analyses

A confocal laser microscope, SEM, micro-FT-IRRAS, EPMA, and AES were used for the observation of morphology and chemical characterization of the tribofilm.

RESULTS AND DISCUSSION

Typical example of the analyzed data that shows the difference in the formation of the ZnDTP-tribofilm is shown in Fig.1. Dispersant and PMA-N significantly reduced the formation of ZnDTP-tribofilm, whereas the other PMA did not show significant interference.

Depth profile of the tribofilm was obtained by AES. Thickness and chemical composition of the tribofilm were similar when thick tribofilm was analyzed in every case.

Details of the analytical results are explained in the presentation.

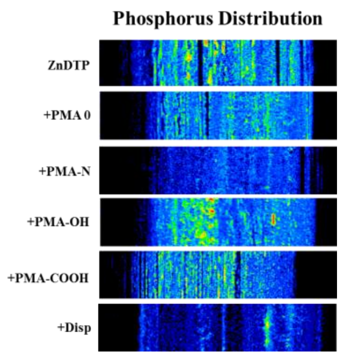

Fig. 1 Phosphorus distribution images by EPMA

ACKNOWLEDGMENTS

A part of this study was financially supported by Council for Science, Technology and Innovation(CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), “Innovative Combustion Technology” (Funding agency: JST) and JX Nippon Oil & Energy Corporation. The authors appreciate Sanyo Chemical Industries Ltd. for providing VIIs.

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DYNAMOMETER TESTING: THE EFFECTS OF FUEL TYPE ON ENGINE OIL CONTAMINATION, ITS PROPERTIES AND TRIBOLOGICAL RESPONSE

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ABSTRACT

The use of ethanol as engine fuel has increased due to environmental requirements, both in flex fuel engines and as increasing amounts of ethanol blended with gasoline in conventional engines. However, the effect of fuel type on oil properties and tribological response due to oil contamination in combustion engines has not been established yet.

This paper presents an investigation *in-situ* into the effects of fuel type on oil contamination during dynamometer tests in terms of oil physico-chemical properties and its effects on lube film formation, tribofilm formation and friction coefficient.

IR-spectra analysis shows that all tested oils oxidized during the test and it shows some anti-oxidant additive depletion. But the ones tested in dynamometers running with ethanol as fuel show lower levels of oxidation than the ones running with gasoline. This is in agreement with the total acid number (TAN) measurements, i.e., the lubricants that performed into an ethanol fueled engine are less acid than the ones performed with gasoline as a fuel. The atomic emission spectroscopy (AES) analysis of the lubricants showed significant differences on the amounts of wear particles and on the composition of the oils tested with ethanol and gasoline. The metal analysis (Energy of dispersive X-ray) also shows that the amount of Zn, P and Mo, which are likely related to the additive package, are nearly the same for the fresh and used samples, with negligible difference among the oils tested with ethanol or gasoline.

During the tribotests at high pressure (1.35 GPa), the fresh oil friction response clearly showed the occurrence of additive activation (MoS2) while the used oils did not, as shown in Figure 1. This causes a difference in friction response of more than 100%, which would significantly increase the engine fuel consumption. At low contact pressure (0.5 GPa) fresh oils presented a boundary film of *ca* 8 nm while the used ones did not. This film generated a slightly lower friction coefficient and it is likely a $CaCO_3$ film from an overbased detergent [1].

ACKNOWLEDGMENTS

The authors acknowledge the financial support of the program “Ciência sem Fronteiras" of CAPES / CNPQ through the project: A014_2013 and the FAPESP via the R&D Consortium “TriboFlex” – PIT Project 2009/54891-8.

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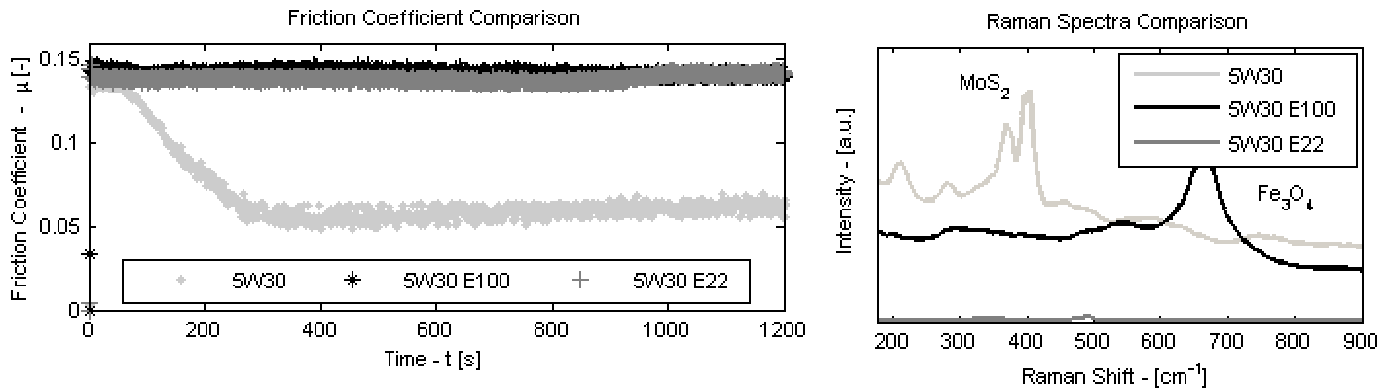

Figure 1 - Friction coefficient and Raman Spectra of the track marks of fresh and used oils. Friction reduction of the 5W30 due to MoS2 activation.

INFLUENCE OF ARTIFICIALLY AGED ENGINE OIL ON THE REAL TIME WEAR AND THE TRIBOFILM FORMING IN THE PISTON RING – CYLINDER LINER CONTACT

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INTRODUCTION

Boundary lubrication is of special importance for industry, as most of the damaging wear occurs in this regime, thus affecting the service life of the components and showing the effectiveness of specially designed anti-wear additives in lubricants [1]. Boundary lubrication can occur in a number of engineering systems, many of which are found in automotive applications such as: cam and tappets, piston rings and cylinder liners, transmissions, gears, etc. It is no surprise that the drive for research for lubricated contacts is strongly related to automotive industry – as the oil industry and car manufacturers struggle with strict environmental regulations concerning improved fuel economy, longer oil drain intervals and lower emissions. Although positive for the environment, introduction of these regulations often has a negative impact on the engine performance, increasing friction and wear. In this work, focus was put on the investigation of the effect oil degradation has on the piston ring and cylinder liner contact during short-term tribological tests, by monitoring the wear of cylinder liner parts in real time and by applying several characterisation techniques to shed light on the anti wear properties of tribofilms forming by sliding in the aged oil.

METHODS

Tribological tests were carried out in a reciprocating sliding tribometer, with custom-built piston ring and cylinder liner sample holders. Wear of the cylinder liner samples was measured continuously during the tests, by means of the Radio-Isotope Concentration (RIC) method [2]. The technique uses radioactive tracers for measuring wear rates in nanometre range during short term tests. Tribometer test parameters were chosen to correspond to the top dead centre (TDC) conditions in the internal combustion engine. Wear and friction performance of the fresh and artificially aged fully formulated engine oil was tested at room and elevated temperature. Materials tested were: nitrided X90CrMoV18 steel (piston rings), and gray cast iron with lamellar graphite (cylinder liners). After the tribometer tests, several characterisation techniques were applied in order to gain understanding of the relationship between the observed wear behaviour and the tribofilm covered surfaces. Morphology of the tribofilms was studied by Atomic Force Microscopy (AFM) and the chemical composition was determined by X-ray Photoelectron Spectroscopy (XPS).

RESULTS

Wear measurement results showed a significant change in wear behaviour of cylinder liners when lubricated with artificially aged oil compared to fresh engine oil. Constant wear rates decreased notably for the liners lubricated with the artificially aged oil.

CONCLUSIONS

The observed wear behaviour is attributed to the differences in the tribofilms formed by fresh and artificially aged oils. However, possible long-term effects of sliding in the aged oil (e.g. for the entire oil drain interval) cannot be evaluated during these short term tribometer tests.

ACKNOWLEDGMENTS

This work was funded by the FP7 program through the Marie Curie Initial Training Network (MC-ITN) entitled “ENTICE – Engineering Tribochemistry and Interfaces with a focus on Internal Combustion Engine” [290077] and was carried out at AC2T research GmbH and University of Ljubljana.

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Proceedings of the 42th Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France

ENGINE BEARING FRICTION WITH HIGH SOOT CONTENT IN ENGINE OILS

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ABSTRACT

One of the demands for automotive diesel engines is longer oil service intervals where it is expected to haven increased soot content in the engine oil beyond the current maximum of ~4%. In some cases, is expected to see soot content as high as 10%, which leads to an increase in wear and change in friction characteristics in the crankcase bearing system. In this study, the effect of soot on friction for three bearing friction materials was investigated using a ball on plate tribometer.

A challenging aspect characterising the effects of soot is the nature of its particles and their strong tendency to agglomerate. Assuming that the larger particles (approximately mm-scale) are caught by the oil filter, the remaining particles in the oil were found to be in the nanometer and micrometer range as measured by Dynamic Light Scattering (DLS) technique. Tribometer friction measurements obtained from used oils out of real engines as well as from oils with artificial soot substitute added will be reported. For reproducible validation trials during the development of new bearing materials, it is much more desirable to obtain a controlled artificial soot substitute.

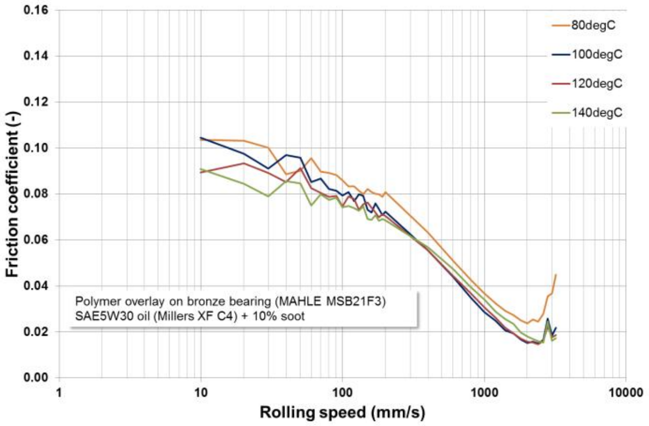

Figure 1 Friction measurement (ball on plate tribometer).

Figure 1 and 2 show an example of the friction and DLS measurements that were used in an effort to validate an artificial soot substitute, which then is used in for formulating test engine oil samples for rig and engine testing with a well-defined and known soot percentage.

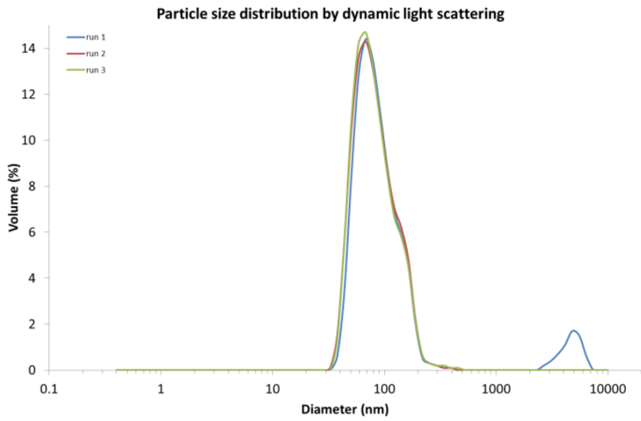

Figure 2 DLS particle size distribution measurement example (heptane dilution).

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T4-3 Teeth and Lipidic

EROSION BEHAVIOR OF HUMAN TOOTH ENAMEL IN THE CITRIC ACID SOLUTION MODIFIED WITH POLYSACCHARIDE FOOD GUMS

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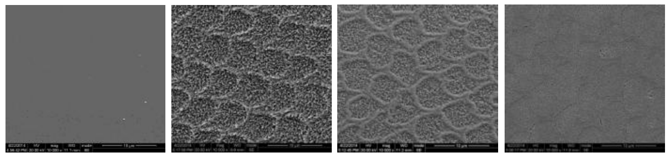
ABSTRACT

With dietary changes in modern society, there has been a worldwide increase in the consumption of soft drinks, fruit juices, and sport drinks [1]. Thus, exposure of teeth to an acid environment is becoming commonplace, and erosion has gradually become a main cause for toothwear. Knowledge of dental erosion and prevention could provide valuable insights into the study of toothwear, the development of improved dental materials, and oral treatments.

Citric acid is a common ingredient in beverages, however, its potential to erode dental hard tissue is an increasingly growing health concern for dental personnel [2]. In this paper, therefore, the erosion behavior of human tooth enamel in the citric acid solutions modified with two kinds of polysaccharide food gums, Xanthan gum and Acacia gum, respectively, were studied in vitro. The surface morphologies of enamel specimens were examined by means of various microscopic examinations. The nanomechanical properties and microtribological behaviors of enamel surfaces were investigated using nanoindentation and nanoscratch techniques. Particular attention was paid to the preventive effect of polysaccharide food gums on the erosive damage of enamel surface.

Results showed that to add a trace amount of Xanthan gum in citric acid solution was helpful to decrease the influence of acid-erosion on the surface morphology, mechanical properties and tribological behavior of enamel. Almost no obvious honeycomb-like structures appeared on the surface of enamel after 10 min erosion in the citric acid solution (pH=3.2) modified with 0.03% Xanthan gum (Fig.1). Compared with the the enamel surface after 10 min erosion in citric acid solution, surface hardness and Young's modulus of enamel were higher after 10 min erosion in the citric acid solution modified with Xanthan gum (Tab.1). Moreover, its friction coefficient and wear loss were much lower (Fig.2). However, Arabic gum seemed to be significantly inferior to Xanthan gum in the contribution to the prevention of dental erosion. The obvious difference may be attributed to their different chemical structrues to some degree. These results indicated that Xanthan gum could decrease the erosive potential of citric acid solution and then reduce the erosive tooth wear.



(a) (b) (c) (d)

Fig.1 SEM micrographs of enamel surfaces, (a) original surface, (b) eroded surface in citric acid solution, (c) eroded surface in citric acid solution modified with Acacia gum, (d) eroded surface in citric acid solution modified with Xanthan gum

Table 1 Nanoindentation hardness and Young's modulus of enamel surfaces

Group	O	E	A	X
Hardness/GPa	5.27±0.17	1.23±0.18	1.33±0.17	2.09±0.13
Elastic modulus/GPa	111.1±2.13	77.1±2.80	78.4±2.39	87.2±2.65

**O-original surface; E-eroded surface in citric acid solution; A-eroded surface in citric acid solution modified with Acacia gum; X-eroded surface in citric acid solution modified with Xanthan gum*

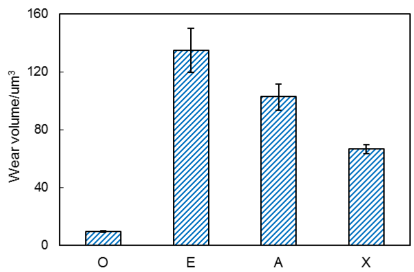


Fig.2 Wear volume of scratches on enamel surfaces at 10 mN, O-original surface, E-eroded surface in citric acid solution, A-eroded surface in citric acid solution modified with Acacia gum, X-eroded surface in citric acid solution modified with Xanthan gum

KEYWORDS: Human tooth enamel; Erosion; Xanthan gum; Arabic gum; Nanomechanical and microtribological properties

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LIPIDIC MEMBRANES FOR AQUEOUS LUBRICATION ? MOLECULAR DYNAMICS STUDIES

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ABSTRACT

Boundary lubrication is a regime where two rubbing surfaces come in close contact, and the friction reduction is ensured by the molecular films coating the surfaces. This process, widespread in engineering applications, is also expected to play a role in cartilage lubrication in synovial joints (hips, knees, etc...). Phospholipid membranes have been detected on cartilage surfaces and in synovial fluids. Experimental studies using surface force apparatus or tribometers have indeed shown that phospholipid coatings can reduce friction very efficiently. But the lubrication mechanism at the molecular level remains debated because of the difficulty to characterize the contact points between the rubbing surfaces at small lengthscales.

In this context, we have performed molecular dynamics simulations of a contact point between two rubbing surfaces coated by hydrated phospholipidic films, and studied the mechanism by which a shear is released. We investigated the viscous drag and characterize it as a function of shear stress. The important result is that the friction mechanism depends on the hydration level and structure of the lipidic bilayers. In particular, when dehydrating a liquid crystalline phase, we observe a transition from a viscous friction within the water layers towards a "dry" friction within the lipidic membranes. We characterize the two mechanisms separately, and show that both mechanisms can coexist. We have used both all-atoms and coarse-grained models, and studied the impact of the lipidic bilayer phase (gel or liquid) on the shear stress **[1]**. In addition, we propose a simple method to estimate friction coefficients starting from our simulations, which permits to explain why the large local viscosities are not in contradiction with low friction coefficients.

These results have implications for future technological or biomedical applications limited by friction and wear: e.g. in the design of boundary lubricants that will optimize interfacial hydration.

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INTERFACIAL FRICTION CONTROL WITH RESPONSIVE SOFT MATTER

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ABSTRACT

Interfacial friction of soft matter most exists in the organism and usually has an ultra-low friction coefficient. However, in nature, the friction is seldom actively regulated. By sliding against responsive soft materials to external stimuli, the molecular conformation and hydration/dehydration state on surface can be altered, providing a feasible way to regulate interfacial friction.

As an example, we have prepared a series thermal-sensitive hydrogels and realized the reversible friction regulation by changing temperature. When incorporating another pH-sensitive monomer into thermal-sensitive hydrogel, a hydrogel with two stimuli responsiveness (temperature & pH) was obtained. This gel displays three stage regulated friction coefficient when changing temperature and pH, from ~0.05, to ~0.1 and then to ~1.0.

Similarly, thermal-responsive microgels can be prepared and used as the additive in water based lubricants. Synergistic effect was found when a thermal responsive microgel was used together with benzotriazole, a metal deactivator. When the hydrophilic polymer brush was grafted onto microgels, it shows both low friction and drug controlled release performance. The materials are of interest as the injectable lubricants for joint lubrication.

Inspired by the structure of articular cartilage, we have used grafted ionic polymer brushes on solid surface for simulation. The friction coefficient of surface can be regulated from ultra-low (~10^{-3}) to ultra-high (>1) level by ion-pairing interaction and so the swelling-collapse of polymer chains. The polymers can be even modified onto inert diamond like carbon film (DLC) to lower its friction performance in aqueous environment, which otherwise would be very high for bare DLC. Integration of polymer brushes with hollow silica spheres can also result a composite material that improve the lubrication characteristic and controlled drug-release property. The ability to tune friction with responsive polymer brushes can be transited to make Gecko foot with chemically switched friction/adhesion. To simulate Gecko foot’s nanostrutures, silicon nanowires were prepared, and grafted with polymer brushes. We realized the controllable friction and adhesion by altering humidity and pH.

Based on research along the front line of friction control, we were invited to contribute a review article on “Interfacial Friction Control”. In this article, we have summarized the state-of-the-art research on controlled friction and envisioned future research direction in the area.

ACKNOWLEDGMENTS

NSFC(20434009, 21125316).

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SATELLITE DROPLET GENERATION BY BREAKUP PROCESS OF STRETCHING LIQUID BRIDGE

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ABSTRACT

In the process of breakup of a stretching liquid bridge, sometimes a smaller liquid droplet is generated. This phenomenon is a potential source of oil misting in internal combustion engine. When the liquid bridge between surfaces is stretched, its waist becomes narrower with increasing the distance between surfaces. Above a certain length of the liquid bridge, its waist spontaneously breaks up. In this process, very small droplet is left between broken bridges. It is called daughter droplet or satellite droplet.

We carried out liquid bridge stretching between rods. The satellite droplet becomes smaller with decrease of the volume of liquid bridge, and with decrease of the stretching speed. The smallest satellite droplet of water is 3pl in volume (20μm in diameter). We also carried out experiments with some reagents. Effects of property of mother liquid bridge on the volume of the satellite droplet are investigated.

INTRODUCTION

To know the oil flow in an engine is important for lubrication, oil consumption and oil degradation. Especially, oil misting process has a key role in micrometer scale. Wide range in size of oil mist can be observed in misting simulator. It is from sub-micrometer to millimeter in the diameter [1].

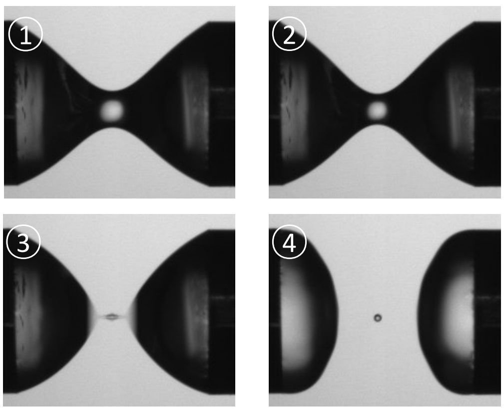

Fig.1 Breakup proces of 3μl distilled water bridge between rods. 480pl satellite droplet is generated. Snapshots are captured with 600flame/s

Satellite droplet generation by breakup process of stretching liquid is main factor for micrometer scale mist. And in future, satellite droplet generation can be used as pico-liter dispensing pipette [2].

EXPERIMENT

A water liquid bridge between rods is stretched. Figure 1 shows the snapshots of breakup process. Small droplet is generated between broken bridges. As shown in Fig.2, the volume of liquid bridge has a linear relation with the volume of mother liquid bridge. In case of 0.1μl mother liquid bridge, the volume of satellite droplet reaches almost 3pl.

ACKNOWLEDGMENTS

The authors would like to thank Wataru Saito and Kento Yamamura of Tokyo University of Marine Science and Technology for contribution to experimental parts of this work.

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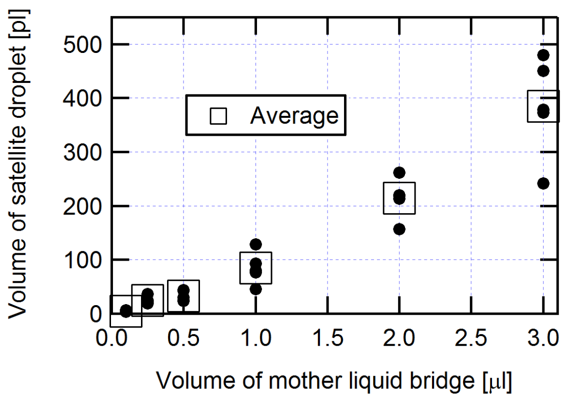

Fig.2 Volume of satellite droplet linearly decreases with decrease of mother liquid bridge

T1-4 Experimental techniques in lubrication

COMPARISON OF MAXIMUM SHEAR STRESS REACHED IN TRACTION TESTS WITH HIGH PRESSURE CHAMBER MEASUREMENTS

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INTRODUCTION

For the calculation of friction and traction in highly loaded elastohydrodynamic contacts a rheological model of the fluid is needed. Several models incorporating non-newtonian behaviour as well as limiting shear stress have been proposed [1, 2]. Most of these models rely on rheological measurements to gather the fluid parameters. A different approach frequently used is the fit of data from traction experiments to allow the calculation of traction [3, 4]. Nearly all models assume a linear relation between limiting shear stress and pressure. In this paper results of the maximum shear stress from traction measurements are compared to results from a high pressure chamber.

Experiment

Traction experiments: The traction tests were conducted on two different test rigs. For regions of contact pressures between 1,2 GPa and 2 GPa the tests were conducted on a twin disc machine using a crowned disc against a cylindrical disc. The regimes of lower pressures (0,4 GPa up to 0,8 GPa) were investigated using a Micro Traction Machine (MTM) from PCS Instruments. The resulting traction curves were analysed and the maximum shear stress reached in the experiment τ_{max} was calculated.

High Pressure Chamber (HPC) experiments: Further experiments were conducted using a high pressure chamber designed by Höglund and Jacobson [5, 1]. Here a fluid sample is trapped between two plungers and then compressed to the given pressure. Subsequently the wall of the container is moved past the fluid sample and the reaction forces are measured. These experiments were conducted in pressure ranges from 0,6 GPa to 1.4 GPa. The resulting shear stresses were calculated.

Results and Discussion

The results gained from traction experiments represent integral values. Thus it cannot be assumed that the limiting shear stress of the fluid was reached in every point of the contact. The HPC experiments on the other hand represent constant conditions for the whole sample volume. Thus it can be speculated, that the maximum shear stress reached is indeed the limiting shear stress of the fluid.

A comparison of the data gained from the HPC and the traction experiment -presented in figure 1- shows that both yield a linear relation between shear stress and pressure.

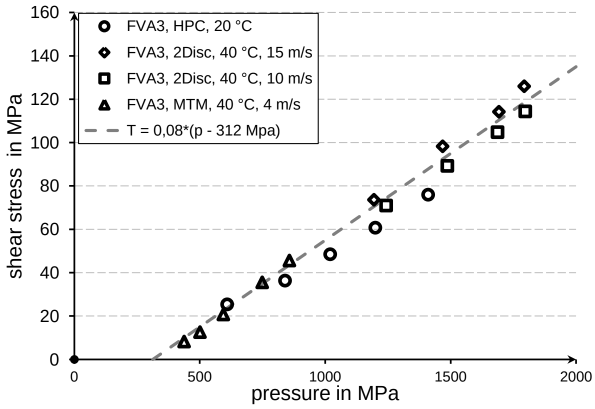

Figure 1: Maximum shear stress reached in the experiments

Furthermore, the results from the integral traction measurement are in good agreement with the results from the HPC. Thus the approximation for the maximum shear stress gained from traction tests may well yield good results when used to gain fluid parameters. However, further investigation of this phenomenon is necessary with special focus on regions of low pressures -where the limiting/maximum shear stress may not yet be reached in the fluid- as well as the influence of temperature and fluid type.

ACKNOWLEDGMENTS

The authors thank the Research Association for Combustion Engines e.V. (FVV), Research Association Drive Train Technology e.V. (FVA) and BP Castrol for funding the research.

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Ultrasonic Determination of Lubricant Film Thickness in an Automotive Transmission Journal Bearing

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ABSTRACT
The film thickness ofa journal bearing was measured in operational condition using an ultrasonic reflection technique in a test rig representing aproduction automotive transmission. The measured film thickness and the attitude angle agreed favorably with the theoreticalcurve obtained bya simplified Reynolds equation.

INTRODUCTION
Lubricant film collapse can cause tribological failures in the transmission journal bearings. Determination of tribological properties require time-consuming and expensive endurance tests since the existing measuring techniques for the oil film thickness usually require the journal bearing and lubricant feed system to be tailored for laboratory test conditions, which may affect the oil film formation. This study aims to measure the lubricant film thickness in a production automotive transmission journal bearing under practical operational conditions in-situ. The oil film thickness measurement is examinedusing an ultrasonic reflection technique which allows no changes in the bearing parts that are involved in the oil film formation due to its non-invasive nature.

MESUREMENT PRINCIPLE
Schoenberg [1] developed a spring model to describe the stiffness of a layer, κ, in relation to the magnitude of the reflection coefficient,$|R|$,of an incident wave:

$$|R| = \left|\frac{Z_1 - Z_2 + i\omega\,(Z_1 Z_2/\kappa)}{Z_1 + Z_2 + i\omega\,(Z_1 Z_2/\kappa)}\right|, \qquad (1)$$

whereω is the angular frequency of the wave, and Z_1 and Z_2 are acoustic impedance (the product of the density ofthe material and the wave velocity through the material) of the bodies separated by the layer respectively. As an oil layer separates the bodies in the hydrodynamic lubrication regime, the layer stiffness is determined by the acoustic properties and the thickness of the layer.

TEST RIG AND ULTRASOUND APPARATUS
The test rig was constructed using a journal bearing (ϕ 98 mm) of a production 12-speed transmission as presented in Fig 1. A PZT transducer of 5 MHz centre frequency was selected for this application, and transducers were then located in the stationary bush (sensor holder) so that a given ultrasound wave was pulsed and received by the same transducer. The lubricant (mineral oil based gear oil, GL-5 at API) was pumped through the bush into the load carrying area, at a controlled temperature and flow rate.

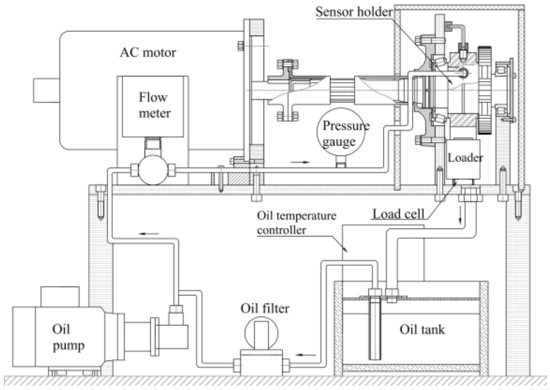

Fig.1: Illustration of the constructed test rig.

EXPERIMENTAL RESULT

The film thickness measurement in steady state conditions was examined at 60 °C and 80 °C in the load carrying area. During these trials oil was supplied to the bearing at 1.5 L/min, and a load of 3 kN was applied (at 270 deg), at a shaft rotation speed of 100 RPM. As summarised in Fig. 2, the measured film thickness and the attitude angle agreed well with the theoreticalcurves deduced by a simplified Reynolds equation, with the simplifying assumptions being the narrow bearing approximation [2].

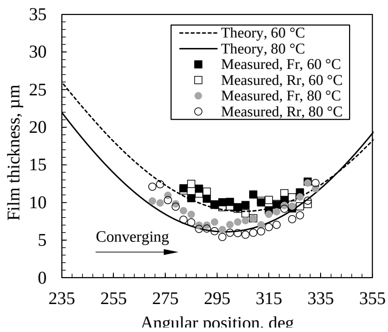

Fig.2: Measured and theoretical lubricant film thickness.

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ACOUSTIC EMISSION AS AN AID TO UNDERSTANDING RACEWAY DAMAGE IN ROLLING ELEMENT BEARINGS

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ABSTRACT

Acoustic Emission (AE) sensors were used to detect signals arising from a cylindrical roller bearing with artificial defects seeded onto the outer raceway. High frequency analysis indicated the condition of the bearings through the determination of an increase in the structural resonances of the system as the size of an artificial defect was increased. As higher loads were applied, frequencies around 100kHz were excited, indicating the release of AE possibly attributed to friction and the plastic deformation as peaks, induced through engraving of the raceway, were over-rolled and worn down. Sensitivity of AE to this level in bearings indicates that detection of subsurface cracking may be possible in future work, providing early indication of incipient failure.

INTRODUCTION

Over recent years, Acoustic Emission (AE) has gained ground as a viable structural health-monitoring tool and has been proposed as a more sensitive technique to detect early-stage damage within tribological systems. Defined as a "transient wave generated by the rapid release of energy within a material" [1], AE is the detection of transient elastic waves caused by plastic deformation, crack tip growth, fluid flow, sharp impacts, and friction/rubbing fractures/dislocations of fibres and is commonly used to detect damage in static structures such as bridges and pressure vessels. For bearings it is thought that AE is induced through subsurface cracking, friction and plastic deformation of surface asperities during the running in phase and rolling fatigue failure, and as such can provide valuable insight into bearing condition [2].

METHOD

The test bearing, a SKF N204ECP single row roller bearing was placed between two, double-row tapered roller support bearings (Type SKF 22202/20E) and subjected to incremental loading of 0.29, 0.79, 1.29 and 1.89kN (L1-L4 respectively) at a speed of 5800rpm (Figure 1). Mistras Group Ltd. (MGL) Nano30 AE sensors were placed on the front face of the bearing housings and four wave streams (raw sensor output) were recorded for each load at a sampling frequency of 2MHz on a MGL PCI-2 system. Using an engraver, defects were artificially seeded into the outer raceway of the test bearing and were characterised using a Taylor Hobson Talysurf surface profilometer before and after being tested.

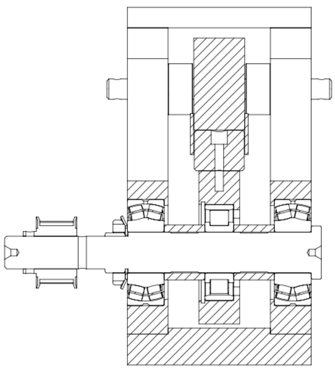

Figure 1) Test Head Schematic

RESULTS

Figure 2 is a stacked Fast Fourier Transform (FFT) used to illustrate the increase in frequency amplitude for a bearing with a 0.6x0.7mm defect seeded into the centre of the outer raceway to an approximate depth of 12μm. Comparison of pre and post-test surface profiles have led to the increase in frequency amplitude at approximately 100kHz being considered to be due to the plastic deformation of small peaks situated around the defect, induced through the engraving process, as they are flattened. Similar behavior was noted for a range of defect sizes tested in this work. Although not truly representative of natural bearing defects, the seeded defects used in this experiment have demonstrated the sensitivity of AE as a tool for gaining understanding of rolling element bearing failure and it is hoped further insight will be achieved through bearing life tests.

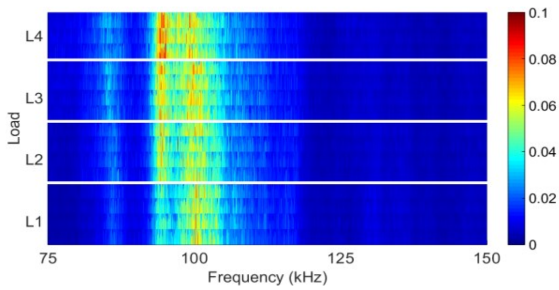

Figure 2) High Frequency Stacked FFT

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of EPSRC Grant references EP/L021757/1, and EP/K031635/1 which facilitated this work in part. The first author acknowledges the financial support of Mistras Group Limited towards his studentship.

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FORENSIC ANALYSIS OF DAMAGE INFLICTING DEBRIS PARTICLES IN ROLLING CONTACT

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ABSTRACT

A set of useful tools were presented for forensic analysis of damage inflicting debris particles in rolling contact. Example results were provided to demonstrate the validity and usefulness of the tools.

INTRODUCTION

The presence of debris particles in rolling element bearings can pose a major risk for premature fatigue damage on modern bearing components made from clean steels. A clear understanding of these surface damage inflicting particles is essential for assessing their impact on bearing fatigue life performance and for prevention of surface damage from harmful particles.

A set of tools were developed for forensic analysis debris particles that inflicted surface damage in rolling contact. It starts with a method of characterizing indentations on contact surfaces. The method allows for virtual reconstruction of indentations on bearing raceway surfaces based on pseudo-random surface mapping of limited sample areas. The regenerated surface indentations maintain statistical signatures identical to the mapped samples. An empirical relationship was developed from extensive finite element analysis (FEA) modeling on surface indentation processes. This relationship allows inference of the size of each and every particle responsible for surface indentations without requiring the full knowledge of the material properties and frictional conditions of the particles and counter-faces.

The results covering a wide range of operating conditions were presented. These results agree well with both published test results and prior art modeling results. In addition, examples of applications were discussed to illustrate the usefulness of the tools.

ACKNOWLEDGMENTS

The author would like to thank The Timken Company for permission to present this work. The author would like to express their gratitude to the Engineering Fundamental Group for support. Special thanks to Dr. Min He and Mr. M. Wilmer for their help in FEA modeling, and to Dr. D. Wu, Mr. A. Borbonus and Ms. M. Petraroli for conducting debris particle size analysis. Thanks to Dr. R. Evans for fruitful discussion on this work..

T2-5 Techniques and macro devices

OTTO RAMAN SPECTROSCOPY FOR THIN FILM LUBRICATION

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ABSTRACT

In this study, a total internal reflection (TIR) Raman spectroscopy with Otto configuration was developed. In this system, three types of techniques, i.e., optical interferometry, surface plasmon resonance (SPR) measurements, and Raman spectroscopy were combined in the single construction.

INTRODUCTION

In the field of tribology, Raman spectroscopy has been taken advantage of for investigating the structure of adsorbed films [1]. In particular, total internal reflection (TIR) Raman spectroscopy has a high surface sensitivity.

This study newly developed a tribotester with TIR Raman spectroscopy. As sample oils, hexadecane or hexadecane with oleic acid were used. Under shearing conditions, the changes in their structure near a solid/liquid interface were investigated.

EXPERIMENTAL DETAILS

Details of the newly developed experimental system were illustrated in Fig. 1. This system has a point contact between a dove prism (made of BK7) and copper ball. Additionally, for Otto Raman spectroscopy, a green laser module, spectrometer, CCD light detector, and some optical constructions were used.

In the contact region, a small clearance (approximately 100-400 nm) was formed. First, sample oil (n-hexadecane or n-hexadecane with 50wt% oleic acid) was dropped into the clearance. Then, the copper ball was rotated with an AC servomotor; shearing rate was set to be approximately 10^5 1/s.

Before and during the shearing, Raman scattering signals from the evanescent field between the dove prism and copper ball was observed by the spectrometer. In addition, after that the polarization direction of laser beam is changed with a λ/2 retardation plate, similar experiments were performed.

RESULTS AND DISCUSSION

Fig. 2(a) shows the intensity ratio ($Peak_{1303}$ / $Peak_{1440}$) under non-shearing condition; $Peak_{1303}$ and $Peak_{1440}$ are the peak intensities of light spectrum at wavenumbers of 1303 and 1440 nm^{-1}, respectively. The former corresponds to the out-of-plane bending mode (γ_{as}) of CH_2 and the later is the in-plane bending mode (δ_s) of CH_2. Thus, this result indicates that applying the oleic acid, the orientation of the alkyl chain near the solid surface was changed.

Fig. 2(b) shows the polarization direction dependence of the intensity ratio ($Peak_{1659}$ / $Peak_{1440}$); $Peak_{1659}$ indicates the stretching mode (ν) of C=C. Noted that these intensities were measured under non-shearing conditions. We can see that the intensity ratio at *P*-polarized is larger than that at *S*-polarized. Thus, it was found that oleic acid molecules are oriented in the vertical direction to the prism interface. Noted that after the onset of the shearing, this relationship was not changed.

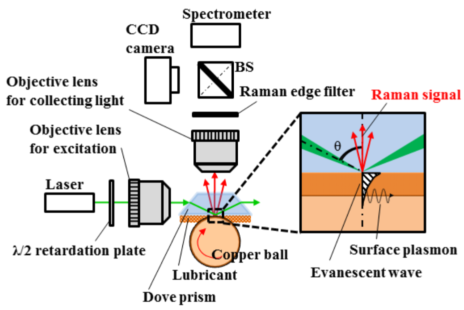

Fig. 1 Experimental setup.

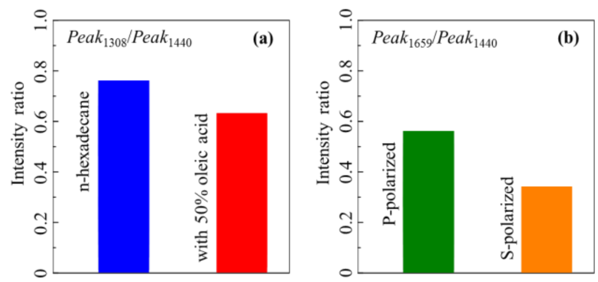

Fig. 2 Intensity ratio under non-shear conditions.

CONCLUSION

Using TIR Raman spectroscopy, the dynamics of adsorbed films under shearing conditions were investigated. It was found that oleic acid molecules are oriented in the vertical direction to the prism interface, although non-shearing is applied.

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Proceedings of the 42th Leeds-Lyon Symposium on Tribology
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CHARACTERIZATION OF THE DYNAMIC BEHAVIOR OF LUBRICITY FUELS USING VIBRATION SIGNALS AND MULTIRESOLUTION ANALYSIS

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ABSTRACT

The wear development in the operation of mechanical systems affects several characteristics related to dynamic behavior of these systems. The vibration signals are an important parameter in this evaluation and its acquisition and characterization constitutes a non-intrusive tool to evaluate the lubricity in a dynamic regime. It can be made by multi resolution analysis using Wavelet Transform due to its features of time-frequency representation. In this sense, the work consisted in the evaluation of different blends of diesel with biodiesel (diesel S50, soybean methyl ester, B10 and B20 blends) using HFRR equipment with a vibration sensor attached to the system. After that, it was applied the Wavelet Transform to analyse the vibration signals and their associations with parameters supplied by ASTM D6079. The wavelet transform allows capturing the subtle changes of vibration signals that come from lubricated contact during the formation of wear scar. The results present a correlation between lubricity and time-frequency representation.

INTRODUCTION

Diesel fuels must have lubricating ability in order to protect the injection system from wear and other tribological problems. However, EU Directives have introduced the specifications of “ecological fuels” (Directive 2009.01) that specifies the maximum sulfur content of 10 $mg.kg^{-1}$ in diesel [1]. The process of desulfurization decrease the diesel lubricity, causing problems related to the lubrication of the parts of fuel injection system. The literature suggests that the biodiesel addition in diesel fuel is capable of restore and improve the fuel lubricity. Therefore, this affirmation, most of times bases on simple microscopic analyses of wear scar diameter (WSD). However, the evaluation of lubricity only by WSD cannot be the best way to do it. According to Maru [2], this method is limited because do not consider the friction evaluation. The friction issue cannot be disregarded since it is straight related to the energy efficiency of engine parts. In addition, it is important to consider that the friction generates vibration. Thus, the purpose of this paper is to discuss a complementary way to evaluate lubricity by vibration signals using multi resolution analysis. This analysis was correlated with WSD measures to establish a comparison.

EXPERIMENTAL PROCEDURE

Blends of ultra low sulfur diesel (ULSD) and soybean biodiesel were prepared with 0, 5, 20 e 100% vol. of biodiesel. The tribological tests were carried out in triplicate using the HFRR equipped with a data acquisition board available at Tribology Laboratory. A hard steel ball (570–750 HV) of 6.0 mm diameter reciprocates on a softer steel disk (190–210HV) of 10 mm diameter. Both ball and disk were made of AISI 52100 steel. The tests consisted of reciprocate sliding (1 mm to 10 Hz, 0.02 m/s) of the ball with a 10 N load on the flat disc, both immersed in 2 mL of fuel and heated at 60°C. During the experiment, the vibration signals were acquired using an Uniaxial Vibration Sensor at a sensitivity of 9.931 mV/g, fixed on the ball holder to measure the vibration in direction of sliding (X) axis, which was coupled to a vibrating module. The vibration signal acquisition was made by LabView software and imported to Matlab where it was implemented the Wavelet analysis considering tests with different families and parameters. After the HFRR test, the WSD ball was measured by optical microscopy (magnification 100X).

RESULTS

From the analysis of the experimental results, it can be observed that the multi resolution analysis of vibration signals adding more information to characterize the biodiesel behavior and it could be correlated with WSD measures to improve the evaluation of fuels lubricity in a dynamic regime.

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Proceedings of the 42th Leeds-Lyon Symposium on Tribology
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THE ACTION OF PENETRANTS FOR RELEASING SEIZED BOLTS

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ABSTRACT

Penetrant producers consider the loosening rate of seized bolted joints as the key performance indicator of their products. Penetrating oils are low viscosity lubricants, which are used to loosen rusted and seized mechanical parts i.e. bolted joints. The oil penetrates by moving through narrow spaces between the bolt and nut threads and reduces the coefficient of friction. In this study, a non-destructive technique based on ultrasound principles was used to measure the penetration time of the fluid in the bolt and nut threads. In addition to this, a theoretical model based on Washburn equation [1] was developed to compare with the experimental data obtained.

Experimental Method

The ultrasonic apparatus consists of six pairs of piezo-electric crystals, mounted circumferentially to transmit and receive the ultrasound waves from the thread contacts. This is better explained with the help of Figure 2.

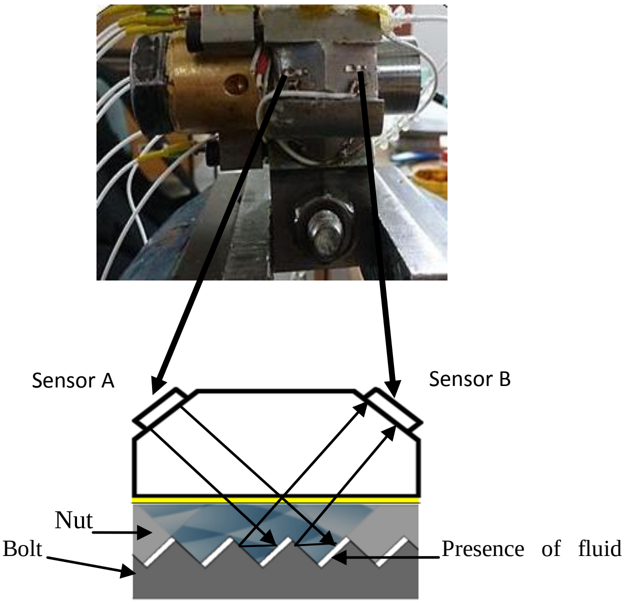

Figure 1. Sensor A sends and sensor B receives the ultrasound waves

The six pair of sensors monitor the fluid penetration in multiple threads and any changes in the ultrasound waves received was noted by further signal processing. These changes were then translated to the time it takes for the fluid to reach the threads.

Theoretical Model

The fluid penetration time in threads is dependent on the fluid properties such as surface tension and viscosity and the geometrical characteristic of the threads. Penetration time data obtained theoretically and experimentally are plotted for some of the tested samples (Figure 2).

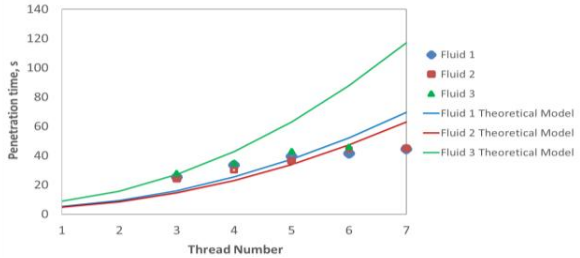

Figure 2. Comparison of theoretical model with Experimental technique

Overall, the current findings show that for lower viscosity fluid samples (1.10 mPa.s), a penetration time of 25 seconds is obtained for reaching the last monitoring thread, whilst for higher viscosity ones (4.35 mPa.s), this can be around 90 seconds. Other fluid phenomenon such as effects of trapped air, bubble formation and oil residual in threads were also observed.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the WD-40 company for funding this work and providing samples, and in particular to Mike Counts, Ernie Bernarducci of WD-40 for helpful discussions.

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Ex-Situ ATR-FTIR Approach for Characterization of Thermal and Tribochemical Reactions of ZDDP on steel and DLC coatings

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INTRODUCTION

Diamond like carbon (DLC) coatings possess low friction and high wear resistance, and because of these particular properties, they have attracted great interest in tribology during the past decades [1, 2]. Despite a lot of empirical results, tribochemical mechanisms of DLC are still not well-known and.

With respect to zinc dialkyl dithiophosphates (ZDDP) antiwear additive action on DLC surfaces, the use of modern analytical techniques has already yielded important information concerning its tribochemistry [3, 4], but no single technique provides the whole picture of the ZDDP thermal and tribofilm formation mechanism and structure.

In this paper we used for the first time an ex-situ ATR-FTIR (attenuated total reflection- Fourier transform infrared) approach for characterization of thermal and tribochemical reactions of ZDDP additive with diamond like carbon (DLC). It also has to be mentioned that FTIR characterization of tribofilm between ZDDP and DLC surface is still greatly missing in the available literature.

EXPERIMENTAL

-TRIBOTESTS

Friction tests were performed using a tribometer with a ball-on-disc reciprocating test geometry at different temperatures of 20, 80 and 150 °C, contact pressure of 600 MPa and velocity of 0.015 m/s, which corresponds to the boundary lubrication regime.

A mineral oil with and without the presence of ZDDP additive was used as a lubricant for steel/steel and steel/DLC contacts. The steel used was AISI 52100. For the DLC, non-doped and Si-doped hydrogenated DLC coatings on AISI 52100 steel substrate were used.

The surfaces were investigated before and after the tribotests using ATR-FTIR to determine chemical composition of the interaction layers.

-THERMAL TESTS

The thermal tests were carried out by covering the sample surfaces with 200 µl of mineral oil with or without the ZDDP additive and leaving the samples at room temperature or in an oven at 80° C or 150° C for 2h. Afterwards the samples were rinsed with n-heptane and sonicated in n-heptane for 10 min to remove the excessive oil and non-adsorbed molecules. After that the samples were purged with dry nitrogen to make the surfaces free of water and drying marks. ATR FTIR spectra were acquired at room temperature before and after the thermal tests.

RESULTS

Our study with use of ATR-FTIR technique shows valuable information about the fundamental chemical interactions between DLC coatings and ZDDP additives in boundary lubrication.

ACKNOWLEDGMENTS

This study was funded by the FP7 program through the Marie Curie Initial Training Network (MC-ITN) entitled “ENTICE - Engineering Tribochemistry and Interfaces with a Focus on the Internal Combustion Engine” and was carried out at University of Ljubljana. The authors would like to thank to all ENTICE partners whom had kind discussions on the topic.

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T4-4 Tactile and Joint

AN ACTIVE FORCE CONTROLLED LAPAROSCOPIC GRASPER BY USING A SMART MATERIAL ACTUATION

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ABSTRACT

In a laparoscopic surgery, it is important to operate on tissue without leaving a damage while grasping. This leads to designing a laparoscopic device in which the applied forces on tissue should not exceed a certain level. This paper deals with the active precise control of applied force by grasper on tissue. In this sense a laparoscopic device with an angular grasping mechanism which is actuated by a shape-memory alloy (SMA) material is designed and resulting force on a non-living tissue is investigated.

INTRODUCTION

Introduction of minimal invasive surgery (MIS) has led to significant advantages such as pain reduction after surgery, less drug usage, minimization of bleeding and risk of infection, reducing the recovery period of the patient. Despite having a lot of advantages, it has its drawbacks such as limited vision, loss of tactile sensing and having a less degree of freedom. This condition leads to the importance of design of the laparoscopy device [1] and one way to overcome having a less degree of freedom is to use shape memory alloys.

MOTIVATION

In laparoscopic surgery, surgeon has no longer direct contact to tissue, only has access through the surgical tools. During the grasping, enough force should be applied in order to hold and not slip while dragging, however the force should not exceed a certain level. Conventional laparoscopic graspers usually have an angular grasping mechanism that leads to a non-uniform pressure distribution on tissue surface [2-3].

SMA has its own unique features which are shape transformation, superelasticity, anti-corrosion and bio-compatibility. As an actuator, SMA materials are good candidates in laparoscopic graspers.

EXPERIMENT

Experimental setup presented in **Fig.1** consists of a laparoscopic grasper with an angular grasping mechanism actuated by SMA material, a force sensor to measure the applied force, and a non-living tissue. In this setup **P** is the applied force for grasping the tissue and $\mathbf{F_{sma}}$ is the actuation force provided by SMA material.

To control the grasping force, SMA actuator which provides a driving force to open or close the jaws is used. As a result of the driving, grasping force is achieved through the jaws. Controlling the driving force of the SMA actuator allows control of the grasping force. Design variables of SMA actuator are obtained based on the force requirement to close the grasper while the applied force on a unit area for grasping is less than the critical value of 200 kPa for a liver [3].

Applied force on tissue is fed back to a PID controller which operate on the error between applied force and desired force. As a result of the error, controller drives the SMA actuator. Controller structure is given **Fig.2**.

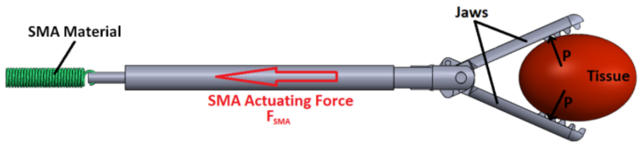

Figure 1 Experimental design of the active control of the laparoscopic grasper.

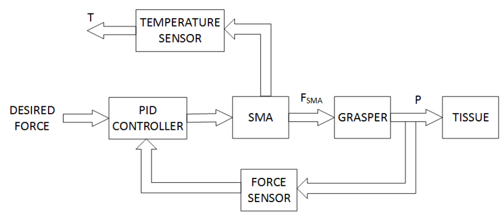

Figure 2 Control structure of the laparoscopic grasper.

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THE START-UP FRICTION PROPERTIES OF POLYVINYL ALCOHOL/GRAPHENE OXIDE HYDROGEL AS ARTIFICIAL ARTICULAR CARTILAGE

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ABSTRACT

Polyvinyl alcohol/graphene oxide (PVA/GO) hydrogels were synthesized by a repeated freezing-thawing method, and their mechanical properties were investigated as function of GO content. Friction tests of PVA/GO hydrogels under migrating and stationary contact were performed on a rotating ball-on-plate tribometer under different conditions. The results showed that the addition of GO significantly improved the mechanical strength of PVA/GO hydrogel. The changes of start-up friction coefficient show the same trends under both migrating and stationary contact with the increasing GO content, load and contact time, except the sliding speed.

INTRODUCTION

The load-bearing capacity and lubrication of PVA hydrogel cannot meet the requirements of natural articular cartilage limits its wide use as artificial cartilage substitute. GO, derived from graphene, is light and has extremely high strength and thermal stability, so it is an efficient filler for enhancement of mechanical properties of composite materials[1]. Most importantly, GO can be well dispersed in water[2]. The combined of GO with PVA hydrogel may improve the mechanical and lubrication properties.

EXPERIMANTAL DETAILS

PVA hydrogels were prepared by a repeated freezing-thawing method with different amount of GO content. Their compressive stress-strain response were measured. The friction tests of the hydrogels under migrating contact (CoCrMo ball-on-hydrogel plate) and stationary contact (hydrogel ball-on-CoCrMo plate) were performed on a rotating ball-on-plate tribometer. The testing variables included the lubricant, GO content, content time, sliding speed, and load.

RESULTS AND DISCUSSIONS

Fig.1 shows that the mechanical property of PVA/GO hydrogels increase and then decrease as function of GO content, hydrogel with 0.1wt% GO has the best mechanical property. Fig.2 shows that friction coefficient obtained under bovine serum lubrication is smaller than that obtained under DW lubricant. Fig.3 describes the effects of various testing condition on the start-up friction coefficient. The results show that the start-up friction coefficient decreases and then increases, and decreases with the increasing GO content and load, while the friction coefficient increases as function of contact time, under both of migrating and stationary contact. With the increasing sliding speed, the friction coefficient under

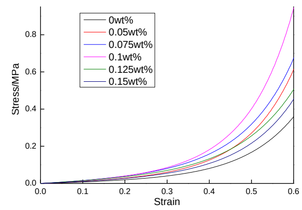

Fig.1 Compressive stress-strain response for PVA/GO hydrogel with various amount of GO

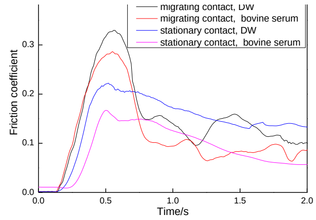

Fig.2 Effect of lubricant on the friction coefficient

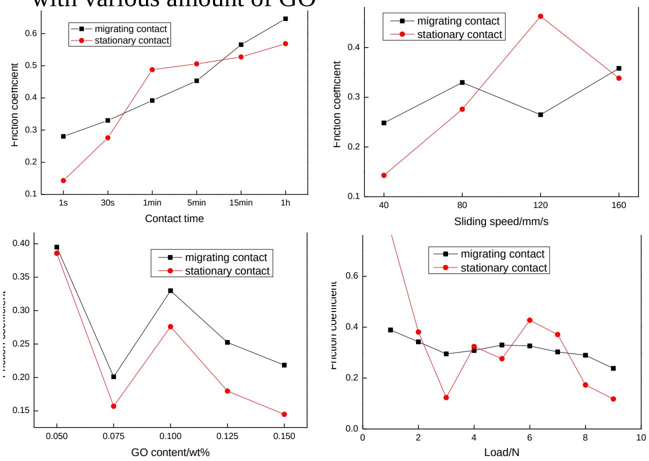

Fig.3 Effects of GO content, load, contact time and sliding time on the start-up friction coefficient

migrating contact increases, and then decreases and increases, while the friction coefficient under stationary contact increases and then decreases.

CONCLUSIONS

The addition of GO significantly improved the mechanical strength of PVA/GO hydrogel. The changes of start-up friction coefficient show the same trends under both migrating and stationary contact with the increasing GO content, load and contact time, except the sliding speed.

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THE CORRELATION BETWEEN PERCEPTUAL STIMULI AND FRICTION CHARACTERISTICS OF FINGER SLID ON THE MOLECULAR-FILM-COATED SOLID SURFACE

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ABSTRACT

The correlation between perceptual stimuli and the friction characteristic of the finger slid on the molecular-film-coated surface was investigated by evaluating an involuntary response of test subjects to haptic and visual information. This study demonstrated that mechanical data such as normal load applied by the subjects were varied with the haptic or visual stimuli.

INTRODUCTION

The use of touch panel display is rapidly spread along with the popularization of tablet PCs and smart phones. An organic molecular film of PFPE-derivatives is currently applied to protect the outer surface of the touch panel display against damages and contaminations caused by finger manipulation. While much attention has been directed to improvement of the anti-fingerprint performance and the durability of the film, fundamental knowledge regarding the friction phenomenon caused by the finger manipulation against the molecular-film-coated surface and its effect on a human perception and action have been still less understood. To address the limitation, this study examined the correlation between perceptual stimuli and the friction characteristic of the finger slid on the film-coated surface by introducing two kinds of perceptual stimuli such as haptic and visual information.

EXPERIMENTAL PROCEDURE

The measurement of friction by finger manipulation was conducted using a laboratory-made tribometer that can measure x and y component force and z component force perpendicular to plane surface simultaneously. The Android® tablet having a laboratory-developed application that can provide positional information of the finger was mounted on the tribometer to measure distance and time of the finger simultaneously with friction force and normal load. Glass plate was used as substrates and then coated with several kinds of organofunctional silane-adsorbed films.

RESULTS AND DISCUSSION

For understanding the effect of visual stimulus of the tablets on the mechanical data obtained from the finger manipulation by the subject, application software which can measure a delay time of a virtual ball moving with the finger slid on the display was introduced to the Android® tablet mounted on the tribometer. In the test, the subjects were required to move the virtual ball in the tablet in one direction from left to right side by using the index finger. They carried out the test twice, and the moving speed of the virtual ball was purposely reduced in the one test of twice. After the second test, the subject answered which the virtual ball in either of the first and second tests induced a heavy feeling. Figure 1 shows the plots of a response ratio which the subjects answered the ball was delayed in the second test versus the delay time of the ball in the second test against the first one. From the results, there was some correlation between the delay of the virtual ball against the movement of the finger and the heavy feeling of the subjects.

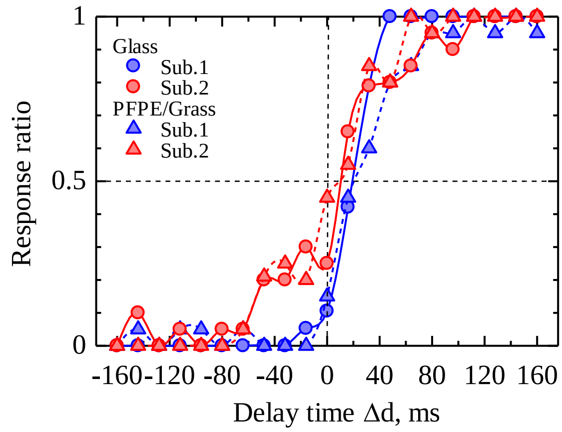

Figure 1 Correlation between the response delay time against the finger manipulation and the heavy feelings of the subjects

ACKNOWLEDGMENTS

This work was supported by JSPS KAKENHI Grant-in-Aid for Scientific Research (C) Number 25420082.

TRIBOLOGICAL ANALYSIS OF THE FRICTION REDUCTION IN TACTILE STIMULATION

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ABSTRACT

In this article, the focus will be put on the tribological investigation of the friction reduction using tactile stimulator. An experimental set-up has been constructed to measure, using a tribometer, the friction reduction between volunteers' finger and the active surface of the plate of a tactile stimulator. By increasing the vibration amplitude of the plate, the friction decreases by the squeeze film effect. The dependence of a new criterion, the friction contrast, to the initial friction coefficient and to the exploration velocity of the user' finger have been observed.

INTRODUCTION

The tactile stimulation using tactile feedback devices has been recently developed in order to more explore the sense of touch. This technology allows giving the illusion of touching a real textured surface by modulating the friction between a finger and the active surface of the stimulator. This technique recognizes the importance of modulating the friction without changing the surface. This friction modulation can be achieved either by increasing the initial friction coefficient using electrovibration [1], or reducing the friction by creating an air gap playing the role of lubricant between the finger and the plate [2]. This latter is investigated in this paper by using two tribological experiments to evaluate the friction reduction dependence to the experimental condition such as the sliding velocity and the initial friction coefficient of the user's finger with the stimulator.

NOMENCLATURE

VA: vibration amplitude,
FC: friction contrast,
V: exploration velocity,
μ_0: initial friction coefficient,
μ_1: reduced friction coefficient.

EXPERIMENTAL SETUP

Two experiments were carried out to evaluate the friction reduction in response to the related conditions.The first one was performed firstly to evaluate the friction contrast in response to the vibration amplitude. The friction contrast is defined as:

$$FC = 1 - \mu_1/\mu_0 \quad (1)$$

Six volunteers (aged between 23-27 years) have participated to this experiment, they had to explore the surface of the plate by maintaining a normal force approximately equal to 0.5 N and an exploration velocity of 20 mm/s. The right half of the plate was excited by a vibration amplitude from 0.5 to 2 µm by steps of 0.5 µm, while the part in the left was not excited. By plotting the measured FC as a function of VA, we found as expected an increasing of FC when VA increases (Fig. 1).

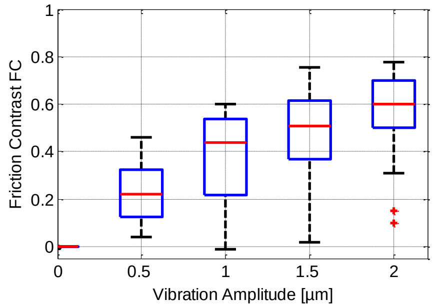

Fig. 1: Friction contrast FC as a function of the VA

For the second experiment, the goal was to determine the evolution of FC as a function of μ_0 and V. 20 volunteers have participated to this experiment. The tactile stimulator is moved under the finger with a constant velocity. A statistical analysis allows us to find a decreasing relation between FC and the initial friction coefficient μ_0 for the same vibration amplitude. This finding indicates that the user having a small initial friction coefficient is more sensitive to this type of tactile stimulation. This study proves also that the FC decreases when the exploration velocity increases, this conclusion can be explained by the time dependence of adhesion.

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T1-5 Lubrication applications II

Proceedings of the 42th Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France
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AN ELASTOHYDRODYNAMIC LUBRICATION CONTACT MODEL FOR VALVE TRAIN SIMULATION

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ABSTRACT

The evaluation of lubricated contacts is an essential step in modern engine simulation to estimate runtime behavior and wear. The prediction of contact pressure and oil film height poses a complex task, especially in non-conformal conjunctions such as between a cam and a follower. A deep investigation of the occurring thin oil films is important to estimate friction and wear. Elastohydrodynamic lubrication (EHL) theory investigates these contacts with high pressure and thin oil films.

In previous decades efficient algorithms and relaxation strategies have been introduced to solve the line contact problem in EHL. The algorithms analyze the underlying equations, such as the Reynolds Equation for the pressure distribution of the oil film, and the Film Thickness Equation, for the elastic deformation of the solid in detail and solve the coupled system efficiently.

One key feature of a tool for multi-body simulation is a versatile yet consistent modeling of the fundamental equations. Different demands on the model result in the need for variable modeling depth (e.g. consideration of cavitation and/or friction) and discretization techniques. Thus, a strong coupling, where the relaxation approach of the EHL solver is chosen depending on the modeling of the Reynolds equation, is not practical for the universal use in a multi-body dynamic tool. The algorithm needs to adapt to the changing conditions and requirements without customizing the implementation. Additionally, consistent run time behavior and results need to be guaranteed.

This paper presents an approach to solve the line contact problem without the above mentioned strong dependence on the modelling of the Reynolds Equation. The introduced method incorporates existing relaxation techniques and uses them in a decoupled EHL solver for multi-body simulation.

Additionally, an embedding in a flexible multi-body dynamic tool is presented. As an example the contact between an exemplary cam and a flat tappet follower of an internal combustion engine is investigated. The cam is attached to a flexible, rotating shaft and the tappet interacts with the valve and the spring. Oil film heights and pressure distributions of the conjunction and the generated contact forces are presented and discussed.

STABILITY CHARACTERISTICS OF HERRINGBONE-GROOVED AERODYNAMIC JOURNAL BEARINGS MOUNTED ON VISCOELASTIC SUPPORTS

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INTRODUCTION

Journal bearings mounted on viscoelastic supports have high bearing stability [1]. However, the proper support conditions have not been fully clarified, especially for herringbone-grooved aerodynamic journal bearings. The main purpose of this study is to make clear the effects of viscoelastic properties of the supports on whirl onset speed and dynamic behaviors of the bearing system.

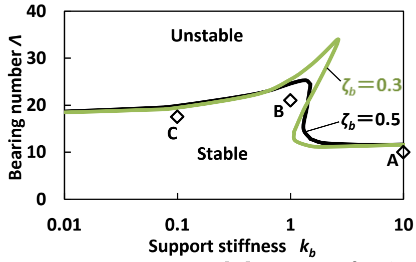
THEORY

In the rotor-bearing system analyzed here, a rotor is supported by two identical herringbone-grooved aerodynamic journal bearings at both ends. In addition, the bearings are mounted on viscoelastic supports. The pressure in a lubricant air film is assumed to be governed by the compressive lubrication equation based on the Narrow Groove Theory.

In this study, the stability maps for various viscoelastic support conditions were obtained by the perturbation method, and dynamic behaviors of the journal and bearing centers on the stable/unstable conditions were analyzed with time by the nonlinear orbit method.

RESULTS AND DISCUSSION

Figure 1 is the stability maps obtained from the perturbation method. The nomenclature ζ_b means the damping ratio of the bearing supports. Figure 2 shows the behaviors of journal and bearing centers in horizontal direction at operating point A-C, shown in Fig.1.



$\zeta_b = b_b / 2\sqrt{m_b k_b}$
k_b: support stiffness
b_b: support damping
m_b: mass of bearing

Fig.1 Stability maps for ζ_b =0.3 and 0.5

At operating point A, the bearing keeps remaining at its steady state point like rigidly supported bearing, regardless of the journal behaviors. At the operating points B and C, the bearing vibrated with the journal vibration. For the point B, the journal and bearing vibrated with almost same phase. For the point C, they vibrated with the phase difference of about 180 degrees. From Fig.1, only near the point B, the whirl onset speed dramatically changed between ζ_b =0.3 and 0.5.

CONCLUSIONS

In this study, the effects of viscoelastic properties of the bearing support elements on whirl onset speed and dynamic behaviors of journal and bearing centers were investigated.

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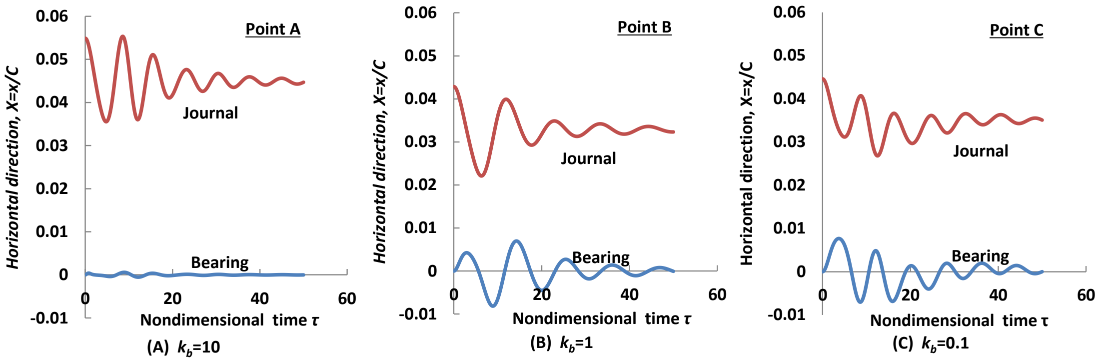

Fig.2 Behaviors of journal and bearing centers for ζ_b =0.5

MODELLING THE LENGTH OF CONTACT PATCH ON DRY, WATER- AND SNOW-CONTAMINATED RUNWAYS

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ABSTRACT

Aircraft performances at take-off or landing depend strongly on runway surface conditions. Accident risk is multiplied at least by 10 when the runway is covered by contaminants. A comprehensive modelling of the tribosystem aircraft tire/contaminants/runways would help to better understand the lubrication mechanisms at the tire/runway interface and to reliably predict aircraft braking performances. In a previous paper, a tire brush model was adapted for aircraft braking on water- and snow-contaminated runways [1]. The tire tread is modeled as a series of independent elastic brushes that sticks, elongates and slips in contact with the surface.

On water-contaminated runways, the tire has to remove water before making contact with the ground. On snow-contaminated runways, the tire displaces and compresses the snow, and finally makes contact with a new surface made of compacted snow. The length of the contact patch should therefore depend on contaminant type and characteristics. The length of the contact patch is a relevant parameter in the brush model as the braking stiffness (slope of the friction-slip curve) depends on the number of brush elements in contact with the surface. Estimating the length of the contact patch on contaminated runways is therefore a key step of the modeling process.

This paper is an attempt to quantify the length of the contact patch on dry, water- and snow-contaminated runways. The tire is modeled as a cylinder deformed by a vertical load. On a dry and rigid surface, the length of the contact patch is calculated from the geometric chord formed by the intersection of the non-deformed circle and the ground. The principle of the model is that the vertical load is reduced on water- and snow-contaminated runways. The length of the contact patch is then calculated as on a dry and rigid runway considering the reduced vertical load.

On a water-contaminated surface, the vertical load is reduced by hydrodynamic forces calculated from the tire wetted length, the water depth and speed. The wetted length is determined from geometric considerations using the tire radius, the tire deflection and the water depth. On snow-covered surface, the mechanism is more complex due to snow compression. Knowing initial and final snow densities, the evolution of snow depth and density is calculated from pure geometric considerations. The vertical load is reduced due to snow compression and displacement forces. The snow compression force was estimated from the relationship between the snow compressive strength and density, and the snow displacement force was modeled considering the dynamic energy required moving the snow in the vertical direction.

As no measurement of contact patch length was found in the literature, a parametric study was conducted to assess the effect of speed, vertical load, contaminant thickness, etc. on the length of the contact patch.

To illustrate the potential of the developed model, two applications are shown. The model was first used to determine the braking stiffness of light vehicle and aircraft tires on contaminated runways. Results show significant differences between aircraft and light vehicle. They provide evidence that the braking stiffness depends on surface conditions and, by means of the model, explain this dependency in a physical way. The model was then used to determine the critical speed at which contact is totally lost between the tire and the runway (full (elasto)hydrodynamic lubrication regime). Results were compared to those found in the literature [2][3].

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DYNAMIC BEHAVIOUR OF THE DOCTOR BLADES USED IN PAPER INDUSTRY

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ABSTRACT

The dynamical behaviour of doctor blades used in paper industry for cleaning press-rolls is studied numerically and semi-analytically. A multiscale approach combining the dynamic effects of uni-directional roughness of the rolls on the lubrication/cleaning process of the blade is established and a parametric study regarding the geometrical and elastic properties of the blade carried out. The ultimate goal is the theoretical prediction of the cleaning efficiency and the estimated frictional energy loss.

INTRODUCTION

With a share of 5.7% of the total industrial energy consumption in 2004, the paper industry is one of the largest energy consumer worldwide [1]. In this study, we focus on the tribological behaviour of the doctor blades, alone responsible for the 3% of electricity losses [2]. In this contribution, we extend the steady-state approach in [3] by introducing in the description of the mechanical behaviour of the blades their design and the impact of irregularities of the roll surface on the lubrication mechanism.

THEORETICAL APPROACH

The blade holder is a rigid body constrained to the frame of the machine by a hinge and its position is controlled by a pressurised hose. The doctor blade is taken as a cantilever beam, subject to small linear elastic deformations and fixed to the blade holder by a fixed joint. The blade deformations in the axial and transversal direction are modelled in terms of two coupled spring-mass systems. The lubrication precess is described in conventional manner by the Reynolds equation. Let x and t denote the streamwise direction along the roll surface and the time, respectively, suitably normalised. As a key feature of our analysis, then the accordingly rescaled film thickness $h(x,t)$ depends on the movement of the blade tip in contact, expressed by h_0, and the resultant waviness of the surface on a macroscopic and microscopic scale, expressed by $r(x,t)$,

$$h(x, t) = h_0(t) + (a-x) \tan \alpha - r(x,t). \qquad (1)$$

Here the blade tip is considered as a pad being in contact at a length a, in the current setting inclined by an angle α.

Specifically, a given particle height s defines the cleaning efficiency C_s as the precentage of time where $\min(h) < s$: Fig. 1.

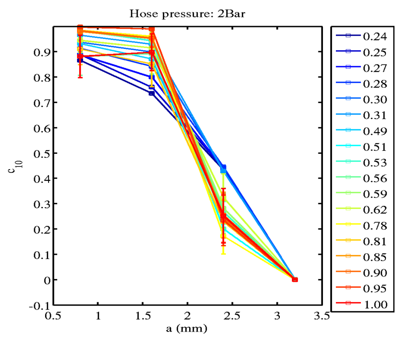

Fig. 1: Cleaning efficiency $C_{10\mu m}$ for various values of the contact lengths *a* and the stiffness, normalised by its maximum value (legend on the right).

ACKNOWLEDGMENTS

Special thanks go to the Austrian Research Funding Agency (FFG, Project Nr.: 848334) and the Austrian Association of Pulp and Paper Chemists and Technicians (ÖZEPA).

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T5-6 Rough Contact 2

Effect of Cross-grooved Type Texturing on Initial Running-in under Lubricated Fretting

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1. INTRODUCTION

At the minimum displacement amplitude in oil-lubricated fretting, the lubricating oil cannot be easily supplied to the sliding surface. Under these conditions, texturing provides functions of oil grooves and pockets to the surface [1], so that texturing can be considered to improve fretting. In this study, we have focused on the initial running-in period, where a significant reduction in the coefficient of friction is observed in the early stage of fretting, for assessment of the lubricating conditions. We have previously investigated dimple texturing [1]; however, in this study, we focus on cross-grooved type texturing. Fretting test observations confirmed that initial running-in occurred faster with cross-grooved texturing than with dimple texturing.

2. EXPERIMENTAL

Figure 1 shows the surface condition of the cross-grooved type texturing on flat bearing steel (HV760). This flat specimen and a ball specimen of the same material were used for room temperature fretting tests. The fretting stroke used was 30-200 μm with poly-α-olefin (base oil, 75cSt @ 40 °C) as a lubricant.

Other flat specimens were dimple textured and mirror finished. The effect of texturing was evaluated by comparison of these surfaces.

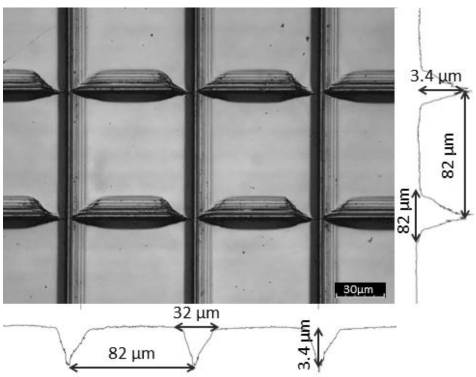

Fig. 1 Micrograph of cross-grooved type texturing

3. RESULTS

Figure 2 shows the relation between the initial running-in cycles and the fretting stroke for the various surfaces. The two types of textured surfaces were observed to have a faster initial running-in than the mirror-finished sample for fretting strokes between 40 and 100 μm. In addition, the cross-grooved type texturing exhibited faster running-in than dimple texturing. The reason for these results is considered to be the oil grooves and oil pockets that the texturing provides.

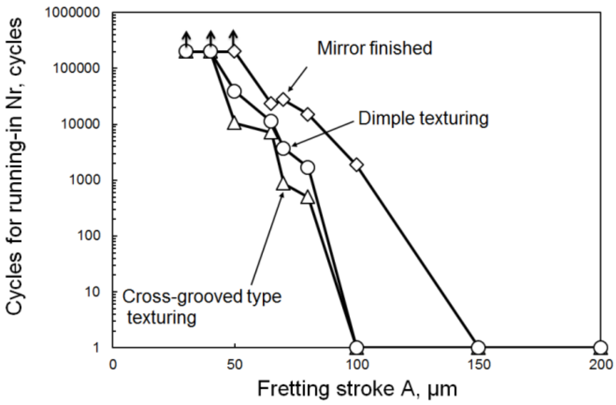

Fig. 2 Relationship between running-in cycles and fretting stroke for various samples

4. ACKNOWLEDGMENTS

This work was supported by Grant-in-Aid for Scientific Research(C) (No. 24560985) from the Japan Society for the Promotion of Science (JSPS).

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MULTIGRID SOLUTION FOR 3D ROUGH CONTACT PROBLEMS IN PRESENCE OF SUBSURFACE HETEROGENEITIES

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ABSTRACT

Multigrid methods have led to very efficient computational tools for the analysis of contact problems. Today's challenges are the optimization of contact behavior on an increasingly small sub-contact (subsurface) scale. In this paper some new developments towards applications for local scale heterogeneous material with surface roughness are presented.

INTRODUCTION

Due to demands of increased efficiency (sustainable energy) nowadays contacts have to operate reliably under increasingly severe conditions. Accurate failure prediction requires taking into account increasingly small scale phenomena in surface and subsurface topology and material properties that before could be ignored. The purpose of this work is to analyze the influence of the roughness and the presence of defects on the contact fatigue. Both phenomena have a strong impact on the pressure distribution and act as stress raisers in the subsurface and significantly reduce the fatigue life of a contact. It is shown that Multigrid algorithms can be used to face today's challenges and for efficient parameter studies to develop failure criteria.

MODEL AND RESULTS

Model

The model used in the current study has been developed by Boffy et al [1]. It can predict both the contact pressure and subsurface stress profiles in the case of a strongly heterogeneous material with good accuracy. The algorithm is based on a Multigrid framework combined with advanced numerical tools to deal with very local property variations. The indenter is considered as a rigid body which can have different shapes (spherical, ellipsoidal, square, etc…). The roughness is first considered adding a sinusoidal function $r(y)=A.\cos(2\pi y/\lambda)$ to the one describing the indenter shape $f(x,y)$. A represents the amplitude of the roughness and λ the wavelength.

Results

To highlight the potential of the method, the results of two simulations are presented. In both cases the contact problem is solved considering a spherical rough indenter with $A/a_h=0.01$ and $\lambda/a_h=0.15$, a_h is the radius of contact in the case of a flat spherical indenter (Hertz solution). 25 inclusions are regularly placed in the subsurface at a certain depth z/a_h. Results are given in Fig 1 in the plane (x,y=0,z). The volume is meshed with more than 200 million of points; the CPU time is 14 hours.

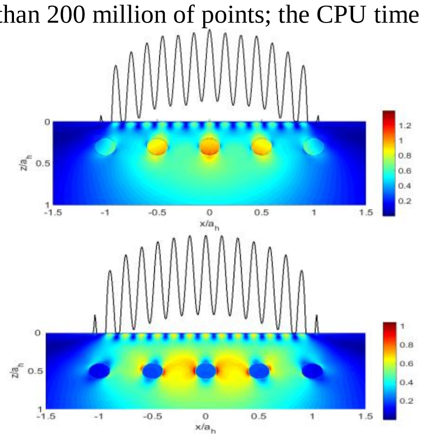

Figure1: pressure profile and Von-Mises stress field in the case of a rough contact in presence of hard ($E_i/E=3.0$, $z_i/a_h=0.3$) and soft inclusions ($E_i/E=0.2$, $z_i/a_h=0.5$).

The results show how the pressure and stress distributions are affected by the local phenomena which can interact when located shallow to the surface. This work can be naturally extended to complex surface roughness and elliptic indenter, which are realistic configuration for bearings application.

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NANOSCALED CONTACT BETWEEN ELASTIC BODIES WITH WAVY SURFACES

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ABSTRACT

Understanding of contact interaction between a wavy surface and a half-space lays a foundation for the design of micro/nano-electromechanical systems. Specifically, the effects of the multiscale surface characteristics on contact analysis mostly rely on the information of the contact between a wavy surface and a half space.

Recently, both experimental and theoretical results have demonstrated that when the characteristic dimensions of materials or structures shrinks to nanometers, surface effects may play a significant role in their mechanical and physical behavior due to the high surface-to-volume ratio. To account for the effects of surfaces in solids, Gurtin and Murdoch [1] established a continuum mechanics model of surface elasticity. Investigations on nanosized structural elements under various conditions showed that the theory of surface elasticity can well explain the results of experimental measurements and atomic simulations. A series of nanoscaled contact analysis has been performed, limited to a simple and rudimentary contact geometry. [2,3]

The investigation of contact problem between a wavy surface and a half space with surface effects [4] shed light on multiscale contact analysis, known as fractal contacts. Development of surface measurement devices reveals surfaces as multiscale process with no obvious smallest length scale. For this reason, there has been considerable recent interest in rough surface contact theories based on the representation of the surface as a fractal. However, the paradoxical result of the fractal contact is that if increased resolution in the surface roughness description leads to increasing numbers of progressively smaller contact areas, leading that the contact areas goes to zero in the fractal limits.[5] This conclusion from the conventional multiscale contact analysis is physically unrealistic because the material properties such as surface properties are invariants. By virtue of the model of surface elasticity in nanometer contact length, the surface properties and the corresponding contact interaction can make us predict an appropriate contact behavior in the realistic scale limits.

The multiscale surfaces in question can be established from a fractal surface, equipped with a series of trigonometric functions. Thus, a contact problem between a single sine wave of surface profile and a half space will give a fundamental and substantial result which may enhance the understanding of the real multiscale contact.

The objective of the present paper is to perform a nanoscaled contact analysis by considering the surface effect for a wavy surface contacting a half space and investigate the influence of the surface stress on the contact region. A classical elasticity solution technique using Papkovitch-Neuber representation with non-classical boundary condition for contact region is introduced and shows some limitations. A finite element methodology is also implemented to solve the problem. Contact pressure distributions for the partial and full contact are identified and are compared with the distribution without surface effects. Through this analysis, we expect to propose a real scale limit for the multiscale analysis.

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Proceedings of the 42th Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France
leeds-lyon - Room 3 - Wednesday, September 9, 2015 - 12:00/12:20 (20min)

CONTACT MODELING IN FINITE ELEMENT AND BOUNDARY ELEMENT ANALYSIS INCLUDING THE SIMUATION OF THERMOMECHANICAL WEAR

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ABSTRACT

Commercial computational mechanics codes include gap, contact or over-closure models to account for contact stiffness. The form and magnitude of nonlinear or linearized contact stiffness can be related to the surface roughness and nominal pressure from Greenwood and Williamson's original paper. Also, the thermal conductivity is a relatively straightforward extension from their work. In this paper, we use the Greenwood-Williamson stiffness relation to relate over-closure models to surface roughness. We then present the results of wear simulation studies with adjustable contact parameters for a ring on ring sliding configuration. We show that the values and forms of the contact parameters influence pressure, temperature and wear distributions.

INTRODUCTION

It has been shown that, following the development of the Greenwood-Williamson Theory, a local contact stiffness k (MPa/µm) can, for an exponential distribution of asperity heights, be written $k = p/\sigma$ where p is the nominal pressure and σ is the combined rms surface roughness [1]. For Gaussian asperity height distributions data show that the stiffness is closer to $k=3p/\sigma$ [2]. At moderate pressures, the Greenwood-Williamson model gives reasonable results. At very low pressures, the Greenwood-Williamson and most statistical models continue to indicate some contact deflection that never goes to zero. Over-closure models overcome this problem by forcing the contact deflection and pressure to go to zero together at some value of over-closure $-c_o$. We look at one type of widely used model to match model parameters to roughness and contact pressure. We then proceed to use this and other models in thermo-mechanical wear simulations.

WEAR SIMULATION

The contact models are combined with a localized Archard type wear model, first proposed by Marshek and Chen [3], in step by step wear simulations of steel rings meant to represent clutch wear over a large number of engagement cycles. Both the commercial code ABAQUS and a proprietary boundary element code are used to solve the non-linear contact problem with an axisymmetric thermoelastic representation of the rings. In the former, the shape of the wear track is only changed between engagements, while with the latter method, the shape of the wear track evolves with the changes of temperature and pressure during an engagement. The parametric studies indicate the extent to which the shape of the wear track can be affected by the initial roughness and wear history. The effects range from minor to moderately significant, with areas of maximum wear shifting radially inward and outward. We note that the roughness parameters are not changed over the course of a simulation, although that is something that could be included if the changes are known.

CONCLUSIONS

We have shown that physically, i.e., roughness, -based over-closure models, calibrated by the Greenwood-Williamson Theory of rough surface contact can be established. This allows the role of surface in wear and other contact simulation to be studied. Definite effects on the wear patterns are predicted.

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T1-6 Slipping surfaces

THE EFFECT OF VISCOSITY ON BOUNDARY SLIPPAGE IN HYDRODYNAMIC LUBRICATION

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ABSTRACT

Recently, no-slip boundary condition has been suspected by some scholars. And our studies also proved the existence of slippage at the interface between lubricants and solid surfaces in hydrodynamic lubrication under some working conditions [1]. Besides, our research proved that contact angel hysteresis, not contact angle, closely correlates with the slippage, which corresponds well with an existing theory derived based on thermodynamic principles that the adhesive strength between the contacting solid and liquid molecules is a strong function of contact angle hysteresis but not the contact angle if its value falls into the range of 20^o to 140^o [2]. On the other hand, the preliminary experimental results also showed that the degree of slippage and critical shear stress are different for 99% glycerol and 65% glycerol, which means more experiments with the same lubricant type of different viscosities are needed for delineating the relation between viscosity and critical shear stress. The results of this study are expected to provide insights in relevant theoretical development.

A self-developed slider-on-disc test rig was used in this study [3]. A fixed inclined slider and a rotation glass disc composed the contact pair. The slider and the disc would be separated by lubricants once the disc rotating for hydrodynamic effect. And lubricant film thickness was measured by optical interference method. Two different sliders with the same size were used, steel slider and steel slider with EGC coating (an oleophobic coating, provided by SKF). Four lubricants with different viscosities were selected as lubricants, 99% glycerol, 85% glycerol, 65% glycerol and 50% glycerol. All the lubricants are polar, so the effect of molecular polarity can be ignored. The lubricant film thickness changed with speed under different loads and inclinations were measured. The critical shear stress which decides the slippage was evaluated based on the measured lubricant film thickness. A new slippage model was proposed to explain the phenomena.

ACKNOWLEDGMENTS

The work described in this paper was fully supported by the Research Grants Council of Hong Kong (Project No. CityU123411) and Natural Science Foundation of China (Project No. 51275252). The authors would also like to thank City University of Hong Kong for providing a studentship for the first author. Thanks are also extended to Dr. X. Zhou of SKF for preparing the EGC coated sliders for the project.

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SHEAR FLOW OF CONFINED LUBRICANTS OVER SURFACES ALTERNATING SLIPPING AND NON-SLIPPING GRAINS

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ABSTRACT

Recent trends in lubrication technology are leading to a decrease in thickness of the oil film, which is reaching the order of a few nanometers. Under this state of severe confinement, the properties of fluids deviate from their typical bulk behavior. Experiments and Molecular Dynamics simulations have reported the occurrence of wall slip, i.e. a velocity jump at the surface-fluid boundary which contradicts the classical no-slip condition of macroscopic lubrication models. This phenomenon was shown to depend on the nature of the surfaces, and appeared mainly in presence of non-wetting materials featuring weak interactions and commensurability with the lubricant molecules [1].

Wall slip is usually quantified over nanoscopic Reference Volume Elements (RVE), representing a small patch of the real contact area without variations in surface nature. MD results from these nanoscopic domains are generally considered representative of the local behavior in macroscopic systems. Thus, they included into macroscopic models based on continuum equations, in the framework of recently developed multi-scale approaches for lubricated contacts [2].

Real macroscopic surfaces present nonetheless a complex nature, exposing grains of different materials and orientations to the fluid. This can lead to local changes in wettability and consequently wall slip. One should understand how slip on each grain is influenced by neighboring domains of different natures. It must also be determined whether local slip behavior can still be quantified through the usual RVE simulations. This is a fundamental hypothesis for the MD-continuum coupling in multi-scale approaches, whose ability to characterize the shear response in presence of grains with different slip should be assessed. To answer these questions a direct comparison between MD simulations and continuum is performed on a system with a patterned surface under shearing.

A short n-alkane is thus confined between two walls, one of which presents slipping and no-slipping domains. Contrary to the usual results of RVE shear simulations where Couette flow is observed, the velocity profiles in the system with grains are curved (Figure 1) to ensure a constant mass flow rate along the shearing direction. Local slip behavior on the non-wetting domain is not significantly affected by the neighboring wetting grain, and can still be quantified through the usual Navier slip length from nanoscopic RVE. Additionally, a pressure gradient (Figure 1) appears in the system under shearing. Hence, both Couette and Poisseuille components characterize the fluid flow despite the application of a simple shearing to the system.

A continuum formulation is then developed. It is based on the Reynolds equation including slip and parameterized from nanoscopic RVEs. This approach is able to reproduce with excellent agreement the lubricant dynamics, pressure and shear stress obtained from the MD simulations of the system with grains for a wide range of operating conditions (Figure 1).

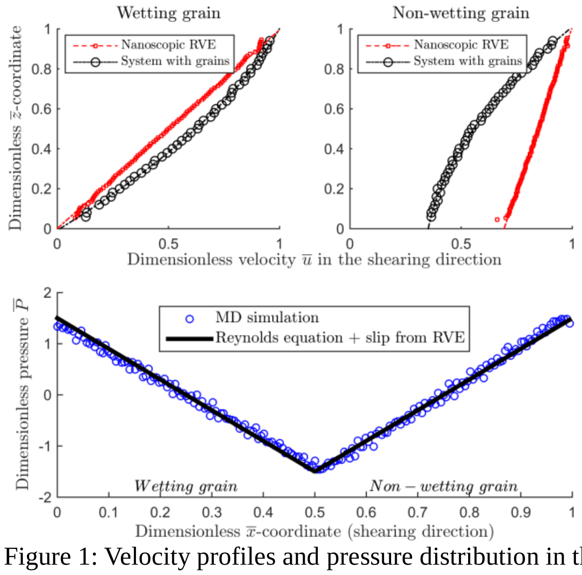

Figure 1: Velocity profiles and pressure distribution in the system with alternating wetting and non-wetting domains

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OIL TRANSPORT IN MICROCHANNELS BY MEANS OF CAPILLARY FORCES

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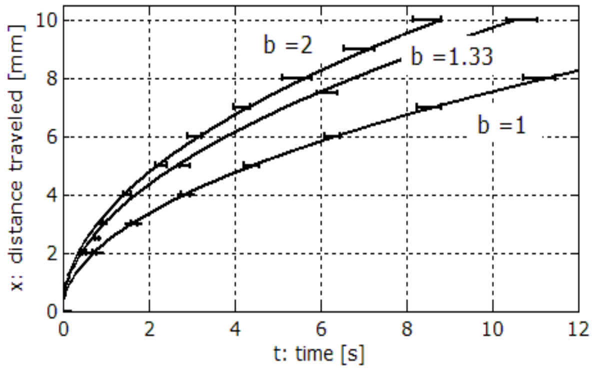
ABSTRACT

To avoid starvation, lubricant supply in the inlet region of a tribocontact must be sufficient. Oil reservoirs (e.g. grease) and tribocontact inlet not necessarily overlap thus requiring the lubricant to be transported. Besides active oil pumping, passive transport mechanisms, often due to surface forces, are highly relevant. These are influenced by micro- and macrogeometry design features such as surface curvature [1], material porosity (as present e.g. in sinter bearings), and surface structure.

A very effective transport structure is microchannels. In contrast to wetting of flat (or even textured) surfaces, a strong front meniscus forms that is responsible for comparatively high transport velocities. Such channels with widths and depths in the micrometer range are researched in chemical, biological ("Lab-on-a-chip") and electrical engineering contexts but - to our knowledge - have not yet been investigated in the field of lubrication, where film flows dominate.

We investigate oil transport driven by capillary forces in structured microchannels with constant cross-section. Our goal is both to summarize and extract the pieces of existing microchannel flow theory we consider relevant in a tribological framework and complement it where deemed necessary.

Basically, microchannel flow can be described by a one-dimensional Stokes equation including body forces. Unlike existing literature (that predominantly deals with closed channels fabricated by photolithography and subsequent etching steps before capping the channels) this study focuses on open channels cut by micromilling or laser into steel and polyoxymethylene. As a consequence, channel cross-section deviates significantly from basic geometries and channel roughness is increased; numerical solution is provided via finite element and finite difference approaches. The pressure difference at the driving front meniscus adheres to the Young-Laplace equation. We work with several of a multitude of available approximations. In order to compare computation with experiments time-dependent fluid advancement is videotaped. Results show good agreement (see figure) and are in line with Washburn's classical equation [2], while parametric uncertainties remain due to channel roughness and geometry, front meniscus pressure jump and temperature.



Oil advancement in microchannels: experiment (+/- std.dev.) against finite differences computation (solid line);
b is nondimensionalized channel width & depth

Due to steep temperature gradients in the proximity of a tribocontact, surface stresses induced by the Marangoni effect may not be neglected. They allow for simultaneous downstream and upstream flow in different fluid layers which might explain flow reversal behavior observed by [3]. In the worst case oil supply to tribocontact is completely suppressed.

The same is true for centrifugal forces. Whereas classical centrifugal microfluidics uses rotating devices to transport and/ or mix fluids we investigate how capillary-driven channel flows can be maintained even against a centrifugal force present. A basic microfluidic law, Washburn's equation still covers Marangoni influence but once centrifugal forces come into play its general validity has to be questioned.

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MOLECULAR DYNAMICS SIMULATION OF A DROPLET SHEARED BY SOLID WALLS

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ABSTRACT

Considering a nanometer-thick droplet shared by two solid walls, shear forces were evaluated by molecular dynamics simulation. Expressly, shear forces around the contact line regions have been focused and evaluated the velocity dependence of forces. As a result, it has been clarified that no difference is observed between the velocity dependence of force around two contact lines.

INTRODUCTION

Recently, due to the development in materials science, new functional materials can be used. These materials realize useful mechanical and energy devices that have small structures in nm-order. Important issues to determine the efficiency of these small devices, mass transport properties are greatly different from those in microscopic states. We have studied this phenomenon through a liquid-vapor interface in a water plug by molecular dynamics simulations [1]. In this study, we have focused on the shearing of a nanometer-thick droplet that can be seen between solids that do not have enough lubricants between them. When a channel size is in nm-order scale, a ratio of a liquid-vapor interface domain among a volume of a droplet is much larger than that of a macroscopic droplet. Therefore the momentum transport through a liquid-vapor interface highly affects the total momentum transport, and cannot be ignored. Thus we clarify the effects of the liquid-vapor interface in microscopic droplet.

RESULTS AND DISCUSSION

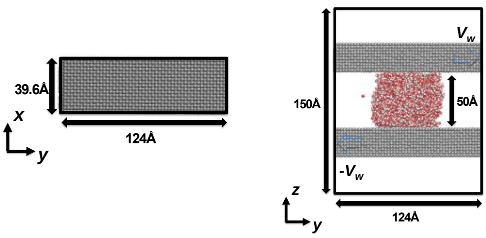

Fig.1 Simulation model.

Figure 1 shows a micro channel model of this simulation. This model is composed of two parallel slabs that have a FCC (001) surface. Two solid walls move along y direction and in an opposite manner. The velocity of the upper wall was set at V_w, and the velocity of the lower wall was set at $-V_w$. Figure 2 shows a velocity dependence of a friction force on each region. At both liquid-vapor interface regions, the slope of the force against the wall velocity can be calculated as 4.4×10^{-13} N/(m/s). This means that there is no difference between the dynamics along the advancing direction and that along the receding direction in terms of the increasing rate of the force on the liquid-vapor interface.

ACKNOWLEDGMENTS

We carried out simulations by the super computer of Advanced Fluid Information Research Center of Tohoku University.

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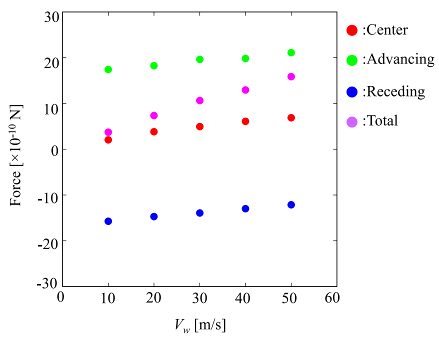

Figure 2 Velocity dependence forces. Red dots show force on the center region, green dots show right interface, blue dots show force on the left interface, and purple dots show the total friction force.

T3-8 Surface topography

TRIBOACTIVE SURFACES IN MULTI-ASPERITY NANOTRIBOLOGY

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ABSTRACT

Friction and adhesion phenomena in microsystems (MEMS) need to be accurately controlled but with a MEMS design which has to be as simple as possible [1]. An interesting way is to design specific surfaces – so-called *triboactive* – whose frictional behavior can be controlled in real time by using external stimuli, as temperature, UV, electric or magnetic fields etc [2]. Frictional behavior occurring in air is generally influenced by two different components, which could be controlled separately [3]:

- (i) the *physico-chemical* one, which can be driven by creating patterned surfaces whose the adhesion behavior is likely to be predicted by means of wettability models [4];
- (ii) the *mechanical* one, of which there are not accurate predictive models [3]. Hence, an alternative way consists of grafting stimuli-driven self-assembled monolayers (SAM) on the rubbing surfaces [5];

In this work, *n*-octadecyltrichlorosilane (OTS) have been grafted on various micro-pillars created by Deep Reactive-Ion Etching (DRIE) of silicon wafers. This multi-architectured surfaces have then been tested with a *ball-on-disc* nanotribometer CSM Instruments (F_n: 3 mN, ball: Si_3N_4 ∅ 1,5 mm) working in linear reciprocating mode, under various environmental conditions. Whereas the pillar's height is always fixed at 10 µm, their shapes and pitches are changed in order to test various wettability models – as *Cassie-Baxter* or *Wenzel* ones [4]. The Cassie-Baxter model can be applied in the densest pillars' area while the Wenzel one matches with weakest pillar's area. Since the frictional behavior of OTS monolayers is known to be thermally sensitive, the temperature of the structure is imposed during the tribological test by using a Peltier module.

Results reveal that the frictional behavior can be accurately controlled in a range of 0.1 to 0.04 by simply varying the temperature from 0 to 80°C. This decrease is mainly due to a reversible increase of disorder (or entropy) within the monolayer [3], without any degradation in this range of temperatures. On the contrary, silicon micro-architecture quickly suffers wear by a shearing process at the bottom of the pillars whatever the DRIE pattern design. The structure's degradation process has been studied with a finite element model on ABAQUS. This process can be attributed to an additional adhesion force in the Cassie-Baxter's area and to an increase of the contact pressure on each pillar in the Wenzel's area.

In order to keep the thermal ability to control the frictional behavior without suffering any wear process, same kinds of patterns are then created on silicon by using micro-contact printing process instead of DRIE [7]. This approach is a soft lithography that uses the relief patterns on a master polydimethylsiloxane (PDMS) stamp to form patterns of self-assembled monolayers (SAMs) as ink on the surface of the silicon substrate through conformal contact.

As a result, nanotribological testings reveal that the wear process of the nano-printed surfaces is strongly reduced in regard to above one. In addition, it can be highly reduced by controlling the printed pattern while the frictional behavior is always thermally-controlled. Hence, a new wear model of SAMs which takes into account the pitch of the printed pattern will be presented and discussed.

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INVESTIGATION OF MATERIAL TRANSFER IN SLIDING FRICTION –TOPOGRAPHY OR SURFACE CHEMISTRY?

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ABSTRACT

To differentiate between the roles of surface topography and chemical composition on initial material transfer in metal forming an aluminum tip, representing the work material, was put into sliding contact with a polished flat tool material. Both DLC-coated and uncoated tool steel was used. By varying the final polishing step, different surface topographies were obtained.

Pre-test and post-test studies were performed using high-resolution FEG-SEM, EDS and AFM on the tool surfaces.

The study proves the importance of the surface roughness on the initial material transfer and friction. The influence of different surface chemistry is discussed.

INTRODUCTION

A well-known problem during metal forming is work material transfer to the tool, increasing the friction and affecting the surface quality of the following piece, i.e. galling. In this study, a deeper understanding of the initial material transfer is gained, by investigating the influence of the topography and the chemistry.

EXPERIMENTAL

An aluminum alloy (6082) was used as work material and a cold work tool steel (Vancron 40), was chosen to represent the tool. The steel consists of a martensitic matrix with hard phase particles; M_6C carbides (5 vol%) and M(C,N) carbonitrides (19 vol%). A thin DLC coating was deposited on some of the tool steel samples, to represent a different surface chemistry [1].

All steel samples were polished 1 min with a 1µm diamond suspension on a Struers NAP cloth, resulting in a surface with minimum protrusion of the carbides while the carbonitrides protruded 10-15 µm [2-3]. By adding a final polishing step 1, 5 and 10min with a 0, 04 µm SiO_2 suspension on a Struers OPS cloth, the protrusion of the carbonitrides increased to 40-45, 40-55 and 50-70 µm respectively.

The friction coefficient and material transfer were studied in sliding tests performed in situ in an SEM, see **Fig. 1**. This technique facilitates observation of the events that cause a particular friction response. The tested samples were studied in a high resolution FEG-SEM with a low acceleration voltage, which allows detection of very thin films of transferred material. The composition of the surfaces was determined by EDS and the surface topography was depicted with an AFM, **Fig. 2**.

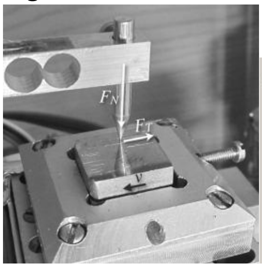

Fig. 1. In situ scratch rig

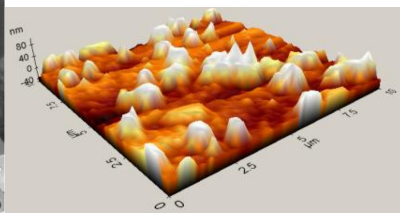

Fig. 2. AFM of Vancron 40 (1 min)

RESULTS AND DISCUSSION

The present results show that the topography of the polished tool steel has very weak direct influence on the friction. However, it influences the tendency to material transfer, which has a strong influence on the friction. For the DLC coated samples this tendency was much weaker.

The results are discussed in detail with respect to their implications for

a) the understanding of the roles of topography and surface chemistry in initiating material transfer

b)the understanding of unlubricated sliding friction, and specifically the dramatic influence from initial tribo-induced modifications of the micro topography, and

c) the industrial problem of galling, including recommendations for the preparation of tools surfaces.

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STUDY ON CUTTING CONTACT INTERCATIONS OF NATURAL FIBER REINFORCED PLASTIC COMPOSITES UNDER MILLING

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ABSTRACT

Finishing operations on natural fiber reinforced plastic (NFRP) composites is becoming a necessity since these green materials are arousing the interest in various industrial applications [1,2]. Unfortunately, the practical finishing setup is difficult and still based on empirical rules because the inherent activated physical mechanisms are still not well understood. This is intrinsically due to the multiscale complex structure of natural fibers within the NFRP [3,4,5]. Various recent studies show that concept of Multiscale Process Signature (MPS) [6] can be used as effective tool to describe the activated physical mechanisms (cutting, ploughing, friction…) during a process of surface modification under cutting [7,8].

This paper aims to identify the MPS of bidirectional woven flax reinforced polypropylene composites at dry milling conditions to track the multiscale effect of machining process variables, such as the tool geometry related to its kinematic, on cutting mechanisms. To this aim, both conventional up-milling and down-milling tests were performed for various helix angles of the tool cutting edge (0°, 20° and 40°) and different tool feed values (0.005, 0.01, 0.02, 0.04 and 0.08 mm/tooth). Friction forces, cutting energy, milled surfaces and interfaces qualities are recorded for each process test condition in order to evaluate the tribo-contact interaction between the NFRP and the cutting tool. Then, the MPS is computed at all the scales of the milled surface topography from roughness to waviness using multiscale approach based on wavelet decomposition.

Results show direct relationship between the quality of milled NFRP surface and the cutting contact geometry. Moreover, the multiscale analysis reveals that this dependence is affected by the cutting scale which governs the activated cutting mechanisms.

ACKNOWLEDGMENTS

The authors acknowledge the urban community of Châlons-en-Champagne (*Cités en Champagne*) for their financial support.

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Proceedings of the 42th Leeds-Lyon Symposium on Tribology
September 7-9, 2015, Lyon, France

Measuring interface conditions in a cutting tool contact with reflected ultrasound

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The measurement of the interface conditions in a cutting tool contact is essential information for performance monitoring and control. In this work, a new method based on the reflection of ultrasound has been evaluated for use in a turning cutting tool. An ultrasonic wave will be partially reflected when it strikes an interface between materials of different acoustic properties. The proportion of the wave reflected depends on the thickness of the layer and its acoustic properties.

A transducer was positioned on the bottom of the insert cutting tool and a pulse propagated through the insert. The pulse was reflected back at the tool chip interface and received by the same transducer. The amplitude of the reflected wave was processed in the frequency domain. Reflection coefficient measurements were then used to investigate the tool-chip interface at different cutting speeds and depth of cut.

Introduction

Contact condition at the interface between the tool-chip has a significant effect on the mechanics of metal cutting. This is because of the interrelationship between the contact condition at the tool-chip interface and the deformation process on the shear plane [1]. Hence, the need to investigate the nature of contact condition at the chip-tool interface is very important. Any change in the contact condition such as contact length or friction result in a substantial change in cutting temperature or energy expenditure, and shear angle [2]. This change again influences tool wear or integrity of the machined surface. Thus, it is very difficult to fully understand the process of metal cutting without detailed knowledge of the contact conditions at the chip-tool interface. Previous studies have measured temperature [3], contact length [4], and cutting forces [5]. However this has not addressed the fundamental tribology contact between tool-chip. The present study aims to do this using ultrasonic reflection.

Instrumentation of a cutting tool

A transducer was bonded to the bottom of the insert. Firstly, the bare element was stuck to the cutting insert using heat resistant glue, and then the bare element with the insert was covered using heat resistant tape, in order to protect the bare element from thermal effects. After that they were pressed together using a G-clamp, and then put in an oven for one hour at 175˚C. Electric wires were soldered on both positive and negative electrodes, and a cable was soldered to the wire as shown in

Figure *1*. The bonded transducer and the wires are covered with an epoxy to prevent the wire from cutting during the machining process. Finally the transducer was connected to the ultrasonic pulser receiver (UPR) which was connected to the digitiser in the PC.

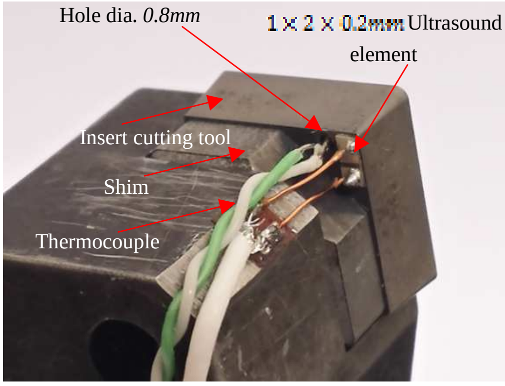

Figure 1: Insert cutting tool with the element and thermocouple

Figure 2 shows the relation between the average values of the reflection coefficient and spindle speed for different cutting depth. At low speeds, the chip maintained contact with the rake surface much longer than at higher speeds. Due to the increased contact length, there is a higher tendency of transmission of ultrasonic waves via the interface. This results in a lower reflection coefficient. At higher speeds, as expected the chip detaches earlier. Therefore, a smaller contact length results in higher reflection coefficient and a reduction in the transmission of ultrasonic waves as shown in figure below.

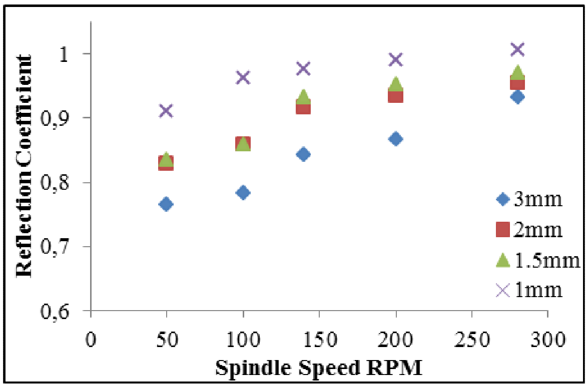

Figure 2: The average reflection coefficients vs. speed of spindle for different cutting depth

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