46th LEEDS LYON

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Author Index

Monday

Sept. 2^{nd}, 2019

46th LEEDS-LYON SYMPOSIUM on TRIBOLOGY

Lyon, 2-4 September 2019

Keynote talk

Cartilage, Contacts and Catheters.

By Nicholas D. Spencer

Surface Science and Technology, ETH Zurich, Switzerland

Our everyday lives involve the articulation of many joints in our bodies, and for the most part, these vital components last for many decades without need of repair. Great progress has been made in the replacement of load-bearing joints by engineering materials, but ultimately better solutions would be either the growth of new, living sliding materials identical to the cartilage that has worn out, or replacement of diseased and worn sliding components with artificial materials with very similar properties to the natural cartilage. We are working on the early stages of the latter approach, using what is known about the behaviour and properties of living cartilage and attempting to imitate it by constructing systems consisting of hydrogels covered by polymer brushes. The knowledge gained from these efforts will hopefully lead eventually to novel implant materials, but in the meantime it will help us to test current theories of joint function, and to develop lubricious polymeric systems that could have applications in other biomedical applications such as contact lenses, intraocular insertion devices, and catheters.

46^{th} LEEDS-LYON SYMPOSIUM on TRIBOLOGY

Lyon, 2-4 September 2019

Keynote talk

Thin Film Lubrication: Molecular Behaviours of Confined Liquids.

By Jianbin Luo

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The behaviour of lubricant molecules within a nano-gap, especially the molecules near the solid surface is very important to the property of the whole tribo-system. Thin film lubrication (TFL) theory has been invoked to characterize the molecular behaviours of lubricant film less than tens of nanometers, which effectively bridged the gap between elastohydrodynamic lubrication (EHL) and boundary lubrication. Unfortunately, the molecular model of TFL which was proposed 20 years ago has not been well proven. Recently a method based on surface-enhanced Raman spectroscopy developed in my group allows us to access the molecular behaviors near the solid surface, along with both the arrangement and orientation of the liquid molecules in TFL regime. The presentation attempts to systematically review the major developments of TFL, including works on experimental technologies, researches, and applications. Future prospects of relevant researches and applications will be also discussed.

46th LEEDS-LYON SYMPOSIUM on TRIBOLOGY

Lyon, 2-4 September 2019

Keynote talk

Oral Friction and Texture Perception of Food: Red Wine, Chocolate and Cream.

By Philippa Cann

Tribology Group, Department of Mechanical Engineering, Imperial College London

It is widely recognised that many food texture attributes, for example creaminess and smoothness, are related to friction experienced in the mouth during eating. Friction is essentially determined by the changing film properties (composition, component distribution, thickness) as the food is masticated in the oral cavity. Currently, the global food industry is making considerable efforts to develop healthy food formulations (less salt, fat and sugar) with acceptable sensory attributes. However, the healthy products, for example low-fat yoghurt, are often disappointing with poor consumer ratings. At present sensory attributes are assessed in panel tests which are expensive, time-consuming and often inconclusive. The development of an appropriate oral-tribology test to measure the friction response of semi-solid foods as they are mechanically degraded could provide an important industry tool. However, the tribology design must be carefully considered if the oral mechanisms are to be simulated in a new bench test and these aspects are considered in the talk. The described approach provides a simple method to assess food friction properties and, if linked to consumer studies, the relationship between mouthfeel properties and preference. It will also provide fundamental insights into food composition and structure changes during mechanical degradation and thus contribute to the development of texture-optimised food formulations.

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HIGH-RESOLUTION LIF-IMAGING OF THE OIL FILM THICKNESS IN THE PISTON-RING / CYLINDER-LINER CONTACT IN AN OPTICAL TRIBOMETER

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KEYWORDS
Friction; Fluid lubrication; Surface topography; Laser-induced Fluorescence

ABSTRACT

The sliding contact of the piston-ring / cylinder-liner assembly (PR/CL) is a major contribution to the frictional power losses in an IC engine, accounting for 45 % of the engine's friction losses [1]. In order to further reduce these losses and improve the engine efficiency, we need to better understand the lubricant film's distribution and dynamics in the contact. Here, a rotational tribometer is used as a model experiment for the PR/CL. It allows investigating the frictional behavior corresponding to global engine operating conditions such as speed, load, and temperature.

One of the main purposes of this model experiment is to use laser-induced fluorescence (LIF) to image the thickness of the oil film between the liner and the piston-ring segment with high spatial and temporal resolution in two-dimensions. For optical access to the contact area, one of the sliding bodies needs to be replaced by a transparent material. In our previous work, in the tribometer this was achieved by a quartz liner [2] or, in a single-cylinder engine, by a sapphire window mounted in the cylinder wall [3]. With this arrangement, the lubricant behavior can be examined with various piston ring surfaces, but the liner surface material must be quartz or sapphire.

In order to investigate the oil-film on liner surfaces as they come from the production line, a new arrangement was developed in this work. As shown in Fig. 1, optical access is created via a sapphire piston-ring segment and a periscope-like mirror arrangement. This allows LIF imaging of the lubricant on a conventional cylinder liner surface, rarely studied in previous works, such as gray cast-iron liner after honing or with a thermally sprayed iron-based coating with fine pores.

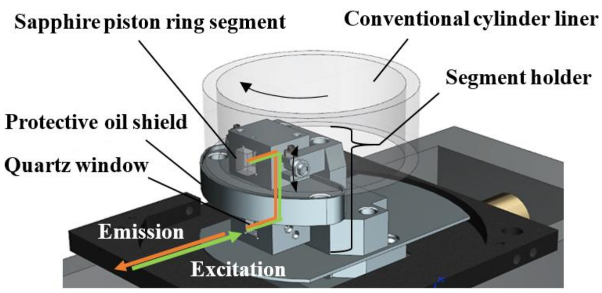

Fig. 1 Optical access in the rotational tribometer for oil-film visualization on a commercial liner surface.

This paper presents the newly developed optical arrangement in the rotational tribometer and results from LIF oil-film imaging. First tests show that the cylinder liner's honing structures as well as the surface pores of sprayed liner coatings can be well resolved. Based on these images, the influence of various test parameters and different liner surface structures on the oil-film behavior and on the minimum oil-film thickness in the contact area is discussed.

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SWITCHABLE FRICTION AT RANDOMLY ROUGH MULTI-ASPERITY INTERFACES THROUGH CAPILLARY CONDENSATION?

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KEYWORDS

Everyday life tribology; Experiments in tribology, Vaporphase lubrication

ABSTRACT

Under ambient conditions, almost all surfaces are covered by a thin water layer. Silicon oxide for instance is covered by 03 nm of water as the relative humidity of the surrounding air is varied from 0-100%[1]. Whenever two surfaces that are covered by such water layers – for instance an AFM tip and a silicon oxide substrate - approach to within a few nanometers, a capillary bridge can form around the contact point[2] and contribute to the contact force, and thus to the friction force. The attractive force exerted by a single capillary bridge is well understood[3-5] and roughly equal to the product of its circumference and the water surface tension. At an interface with roughness, the total contact circumference over which capillary effects can contribute to the effective normal force – and thus the friction - is not trivial[6]. The larger this circumference[7], however, the larger the contrast in friction measured in dry or humid environments. In order to establish friction that can be switched from low to high and vice versa, by externally changing the humidity, we therefore need to understand the roughness- and humidity-dependent capillary force.

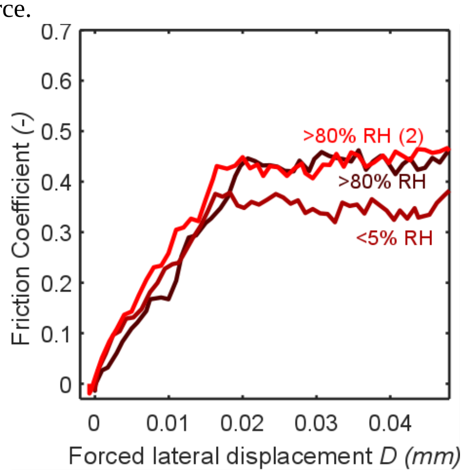

Fig.1 Friction coefficient measured at the interface between a rough SiC ball and a smooth Si wafer. The friction can be switched from high to low and back by changing the relative humidity of the surrounding air.

Here we will present rough sphere-on-smooth substrate friction experiments, conducted in a controlled humidity environment. We will show that friction can be switched from low to high and vice versa by changing the humidity, and compare the friction measurements to multi-asperity contact models that account for capillary effects.

ACKNOWLEDGMENTS

This work is part of the FOM-Programme Fundamental Aspects of Friction, financed by FOM/NWO.

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ELECTRICAL PROBING OF SHEARED METALLIC ROUGH INTERFACES

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KEYWORDS
Experiments in tribology, Physics of friction, Contact and adhesion, Electrical contact resistance.

ABSTRACT
Contact between rough surfaces is realized by tiny contact spots [1] where their number, distribution, shape or their size – so their geometrical properties – depend from the roughness, the used materials, and the stress applied on the contact interface. Many studies describe the multi-contact interfaces state under stresses and are currently used in many ways [1 - 5].

In this work we expose the results of the experimental study about the shear stress applied on multi-contact interfaces made from metallic rough surfaces [5 - 8]. We use different kind of metal (Copper, Steel, Brass…) and different surface polishes to explore a wide range of mechanical parameters. To probe the contact interface, we use a pair of cylindrical samples - sized to have a homogeneous current distribution in the bulk - in which a constant DC current is applied thus to measure the voltage at each end of the set during an increasing shear stress. Through these measurements we deduce the contact resistance vs. the shear stress and so, highlight the contact area evolution.

Results show that the contact resistance decrease with the shear stress. A first hypothesis consists in to consider that either real contact area, the contact number, or both increases with shear stress. As shown in Figure 2, some occasional resistance rises during shearing shows that spots rearrangement phenomena seems to occur.

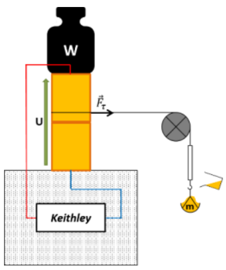

Fig.1 Experimental setup: metallic cylindrical samples in contact, undergoing a normal and a tangential stress. Voltage is measured at each end of the set during the shear increasing.

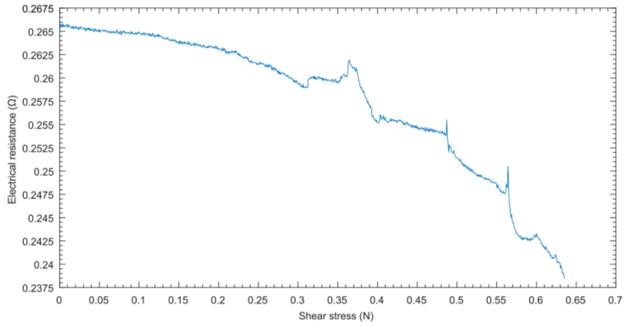

Fig. 2 Contact resistance vs. shear stress of an Al/Al interface

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FRICTIONAL SLIDING OF AN ELASTOMERIC/GLASS CONTACT: EXPERIMENTAL STUDY OF REAL CONTACT AREA

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KEYWORDS
Friction; Experiments in tribology; Contact and adhesion; Real Contact Area.

ABSTRACT

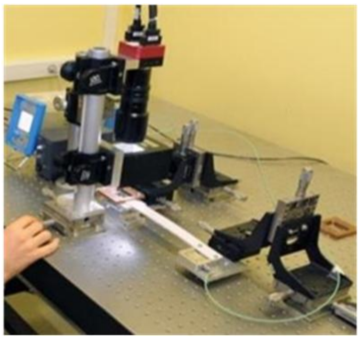
Contact mechanics of elastomers is a crucial issue in many daily applications [1] (e.g. road/tire, shoe/ground or piston /syringe contact) all the more so as new needs have been identified in emerging fields like haptic devices, flexible electronics and remote surgery.

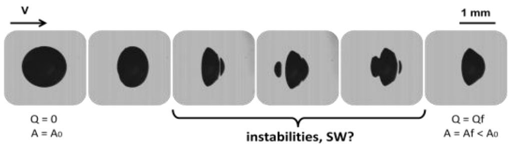
In this context, we studied the dynamics of elastomer/glass contacts near the transition between static and kinetic friction. We carried out experiments on a laboratory-built tribometer (Figure 1a) [2] that allows in-situ imaging and high resolution measurement of the evolution of the real contact area on model sheared interfaces.

Firstly, we study the evolution, under increasing shear, of the real area between a crosslinked polydimethylsiloxane (PDMS) sphere and a smooth glass plate, for a wide range of normal forces, from -0,001N to 5N. We observe a significant anisotropic reduction of the contact area with the increase of the tangential force (Figure 1b). We compare those results with a recent fracture based adhesive models from the literature [3].

Secondly, we report experimental observations and quantitative measurement on how a small initial misalignment of the glass plate can strongly affect the contact dynamics.

Finally, these results on the frictional behavior of single elastomeric contacts represent the necessary basis for designing more complex functional multi-asperity interfaces.


(a)



(b)

Fig.1 In-situ visualization tribometer (a). Evolution of the contact area morphology (in black) in a PDMS/Glass interface during shearing (b).

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REAL-TIME MEASUREMENTS OF PISTON RING AND LINER LUBRICATION AND LUBE OIL INLET VISCOSITY IN A MARINE DIESEL ENGINE USING ULTRASOUND

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KEYWORDS

Mixed Lubrication; Rheology; Fluid lubrication; Experiments in tribology

ABSTRACT

Lubrication between engine piston and liner is vital to prevent direct metal-metal contact and scuffing on the interior of liner to maintain the efficiency of a marine diesel engine. Breakdown of lubrication film results in metal-metal contact and scuffing. This can result in severe damage on interior surface of liner, can reduce engine efficiency, and an result in catestrophic failure. There are currently very few tools available to understand the efficiency of this lubrication process other than monitoring liner temperature, cylinder pressure and periodic invasive measurements of wear.

Real-time monitoring of liner lubricant film and detection of scuffing would facilitate how operating parameters affect engine performance at the critical location. A non-invasive ultrasonic measurement system has been implemented on a test engine to monitor the lubrication in-situ. Longitudinal and shear polarised sensors were mounted on the liner at Top Dead Centre. Low-frequency ultrasound was transmitted to strike the contact interface between engine liner and piston rings. Test results found the returning signals changed with engine operating conditions which suggests that lubrication characteristics can be monitored in real-time using this ultrasonic tool.

In some lube oil delivery mechanisms, the lubricant injection time and rate is dependent on viscosity of the lubricant. Measurement of the lubricant viscosity in feeding channel in-situ would thus be a valuable tool for intelligent injection control and it also provides a robust way to monitor the quality of the lubricant oil.

A bespoke in-situ viscosity sensor is developed and implemented on the lubrication oil feeding channel of a test engine using a novel ultrasonic technique. The lubricant oil is oscillated ultrasonically by a shear polarised transducer. The sensitivity is improved using an acoustically soft material sandwiched between the oil and the transducer. Tests found the ultrasonic signal varied with the engine operating conditions, which suggest that the measurement of lubricant viscosity would enable real-time feedback into injection control system.

A photograph of the in-line viscosity sensors can be seen in Figure 1.

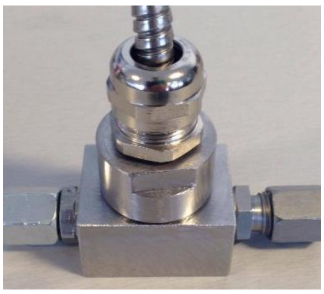

Fig.1 A photograph of the in-line viscosity sensor.

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THE EVOLUTION OF SURFACE DAMAGE ON NiAl-BRONZE DUE TO CAVITATION OF REPEATED SINGLE LASER-INDUCED BUBBLES

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KEYWORDS
surface topography; experiments in tribology; wear; cavitation

ABSTRACT

Cavitation is the formation and collapse of bubbles in liquids caused by pressure changes. Damage of technical surfaces caused by cavitation, due to the bubble collapse occurring close to a solid surface, is an important engineering issue. However, difficulties are encountered to date in modelling and predicting such material damage. When a bubble forms close to a solid surface, its collapse will occur as a complex sequence of liquid-jet formation, movement of the bubble, repeated collapse and re-expansion, partitioning into several bubbles, and the formation of vortices and high-shear flows. Typical studies of cavitation-induced material damage and wear utilize ultrasonic vibration, creating bubble clouds with thousands of collapses per second. Alternatively, for fundamental investigations of cavitation, single bubbles can be created and studied by focusing a short, high-power laser pulse in water. When the material is soft, the bubble's collapse can indent a nearby solid surface in a single event. For most technical alloys, however, repeated impacts are needed to produce detectable damage.

The goal of this study is to correlate the increasing number of collapsing bubbles with the evolving damage on the surface during the incubation phase of cavitation erosion. To this end, single bubbles of 3 mm diameter are repeatedly created in water using a Q-switched Nd:YAG laser focused at a defined distance from the polished surface of samples from NiAl-bronze. The bubble shapes during cavitation events are recorded with a high-speed camera. The resulting damage on the surfaces is quantified using white-light confocal microscopy. The dynamics of "typical" bubbles, as well as those showing an asymmetric collapse behavior are analyzed and correlated with the observed damage patterns.

The results show that until 70,000 bubbles no obvious material removal takes place, and the depth of indentations formed via plastic deformation does not increase, indicating that the material is still in the incubation phase. The soft solid-solution α-phase is indented preferentially, displaying slip lines, and cracks form along the phase boundaries with harder precipitates. When the bubble collapse takes place asymmetrically, the observed damage tends to be deeper, indicating that asymmetric collapse leads to higher shear stresses, causing heavier deformation. Also, frequently two damaged areas appear, because bubbles drift over the surface during repeated expansion and collapse. Therefore, a single bubble can cause several indentations and, if occurring repeatedly, result in more than one damaged region.

The results of this study reveal the wide range of non-uniformity that must be expected in fluid-flow induced cavitation in technical applications, indicating one reason for the difficulties encountered in reliably predicting cavitation erosion.

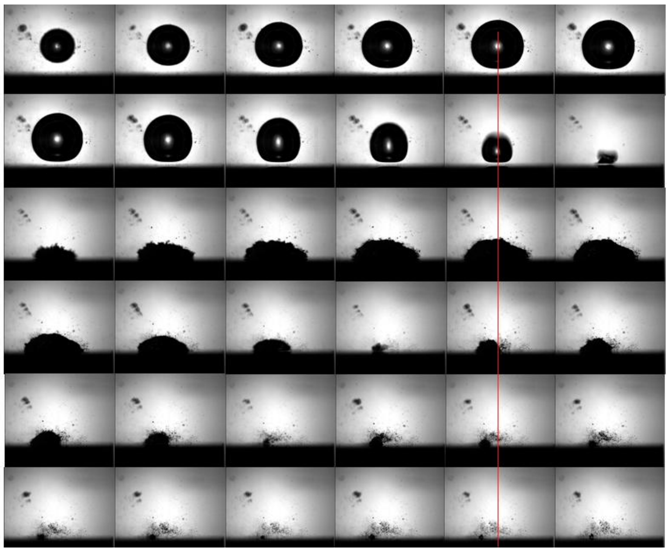

Fig.1 Single cavitation bubble drifting towards the left during repeated expansion and collapse.

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NON-LINEAR DYNAMICAL EFFECTS IN FRICTIONAL ENERGY DISSIPATION

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KEYWORDS
Keyword: Nano Tribology; Modelling in Tribology; Friction; Non-linear Dynamics, Chaos in Friction

ABSTRACT

Dynamics in friction is studied from an atomistic point of view. Friction is formulated as a problem of whether or not a given kinetic energy for the translational motion dissipates into the kinetic energies for the internal motions during sliding. From the study of the Frenkel-Kontorova model (FK model) with kinetic energy terms, it is found that two different regimes appear in a parameter space specifying the FK model: the superlubricity and the friction regimes. We have also found the peculiar frictional behavior at the specific frictional parameters, showing the abrupt decrease in the sliding velocity at unexpected time while superlubricity appears for a while, i.e. the upper body slides at constant velocity for a while after it has been pushed along sliding direction at initial sliding velocity. It has been observed that the state of superlubricity has collapsed and the catastrophic reduction of the sliding speed has occurred. This paper discusses to elucidate how the catastrophic transition for the appearance of friction occurs from the viewpoint of non-linear dynamics and chaos.

The atomistic origin of friction forces stemming from atomic interactions has been investigated from both of theoretical and experimental viewpoints [1-5]. We have for the first time defined the atomistic origins of static/dynamic friction and superlubricity for clean surfaces and potentially offers a rigorous solution to this problem [2]. Graphitic nano-structured materials have been recently explored to test this idea [3-5]. The ultralow friction forces have been identified at scales from a few micrometers [5] to large macro scale [6].

This study has examined the one-dimensional Frenkel-Kontorova atomistic friction model, given by

$$H = \sum_i^N \frac{p_i^2}{2} + \sum_i^N \left\{ \frac{1}{2} k (x_{i+1} - x_i - \ell)^2 + \frac{f}{2\pi} \sin(2\pi x_i) \right\}, \quad (1)$$

where, p_i, x_i k, ℓ, and f stand for the momentum of atoms, the atomic position, the inter-atomic interaction, the mean distance between two adjacent atoms, and the amplitude of friction energy. This is one-dimensional dynamic Frenkel-Kontorova model with kinetic energy terms. The periodicity length of the sinusoidal potential in Eq. (1) is taken as a unit, while ℓ is assumed to be equal to the golden mean number $\ell = (1 + \sqrt{5})/2$. To examine the frictional properties including superlubricity, the dynamics has been studied after the upper solid surface at the ground state is pushed with initial sliding velocity $P(0)$ with the Hamiltonian dynamics conserving the energy. The friction dynamics is studied by examining the quantities such as mass center velocity $P(t)$, mass center position $Q(t)$, and the sliding distance defined as the distance over which the upper solid surface slides during time. These quantities are obtained by numerically solving Eq. (1) by using the velocity Verlet algorithm. The high-resolution friction phase diagram, where friction and superlubricity regimes is described in a parameter space specified by the two parameters such as the initial sliding velocity and the magnitude of friction energy determining friction forces, has been presented. The two distinct regimes representing the appearance of friction and superlubricity, and their boundary have been determined in the friction phase diagram. We have discucussed the spectral analysis and the Poincaré mapping in phase space for the atomic oscillation appeared in the FK model in sliding motion and proposed the role of the non-linear dynamics appeared in the friction and superlubricity.

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SEVERE DEFORMATION OF PEARLITIC STEEL DURING MICROSCALE TRIBOLOGY

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KEYWORDS
Wear; Physics of friction; Experiments on tribology; Micromechanics

ABSTRACT

Tribology at the macroscale is the collective interaction of micrometer asperities as well as the evolution of microstructures below the surface. Wear resistant surfaces depend on an understanding of these evolution mechanisms and on developing tailored surface layers and microstructures.

This contribution starts with a comparison of macroscale and microscale tribology. In this study, we investigate the severe microscale deformation mechanisms of pearlitic steel, i.e. the ferrite and cementite composite, during single stroke wear experiments. We perform microtribology experiments using a diamond indenter and observe severe irreversible cementite deformation strains on the order of tens of percent. We detail the multiple deformation mechanisms and compare them to the observations from literature [1,2]. Additionally, we use microcantilever experiments with and without a pre-crack to understand the origin of the ductile cementite deformation (see Fig. 1). The samples without pre-cracks are used to determine the amount of irreversible deformation in the absence of ferrite support. We will close with a discussion of the temperature evolution in the microscale contact and the discussion of cementite ductility. As such, we argue about the mechanisms that result severe microscale deformation in pearlite.

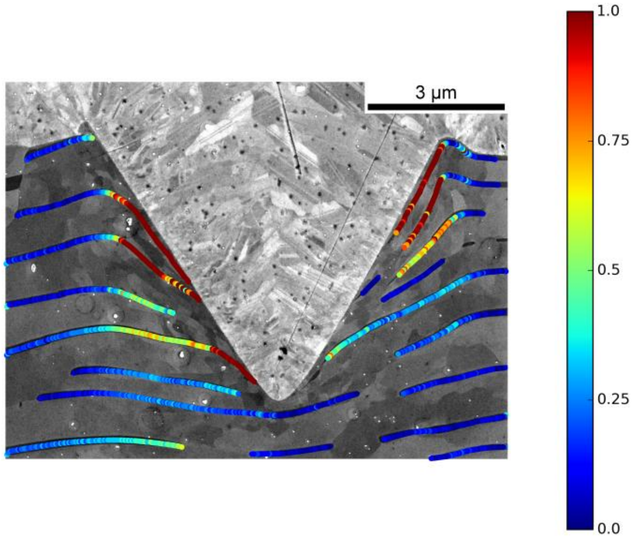

Fig.1 SEM image of cross-section after microscale tribology with superimposed shear strain distribution in cementite lamellae

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We acknowledge the valuable contributions of the summer internship students Haleh Taghinejadi and Chris Talbot of Cambridge University.

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ENHANCING OF CUO NANOLUBRICANT PERFORMANCE USING ORGANIC DISPERSANTS

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KEYWORDS

Nanotribology; lubricant additives; friction; organic dispersants

ABSTRACT

In this paper will be exposed to the influences of the use of organic dispersants agents to avoid agglomeration of tiny CuO nanoparticles in the synthetic oil, developing nanolubricants with good stability at low concentration of oxides. The stability of the suspensions, state dispersive of the nanoparticles, morphology and size distribution will be reported. The tiny nanoparticles (2.5, 4.4 and 8.6 nm) were added to PAO oil with the aid of three organic dispersants in PAO oil at a low concentration of 0.1wt%. The tribological performance of nanolubricant was evaluated under boundary lubrication conditions. The dispersion results showed more uniform size distribution of the NNP dispersed in lubricant oil when toluene was used as the dispersant. Furthermore, this dispersant provided a substantial decrease of the friction and lower losses by wear. A good dispersion provides friction coefficient and wear reductions.

INTRODUCTION

The main challenge in using nanoparticles in lubricants is related to their dispersion in liquids because the metal nanoparticles easily agglomerate due to their high surface tension. This agglomeration results in many problems, such as clogging and contact starvation [1]. This problem can be solved by surface modification technique or using organic dispersants. In the first technique, it is common the use of a coating with high molecular weight hydrocarbons, like oleic acid. Also, toluene, ethylene glycol, and hexane have been used as organic dispersant [2-3]. The tiny nanoparticles are more susceptible to increase antiwear property and reduce friction [3]. Therefore, nanoparticles agglomeration can act negatively in lubrication [4]. This study aims to evaluate the nanolubricant with tiny CuO NNP of three sizes and its performance improvement using organic dispersants.

METHODOLOGY

CuO nanoparticles were prepared by an alcothermal method using copper nitrate, sodium hydroxide, and ethanol as starting materials in microwave reactor. Three sizes of nanoparticles were produced (2.5, 4.4 and 8.6 nm). They were characterized by DRX and MET. After that, the nanoparticles were covered with oleic acid for surface modification and added to PAO with the aid of three dispersant agents (Toluene, Hexane and Ethylene Glycol) at 0.1wt % of concentration. The nanolubricant stability was measured by visual analysis and characterization by UV-visible, zeta potential analysis, and small angle X-ray scattering- SAX). Tribological tests were performed in tribometer HFRR using a highly stressed ball against a disc. The ball slides against the disc fully submerged in 2 mL of lubricant under a 1 mm stroke length at a frequency of 20 Hz at a normal load of 10 N m/s for 60 min. The wear was analyzed by scanning electron microscopy (SEM). After, the suspensions were collected and analyzed chemical, morphology and stability changes.

RESULTS AND DISCUSSION

Considering good stability and tribological performance (Friction coefficient reduction) the best results were found to Toluene, followed by Hexane and Ethylene Glycol. Also, an important observation was that no changes in nanoparticle geometry and the stability were verified after the tribological test when Toluene was used as dispersant agent by UV visible analysis.

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THE EFFECT OF MICRO-EHL AT ASPERITY SCALE ON THE SIMULATED STRIBECK CURVE OF CONFORMAL CONTACT MIXED LUBRICATION

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KEYWORDS

Mixed Lubrication; EHL; Modelling in tribology; Conformal contact

ABSTRACT

The experimental work of the conformal contacts such as plain bearings have proved that the flat-on-flat surface can form a hydrodynamic effect under lubricated condition. Various numerical models have been developed and tried to explain the mechanism of such hydrodynamic effect. Stochastic models take the average of roughness on the lubricated tribo-pairs. The output of stochastic models are average pressure distribution, film thickness distribution, and average fluid flow of the lubricated gap, which are quite difficult to be verified by experiments. In contrast, the deterministic models can predict parameters which are easily to be measured such as the coefficient of friction (COF).

In the previous deterministic models developed for conformal contacts, the fluid regime and asperity contact regime were calculated separately [1]. The coupled effect of fluid and asperities was ignored. This effect also can be defined as micro-EHL at asperity scale. In this paper, the effect of micro-EHL at asperity scale is included in the modelling of conformal contact mixed lubrication. Published Stribeck curve results about thrust bearings with plain surfaces [2] are used to verify the proposed model. The results obtained based on previous model are also compared with the experimental results and the simulated results by the proposed model considering the micro-EHL effect at asperity scale.

Fig.1 shows the simulated Stribeck curves with and without the effect of micro-EHL at asperity scale and the experimental results reported in Reference [2]. Fig.1 also shows the percentage of contact load in the applied load. The plots clearly illustrate that only the simulated Stribeck curve with the effect of micro-EHL at asperity scale matches very well with the experimental results. And the corresponding contact load ratio significantly decreases with the increase of speed. Without the effect of micro-EHL at asperity scale, the deterministic models can't correctly predict the Stribeck curve, and the corresponding contact load ratio decreases slowly compared with the results obtained with the effect of micro-EHL at asperity scale.

In this paper, the effect of micro-EHL at asperity scale on the simulated Stribeck curve of conformal contact mixed lubrication was addressed. The results proved the significant role of the micro-EHL at asperity scale in the mechanism of forming load capacity under conformal contact mixed lubrication.

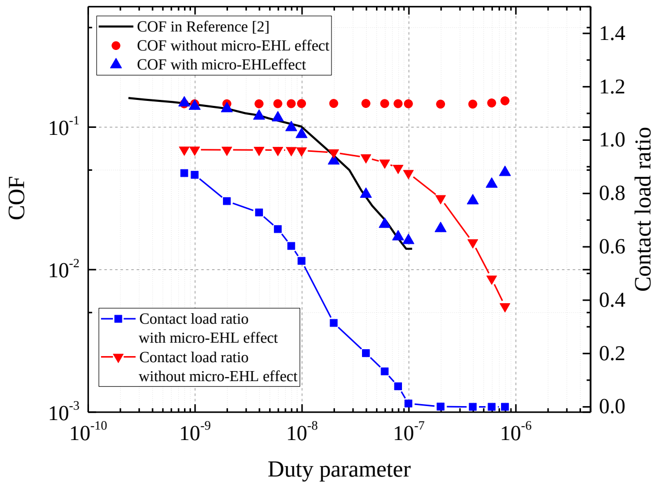

Fig.1 Comparison of simulated and experimental Stribeck curve and contact load ratio results with and without the micro-EHL effect at asperity scale

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MORPHOLOGY-DEPENDENT FRICTION OF ADSORPTION FILMS: MOLECULAR DYNAMICS OF SDS AND CTAB AT THE H_2O | AU(111) INTERFACE

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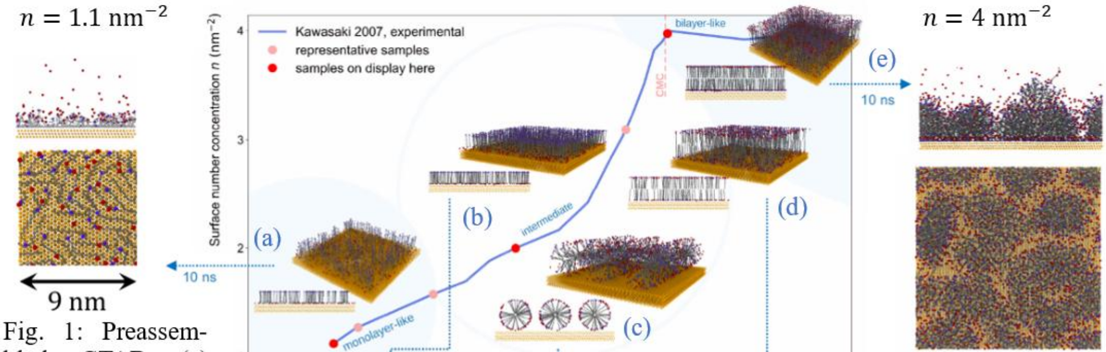
KEYWORDS
Modelling in tribology; Nanotribology; Lubricant additives; Friction force microscopy

ABSTRACT

In solution, amphiphilic surfactants aggregate on immersed surfaces. The resulting physisorbed film exhibits morphology-dependent boundary lubrication behavior, in particular with respect to the static and kinetic friction coefficient in the stick-slip regime [1]. In order to illuminate this interdependence of morphology and friction on the nanoscopic scale, our present work focuses on two model surfactants of broad application in industry and science: the anionic sodium dodecyl sulfate (SDS) and the cationic cetyltrimethylammonium bromide (CTAB), at idealized water–gold interfaces. We utilize existing SDS and CTAB parametrizations to conduct numerical atomic force microscopy (AFM) and friction force microscopy (FFM) experiments by means of classical all-atom molecular dynamics (MD).

Adsorption films and their nanotribological properties are typically characterized by AFM probing. Such measurements yield topographic profiles, but the conclusion upon a film's underlying structure is not straightforward and oftentimes debated: Are observed patches actually mono-, bi- or multilayers? Are stripes to be interpreted as hemicylinders or cylinders? In our sample case of SDS and CTAB on Au(111), both surfactants are known to form flat-lying monolayers at low concentrations. With increasing surface coverage, stripe-like aggregates assemble. These are of hemicylindrical nature in the case of SDS [2], whereas CTAB has been argued to form full cylinders [3]. At these concentration regimes, equilibrium MD of postulated film aggregates do not necessarily distinguish physical from non-physical configurations: Fig. 1 shows both (b) dense monolayers as well as (c) cylindrical aggregates of CTAB to behave metastable throughout MD-typical time scales. Thus, we map out force-distance curves on AFM probe approach towards substrates covered with different film morphologies across a range of concentrations as well as anisotropic lateral forces felt by an FFM probe tangentially sliding on these films. Contrasted against the response in experimental reality, we investigate how such measurements might help to discriminate between competing interpretations of AFM measurements.



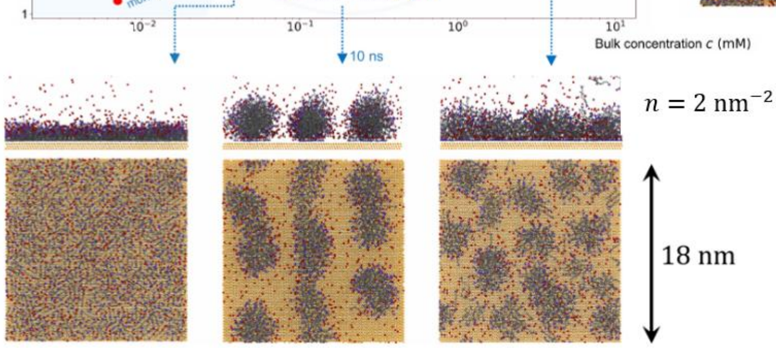


Fig. 1: Preassembled CTAB (a) monolayer at low, (b) mono-, (d) bilayer and (c) cylinders at intermediate as well as (e) bilayer at high coverages n on Au(111) along experimental adsorption isotherm (center) [4] and evolved after 10 ns.

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FRICTIONAL REGIMES ON SOME PARTICULAR, NATURE-INSPIRED APERIODIC ATOMIC CHAINS

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KEYWORDS

Friction; Surface topography; Modelling in tribology; Prandtl-Tomlinson models

ABSTRACT

Inspired by the role of irrational numbers and that of the most prominent one: the golden ratio, in particular, frequently observed in the arrangement of leaves and seeds in various plants, e.g., red cabbages and sunflowers, this contribution will aim to clarify the frictional peculiarities of such aperiodic atomic configurations based on so-called analytical models of friction.

Nowadays, the Prandtl-Tomlinson models (PT-models) in one- and two-dimensions are very popular for their explanation of nanotribological experiments performed by using a friction or atomic force microscope (AFM). [1] In its original formulation, [2] Prandtl was introducing this model for developing a kinetic theory of solids by assuming a periodic interaction between the bodies. Curiously, in the paper ascribed to the PT-models, [3] Tomlinson was not dealing at all with these, since he was outlining a molecular theory of friction based on the findings by Lennard-Jones. Despite of this historical inaccuracy, currently in a 1D PT-model, one can clearly distinguish between frictional regimes by considering as parameter the ratio between the average interaction and elastic energies, [4] for an illustration see Fig. 1.

In this contribution, the aperiodic corrugation of interest is derived and directly introduced into the corresponding 1D PT-model such that the so resulting Newtonian equation of motion is then solved numerically by applying an adequate fourth-order Runge-Kutta method. [5] The frictional behavior of such a system will be also discussed, especially in comparison to "engineered" periodic corrugations.

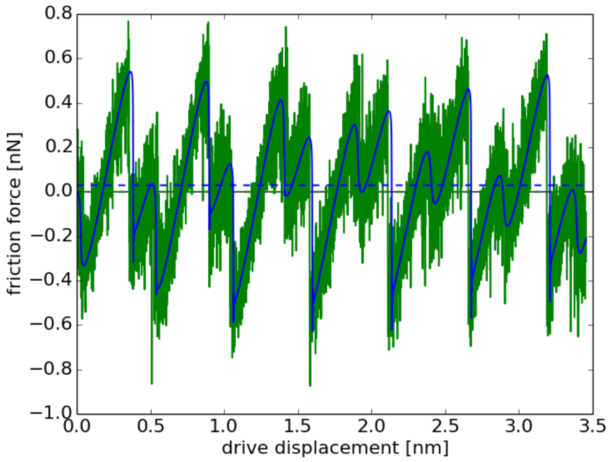

Fig.1 Friction force at 0 K (blue) and room temperature (green) obtained from a 1D PT-model with a periodic corrugation.

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PHONONIC EXCITATIONS DURING SLIDING FRICTION

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KEYWORDS
Modelling in tribology; Friction; Physics of friction; Phonons

ABSTRACT
The Prantl-Tomlinson model is frequently used to explain friction phenomena on the atomistic scale [1]. In this model energy dissipation is often modelled as viscous damping. The associated damping parameter is typically guessed or fitted to experimental data. This description lumps all microscopic dissipation channels into a single constant and allows no conclusion on the atomistic mechanism of energy dissipation.

Fundamentally, energy dissipation in friction is due to the excitation of lattice vibrations, the phonons. We study the coupling of external sliding to the phononic modes by means of large-scale molecular dynamics (MD) simulations for both crystalline and amorphous solids. The atomic interaction in our model systems are modelled using a modified Lennard-Jones potential.

In order to understand which phonons are excited by the external action of a sliding object, we carry out non-equilibrium MD simulations of a sliding Hertzian indenter. Decomposition of the resulting displacement field into contributions from vibrational modes allows to extract the excitation of phonon modes due to the external sliding action. Figure 1(a) shows typical displacement fields of selected phonon modes for an amorphous solid. We show that in particular low-frequency modes are excited. While low frequency modes in crystals are plane waves and follow the Debye prediction, plane-wave like phonons and quasi-localized modes coexist in amorphous solids [2,3,4]. The type of phonon mode in the amorphous solid plays a crucial role for energy dissipation.

By additionally measuring lifetimes of normal modes, we predict the energy dissipated by the sliding indenter. The lifetimes are computed from total-energy autocorrelation functions [5]. Figure 1(b) and (c) demonstrate the lifetimes of the crystalline and the amorphous solid. We show that the empirical viscous dissipation constant in the Prantl-Tomlinson model can be described by the collective decay of phononic modes excited during sliding.

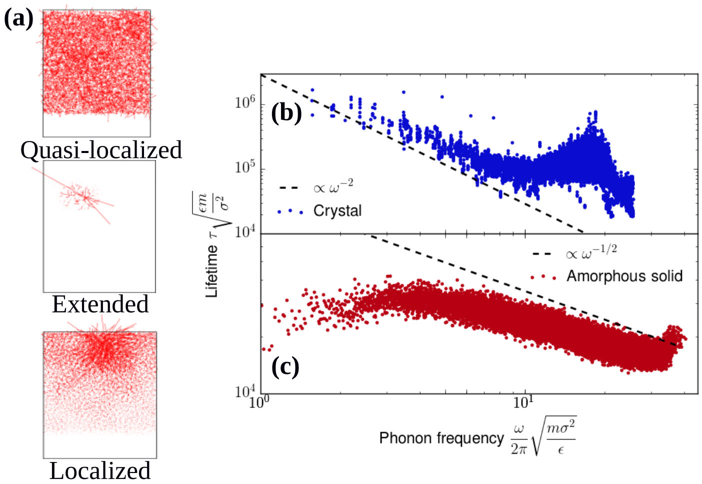

Fig.1: (a) Displacement field of normal modes in a model amorphous solid showing exemplary a low-frequency quasi-localized, an intermediate frequency extended and a high-frequency localized mode. (b) Measured lifetimes of vibrational modes of the crystal. (c) Measured lifetimes of vibrational modes of the amorphous solid.

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MD SIMULATIONS OF FRICTION AND WEAR OF FUEL SURROGATES

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KEYWORDS

Fluid lubrication; Nanotribology; Friction; Wear

Keywords list:
- Friction
- Rheology
- Rolling contact fatigue
- Coating
- Lubricant additives
- Biotribology
- Mixed Lubrication
- Surface topography
- Experiments in tribology
- Physics of friction
- Texturation
- Wear
- Fretting
- Solid lubrication
- Fluid lubrication
- Tribofilms and 3rd bodies
- Hydrodynamic Lubrication
- EHL
- NanoTribology
- Modelling in tribology
- Contact and adhesion
- Everyday life tribology

ABSTRACT

The application of carbon-based coatings to engine components has become increasingly more common. Coatings, such as ultrananocrystalline diamond (UNCD) and amorphous carbon (a-C:H) can have a wide-range of properties but are generally attractive due to their wear resistance. At the same time, alternative fuels, such as Catalytic Hydrothermal Conversion Jet (CHCJ), diesel (CHCD) and others are being developed. Because these fuels are complex, surrogates for these fuels have been developed so that impacts of changes in composition on properties and combustion can be studied. To date, little effort has been devoted to the study of the interactions of these fuels with engine coatings. The results of molecular dynamics (MD) simulations using both the REBO+S and the ReaxFF potentials, that examine the interaction of two- and three-component CHCJ surrogates with carbon-based engine will be presented.

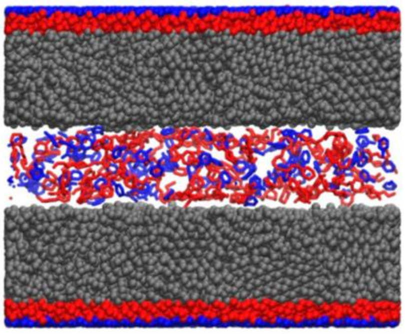

Fig.1 This is a snapshot of a molecular dynamics simulation system. In this system, a 50:50 mixture of toluene (blue molecules) and butylcyclohexane (red molecules) are confined between two ultrananocrystalline, UNCD, coatings (gray spheres). Hydrogen atoms on the confined fuel molecules are not shown for clarity. The outer red and blue UNCD layers are thermostated and held rigid, respectively. The distance between the rigid layers is changed to control the load and the upper surface is slid to the right to simulate sliding.

Your abstract should be submitted **via the website**, http://leeds-lyon2019.sciencesconf.org/

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WETTABILITY@Al_2O_3: ADSORPTION OF LUBRICANT ADDITIVES BY MOLECULAR MODELING

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KEYWORDS

Contact and adhesion; Lubricant additives; Modelling in tribology; Wettability

ABSTRACT

In lubricant development, changes in formulations triggered by modifications of legislations, might affect the behavior of the lubricant towards the surface. This can lead to modifications of the wettability properties and the ability of the lubricant to spread over the surface. Better wettability involves a better adhesion of the lubricant on the surface and a faster wettability kinetic. Therefore, it is important to better understand the interactions between the lubricant and the surface, and how wettability can be linked to the lubricant formulation.

In this study, we use density functional theory calculations to describe the interactions at the interface between the lubricant and the surface.

Here, we focus on industrial lubricants for applications in metal working, especially on aluminum sheets. As aluminum oxidizes immediately when exposed to air, γ-Al_2O_3 has been chosen as a model for the surface. The major interaction of the lubricant with the surface comes from the additives it contains. For this reason, the solid-liquid interactions studied here are the ones between the surface and the functionalized head groups of the additives, which is equivalent to consider that their carbon chains are all the same. This study has been conducted on a wide range of head groups: polar molecules, apolar molecules, functionalized aromatics and phosphorous compounds.

By comparing the adsorption energies of different additives on the surface and their solvation energies in a model lubricant base oil, we aim at determining the influence of the different types of additives in the wetting process. Indeed, it has been shown that up to a certain point, solid-liquid interactions favor the wetting of the surface [1]. As a consequence, good additives should have the tendency to go to the solid-liquid interface rather than to stay in the liquid bulk. As the solvation energies obtained for the different head groups are quite similar (Fig. 1), they are not a significant parameter to discriminate the additives, contrary to the adsorption energies. Phosphates and carboxylic acid are the most adsorbed head groups (Fig. 1). For this reason, the additives containing these head groups should improve the lubricants wettability on aluminum sheets better than the ones containing head groups which are less adsorbed as water, alcohols and esters for example.

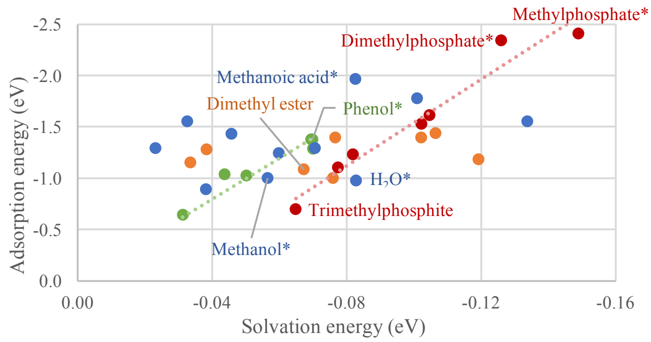

Fig. 1 Comparison of adsorption and solvation energies for various head groups: polar molecules (blue), apolar molecules (orange), functionalized aromatics (green) and phosphorous compounds (red). * indicates dissociative adsorptions.

In conclusion, the results obtained are consistent with previous studies, showing that acids are improving dynamic wetting of an oil on aluminum better than alcohols and esters [2] and that phosphates are better lubricant additives that phosphites, as the friction coefficient of an oil on aluminum can be reduced by adding phosphates whereas phosphites are increasing it [3].

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GREASE FLOW BASED ON A TWO-COMPONENT MIXTURE MODEL

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KEYWORDS
Rheology, Fluid lubrication, Modeling in Tribology, Grease.

ABSTRACT
Greases are complex materials that are widely used as lubricants in tribology. Despite the increasing sophistication of models for many tribological materials and applications, those for grease are not much different than in the 1960s. The likely reason, as pointed out by Cann [1], is that there is little agreement among researchers as to the basic physical mechanisms at work.

Greases consist of a thickener of a fibrous material or a porous polymer, impregnated with a base oil. Roughly stated, the function of the thickener (the lower layer of Fig. 1) is to hold the lubricant mixture in place, and the function of the oil in the upper layer is to provide the lubrication itself. In this work, grease layer is considered to be a two-component mixture: a highly viscous non-Newtonian thickener and a base oil. The interaction between the two components is the porous media mixture law of Darcy-Brinkman [2].

The figures illustrate some preliminary results of this study.

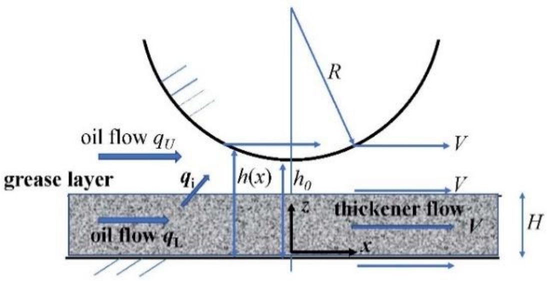

Fig.1 Schematic of grease layer in cylinder/plane rolling contact. The gap contains a lower grease layer (thickener plus oil) supplying an upper oil film.

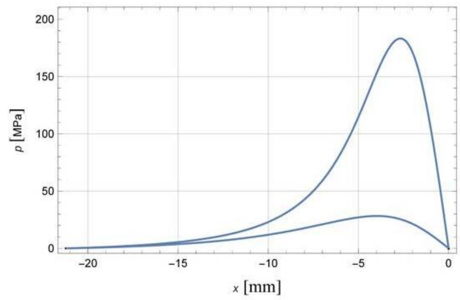

Fig.2 Pressure profiles in rolling contact, two cases. For the lower curve, the gap is pure oil; for the upper curve, a grease layer is present.

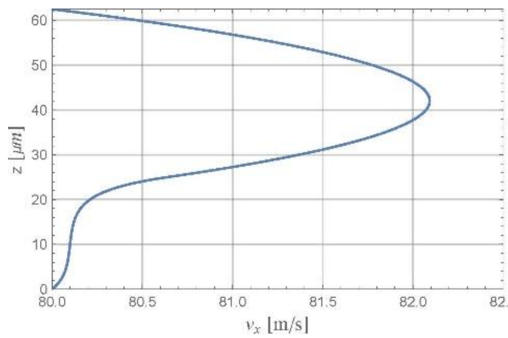

Fig.3 Typical oil velocity profile in rolling contact at a location of negative pressure gradient. Upper portion of the curve is pure oil, the lower portion is oil flow in thickener.

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NUMERICAL SIMULATION OF HYDRODYNAMIC LUBRICATION BY SPH METHOD

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KEYWORDS
Hydrodynamic lubrication; Fluid lubrication; Modeling in tribology, Numerical simulation

ABSTRACT

Appropriate boundary conditions are required to solve Reynolds' equation for hydrodynamic lubrication. Especially, oil film rupture at the outlet of lubricated area has been an intense subject of interest [1]. It is difficult to predict exactly both the position at which oil film rupture will occur and the pressure in the area of oil film rupture.

To correctly solve the problem of boundary conditions, we applied Smoothed Particle Hydrodynamics (SPH) method [2] to hydrodynamic lubrication. Spontaneous film rupture can be simulated with SPH. However, nonphysical fluctuations in pressure profiles may develop and prevent a simulation for a long time [3]. Actions of surface tension on inside particles, and a discontinuity in between free-surface and the nearby particles cause fluctuations.

To avoid the occurrence of nonphysical fluctuations, we developed a new way to calculate surface tension which includes an accurate detection of free-surface particles [4] and rearrangements the particles for the smoothness of the free-surface by an optimized particle shifting scheme [5].

Pressure profiles by SPH simulation with the newly developed surface tension calculation show a good agreement with the FEM approach [1], see Fig. 1. The method also allows to compute hydrodynamic lubrication cases with a smaller amount of lubricant, therefore under starved condition as shown in Fig. 2.

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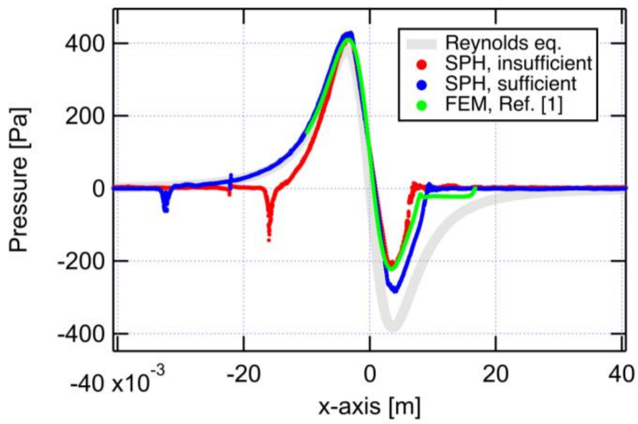

Fig. 1 Comparison of pressure profiles

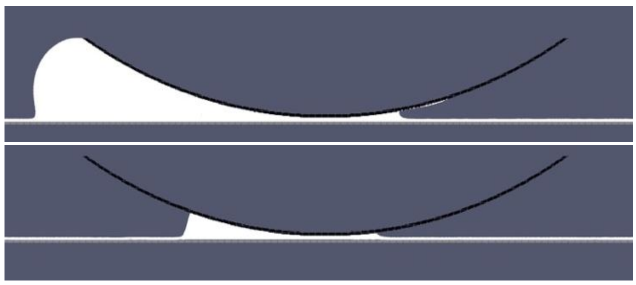

Fig. 2 Snapshots of hydrodynamic lubrication with sufficient (upper) and insufficient (lower) lubricant film, model geometry and condition are same with the Fig.3(a) of ref. [1].

CHARCATERIZATION OF GREASE AGING BASED ON CHEMICAL AND MECHANICAL DEGRADATIONS

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KEYWORDS
Rheology, modelling in tribology, EHL, grease

ABSTRACT
Greases used for rolling bearings lubrication are subjected to high thermal and mechanical solicitations [1] that can lead to the loss of grease lubricating properties. [2] It causes wear, serious materiel damage and safety hazards for users. The aim of this work is to develop an empirical model of grease aging based on chemical and mechanical degradations.
A series of experiments on fresh greases was first conducted in order to reproduce their real aging conditions. The impact of mechanical degradation was studied by the shearing action of a grease worker (155 to 180 rpm at 105 °C, NF ISO 2137). The chemical degradation by oxidation was evaluated on air at 130 °C.

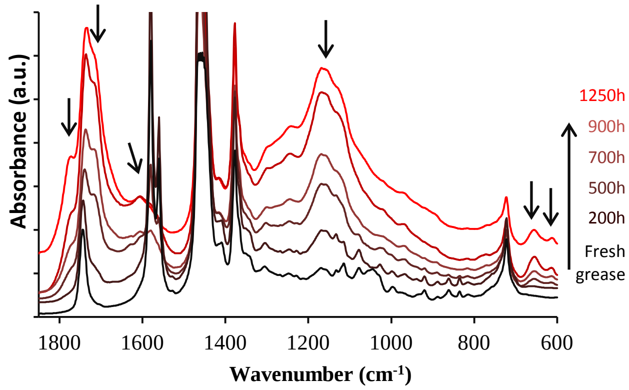

Fig.1. IR spectra of fresh grease oxized from 200 to 1250h at 130 °C from 600 to 1800 cm^{-1}

The chemical structure of the grease is clearly modified by oxidation as seen by IR spectroscopy (Fig. 1). From 200 to 1250h of oxidation, in comparison with fresh grease, several new bands for example located between 1780 and 1700 cm^{-1} appear corresponding to new carbonyl species (aldehydes or ketones). [3] In addition, the thickening carboxyl bands located at 1580 and 1560 cm^{-1} disappear after an oxidation time of 500h. [4].

Grease oxidation and shearing affect its ability to lubricate (Fig. 2) as seen in rheology with the drastic flow point decrease from 24h of shearing from 1328 to 238 Pa.s. These degradations are confirmed by Scanning Electron Microscopy (SEM) (Fig. 3) for the thickener separated from the oil. The grease thickener is a matrix of fibers characterized by a large surface area. Oil is held in the holes formed in the matrix. Long twisted fibers are observed for fresh thickener. But oxidized fibers soften and tend to aggregate and sheared fibers are broken. The degradations by oxidation and shearing impact the thickener/oil chemical interactions, the morphology and the mechanical stability of greases that cause the oil bleeding.

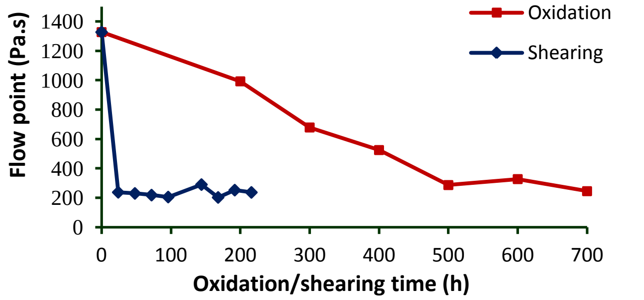

Fig. 2. Impact of churning time on fresh grease flow point

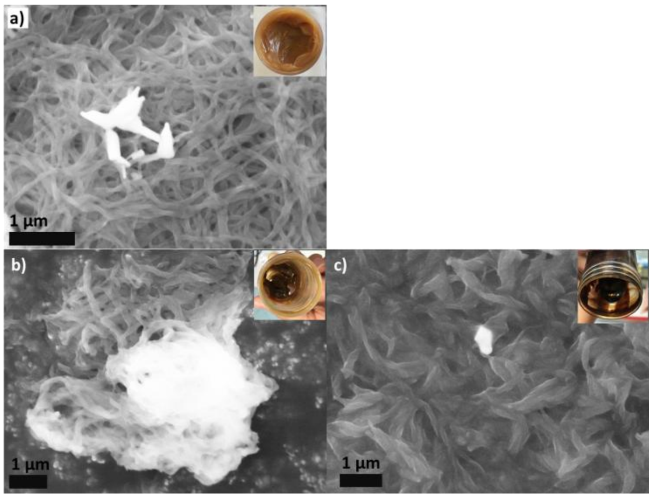

Fig. 3. SEM images of: a) fresh thickener, b) oxidized thickener c) sheared thickener

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HYDRODYNAMIC LUBRICATION THEORY FOR AN EXACT BINGHAM PLASTIC FLUID MODEL

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KEYWORDS

Hydrodynamic Lubrication; Fluid lubrication; Rheology; Smart fluids

ABSTRACT

Grease is an important lubricant in modern tribological systems, yet modelling of these fluids in thin lubricating films is hard due to the discontinuities in the rheological properties caused by the yield stress. A good method to model this behaviour is especially relevant in the design of bearings using Magneto- or Electrorheological fluids.

In [1], [2] an approximation of the lubrication theory of a Bingham plastic was presented based on a regularization technique (Bingham-Papanastasiou) to take care of the discontinuity. This method is a numerical approximation and relatively slow.

The method presented in this work does not require this regularization technique, and thus uses the exact Bingham Plastic rheological model. This makes the method fully analytical and therefore relatively fast. The method furthermore starts with an assumed surface stress value, which is iteratively modified to match the given surface velocity.

Figure 2 and Figure 1 show the resulting flow fields for both a full numerical approximation (double Riemann integral of stress distribution) , the numerical approximation presented by [2] and the analytical method presented in this work. The results show that the different methods are in good accordance.

The analytical integration of this flow field gives the flow rate. A pressure distribution is achieved by solving for the pressure, using conservation of mass, similar to the classic Reynolds equation approach.

ACKNOWLEDGMENTS

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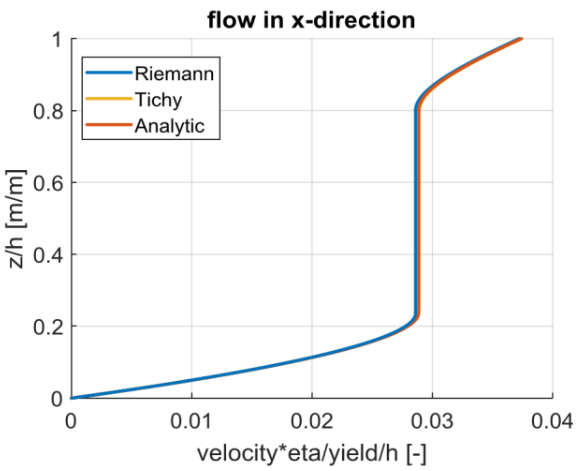

Figure 1 : Typical flow field in x-direction for a Bingham fluid with the use of different methods.

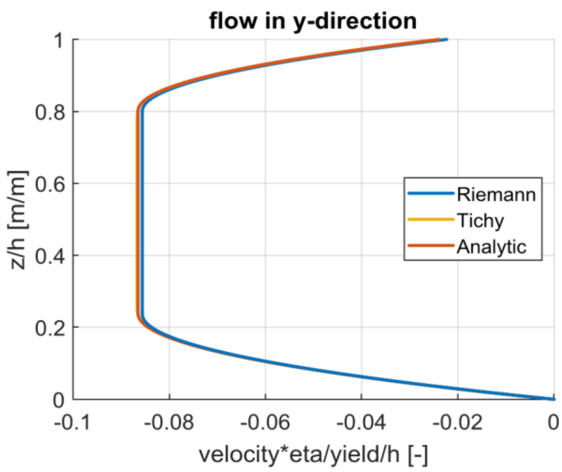

Figure 2 Typical flow field in y-direction for a Bingham fluid with the use of different methods.

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VISCOSITY INDEX IMPROVERS FROM FIRST-PRINCIPLES IN-SILICO SCREENING

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KEYWORDS
Lubricant additives; NanoTribology; Modelling in tribology

ABSTRACT
Reducing fuel consumption and emissions in transportation has become a main challenge for society. One way to achieve this is by focusing on the reduction of friction between engine parts, to improve overall efficiency. To control the film thickness between the sliding surfaces in an engine, the main factor appears to be the viscosity of the lubricant and more generally its rheological behaviour as a function of temperature and pressure. Adjusting the viscosity of base oil lubricants can be achieved via Viscosity Index Improvers (VII). VIIs enable finer control of the viscosity as a function of temperature and pressure, e.g. by increasing overall viscosity at high temperature, to counteract the lower base oil viscosity without affecting the low temperature behaviour. Over the years, advancements in VIIs technology have been focused on either modifying chemistries or manipulating the structure and architecture of traditional VI polymers. The mechanisms behind the functionality of VI additives are still poorly understood and, therefore, the release of disruptive, innovating polymers is scarce and limited.

In this work, we propose a molecular modelling and simulation framework (Fig.1) for in-silico screening of VIIs. Our framework uses machine learning algorithms to predict novel polymer compositions and structures, based on fitness functions compounded from thermodynamic, chemical and viscoelastic properties obtained via hybrid first-principles based multiscale modelling. More specifically, this involves: a) systematic coarse-grained polymer structure and composition model building stage, b) a machine learning (ML) stage to evolve and determine the best performing structural and compositional (including polar groups) cues from the non-linearities in viscosity vs shear-rate, from a first-principles derived coarse-grain force field, c) a systematic atomistic to coarse-grain mapping scheme to determine the closest off-the shelf polymer compositions that reproduce the coarse-grain models interactions, d) a characterization stage to determine the atomistic scale thermodynamic, chemical, viscoelastic and rheological mechanisms that distinguish high performing VIIs, from our 1st principles reactive and polarizable molecular dynamics simulation methods, and e) an experimental validation stage to synthesize the best performing VIIs determined from the in-silico strategy, within the top-down optimization cycle.

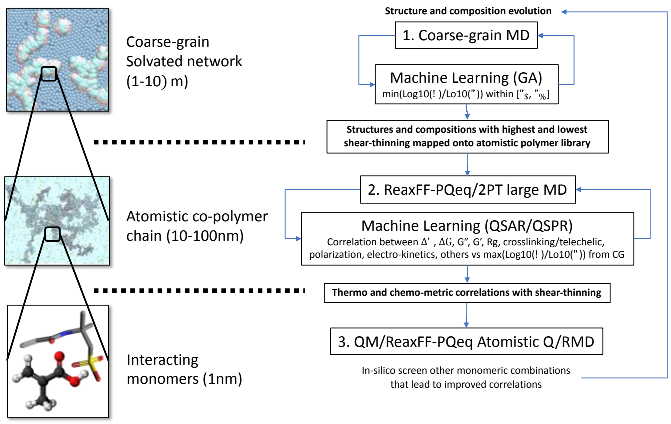

Fig.1 In-silico multiscale screening framework for development of enhanced VIIs, incorporates breakthrough technologies from the group at CALTECH including the reactive force field and molecular dynamics method ReaxFF[1], the polarizable force field PQeq[2], the 2PT method[3] for entropy and free-energy from short MD runs, the multi-objective ML framework [4], and others.

ACKNOWLEDGMENTS
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DESIGN AND ANALYSIS OF A HYDRAULICALLY CONTROLLED MECHANICAL SEAL FOR NUCLEAR APPLICATIONS

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KEYWORDS

EHL; Modelling in tribology; Fluid lubrication; Seals

ABSTRACT

Nuclear reactor coolant pump (RCP) multi-stage seals occasionally exhibit excessive leakage or, less frequently, insufficient leakage from the first stage. To mitigate such problems, it would be desirable to employ a seal in which the leakage could be controlled manually or by an automatic control system.

In the present study the operation of such a seal, to replace the first stage mechanical seal in conventional RCP seal systems is simulated. To vary the leakage, the geometry of the non-rotating seal face is varied. Two options are considered: i. a carbon graphite face with multiple internal cavities containing hydraulic fluid at controlled variable pressures, and ii. a stainless-steel face with a single internal cavity containing hydraulic fluid at a controlled variable pressure. These options are simulated with a soft elastohydrodynamic analysis consisting of a Reynolds equation solver coupled with a finite element deformation analysis. The results show that both of these options yield sufficiently large control ranges, as shown below. In addition, it is apparent that this conceptual design could be applied to any controlled leakage seal where predictable control of leakage is desired.

Fig. 1 Leakage rate vs. cavity pressure, multi cavity carbon graphite face.

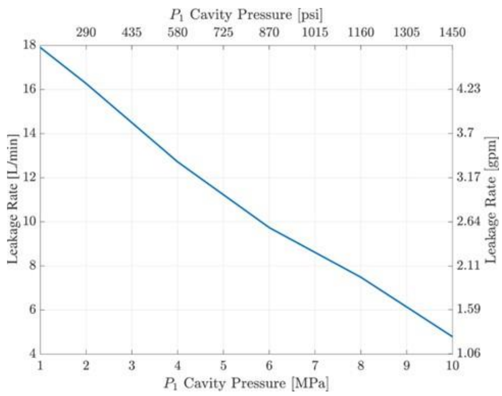
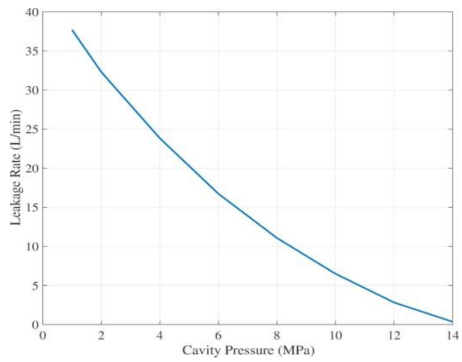


Fig. 2 Leakage rate vs. cavity pressure, single cavity stainless steel face.



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MODELS FOR TWO-COMPONENT LUBRICATION FLOW

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KEYWORDS
Rheology, Fluid lubrication, Modeling in Tribology, SEALS.

ABSTRACT

The present paper is a contribution to a special session honoring Professor Emeritus Richard F. Salant of the Georgia Institute of Technology in the US. Professor Salant is perhaps best known for his innovative work on seals in which he has drawn upon models for lubrication flow behavior and applied them to seals in an original and unique fashion. In particular, he has incorporated Reynolds equation flow factors [1]-[2], and what he calls 'soft' elastohydrodynamic analysis [3]-[4]. Regarding his body of work as limited to seals is far too restrictive and does not do him justice. The present author has used these same notions (flow factors and soft EHL) as applied to chemical mechanical planarization (CMP) with some success and recognition [5]-[6].

The original motivation for this work is the need for applicable models for grease behavior. Grease is considered to be a two-component mixture: a highly viscous thickener and a base oil. Roughly stated, the function of the thickener is to hold the lubricant mixture in place, and the function of the oil is to provide the lubrication itself. Two models are presented for the interaction between the two compliments: a porous media mixture following the well-known law of Darcy; and the flow factor approach, originally proposed by Patir and Cheng, and cleverly applied by Salant to seals.

The paper will develop predictive models based on these two approaches. Figure 1 below shows a result of the porous media model. A negative pressure gradient is applied to a simple channel. The velocity profiles of the thickener and the oil are shown, as well as an aggregate flow velocity of the mixture. Flow resistances are due to viscous forces as well as the interaction between the two components.

A complete development will be presented in the paper along with a corresponding model for the flow factor approach.

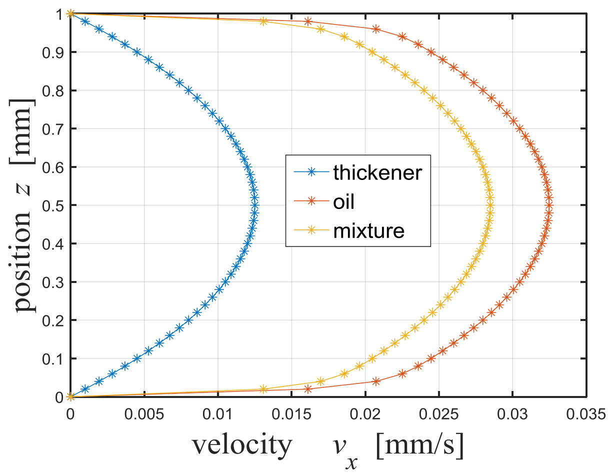

Fig.1 Velocity profiles in channel flow of grease, Darcy-Brinkman model

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TRANSPORTATION OF LIQUID AND DISSOLVED GAS AND THEIR DEPENDENCE ON SURFACE TOPOGRAPHY IN RADIAL SHAFT SEAL

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KEYWORDS
Surface topography; Fluid lubrication; Modelling in tribology; Seal

ABSTRACT
The sealing function of radial shaft seals originates from the hydrodynamic force to pump oil back at narrow gap between a seal lip and a shaft. This hydrodynamic effect is produced by surface roughness on the lip surface. Previous experiments revealed that surrounding gas in one side of the seal is transported to the other side, and that his occurred through convection of gas dissolved oil, as shown in Fig. 1. Further study demonstrated that simple protrusions produced disturbance and gave rise to axial flow of oil and transportation of gas, which did not occur with a smooth surface.

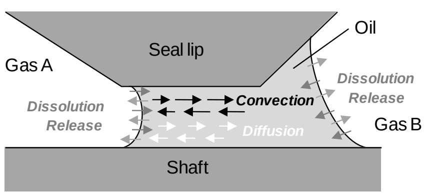

Fig.1 Gas transportation at seal lip

In this study, a numerical analysis is made in order to understand the effect of surface roughness on the axial flow of oils and transportation of dissolved gas. Random asperity models are made to represent variations in asperity spatial distribution. The flow between a rigid rough stationary surface and a rigid smooth moving surface is solved by the finite-difference method. The rate of gas transportation is obtained by assuming convection of the oil and boundary films at gas/oil interfaces. The results show that the asperity spatial distribution affects the direction and rate of the oil flow, and the flow rate of gas. No clear relationship can be found between the oil flow and gas transportation. Properties of surface roughness that control oil and gas flow are discussed.

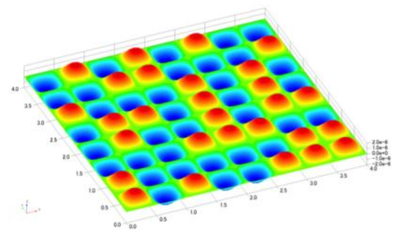

Fig. 2 Random distribution model

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OPTICAL INVESTIGATIONS INTO ROTATING AND OSCILLATING RADIAL LIP SEAL CONTACTS

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KEYWORDS
Mixed Lubrication; Surface topography; (soft) EHL; Radial Lip Seal

ABSTRACT

In continuation of earlier work [1, 2], an optical radial lip seal test rig was set up implementing a servo direct drive, a transparent sapphire hollow shaft, and a high resolution high-speed CCD camera attached to a stereo microscope (fig.1). Complementary to the previously used total internal reflection white light illumination approach, the light was now directly and nearly radially fed into the sealing contact via the tilted mirror used for radial redirection of the optical path (i.e., very similar to [3]). Using this technique, the actual elastomer asperity / sapphire contacts appear as dark regions, while cavities within the elastomer contact topography appear as dispersed bright areas and spots; the presence of lubricant leads to a noticeable contrast attenuation within the wetted regions of this contact pattern.

A first series of optical investigations was conducted at room temperature and low sliding speeds up to approx. 0.2 m/s (CW/CCW stationary rotation), and oscillation of ±90° with a frequency up to approx. 2 Hz, respectively. The tested sealing systems were plain FKM radial lip seals lubricated with polyglycol (PG), and NBR seals lubricated with mineral oil (MO). The lubricants were pure base oils without any additives. The test seals had been previously run in on a standard steel shaft (CW stationary rotation at 5 m/s, 36 km sliding distance, 60 °C sump temperature).

In both sealing systems, each during stationary CW/CCW rotation as well as during oscillation, the asymmetric tangential distortion of the elastomer seal lip contact topography could clearly be seen from the contact pattern brightness distributions. In addition, axial oscillations of individual contact spots were consistently observed, clearly indicating the “stretch effects” previously described in [4]. Moreover, during oscillation, the angular positions of zero sliding velocity do not coincide with the angular end positions of the shaft, as could be assumed at first glance. Instead, as soon as the angular position corresponding to maximum sliding speed (and, therefore, corresponding to maximum viscous and contact shear forces) is passed, the circumferentially distorted seal lip starts to deform back; in the meantime, the shaft passes through the angular end position, until, in the reverse direction, at a certain angular position, the shaft surface velocity reaches the surface velocity of the seal lip, thus resulting in zero sliding velocity. Then, the same behavior is seen in the remaining part of the oscillation cycle, i.e., in the reverse direction.

In the constantly CW rotating NBR/MO sealing system, the oil on the air side of the seal lip was pumped to the oil side, until a stationary size of the air side oil meniscus was reached; in the opposite rotation direction, the meniscus slowly increased. No clear oil transport was seen during oscillation. In the constantly CW rotating FKM/PG system with its lower wettability, the entire air side lubricant was quickly pumped to the oil side, i.e., the meniscus was apparently totally ingested into the sealing contact, thus leading to starved lubrication in a large air side portion of the contact beyond the seal lip pressure maximum [5]; in the reverse (CCW) direction, the oil leaked back to the air side. During oscillation, this behavior was cyclically reproduced. Thus, it could be demonstrated that meniscus ingestion strongly depends on the wetting behavior of the entire sealing system, as can be inferred from [5].

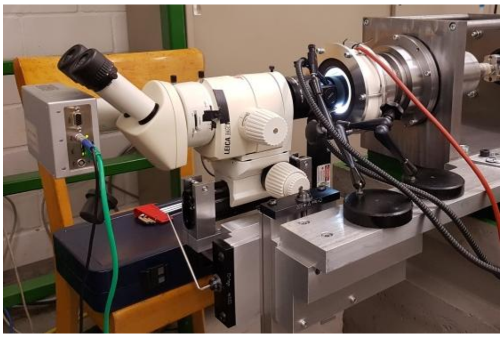

Fig.1: Optical radial lip seal test rig

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NUMERICAL MODELLING OF A GREASE LUBRICATED PNEUMATIC SEAL

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Keywords: mixed lubrication; modelling in tribology; friction; seal

ABSTRACT

This work addresses the numerical modeling of greaselubricated pneumatic sealing systems. An EHL model have been developed by coupling a non-linear commercial software (Abaqus) with an unsteady Reynolds equation. Mixed lubrication and non-Newtonian rheological behavior of the lubricant are taken into account. Comparison with experimental measurements are made for two different piston velocities and pneumatic pressures. Starved lubrication conditions seems to be a key aspect in obtaining good friction force predictions.

MODEL DESCRIPTION

The numerical model used in this study has already been presented in reference [1]. It consists in creating a new element in Abaqus, called Reynolds User Element (RUE) that deals with the interface between the seal and the cylinder. The RUE solve the Reynolds equation by taking into account mixed lubrication conditions, mass conserving and grease rheology. A U-Cup 100 mm in diameter classical piston seal is investigated. The seal is tested experimentally on a specific test bench and the friction force has been determined as a function of piston velocity and pneumatic pressure [2]. It has been observed that the friction increases with both the velocity and the pneumatic pressure. In addition, the friction force values are of the same order in both directions of movement (outstroke and instroke).

NUMERICAL RESULTS

Visualizations made with a transparent cylinder show that, after one outstroke/instroke cycle, the contact zone is only supplied by a thin lubricant layer deposed on the cylinder. Therefore, it seems incorrect to impose, as a boundary conditions, a fully supplied lubricated contact. Indeed, the first simulations showed that if starvation lubrication conditions are not taken into account, the numerically predicted friction force is much lower than that measured experimentally. More importantly, great differences are predicted between the instroke and the outstroke movements. Also, the overall friction decreases with increasing piston velocity, which contradicts the experimental measurements.

A second series of simulations was performed by imposing a given quantity of lubricant present in the contact inlet. In this case, the numerical simulations predict an increase in friction force as a function of piston velocity and similar friction values during instroke and outstroke movements (Fig. 1). The absolute values of the friction forces are directly influenced by three numerical parameters: the effective film thickness applied as a boundary condition in the inlet zone, the lubricant apparent viscosity and the friction coefficient used to compute the tangential shear stress generated by the asperity contact pressure. Unfortunately, these parameters have not been measured experimentally. The friction coefficient was considered to be 0.2, a value already used in previous work for elastomer/steel contacts. Different sub-micrometer values for the effective film thickness have been tested and their influence on the friction force seems to be very important. Also, even if the rheological behavior of the grease has been measured on a conventional rheometer, the film thickness predicted numerically in the contact zone is two orders of magnitude smaller than the film thickness used to identify the grease rheological behavior. It is than assumed that the apparent viscosity of the lubricating fluid is close to the base oil of the grease.

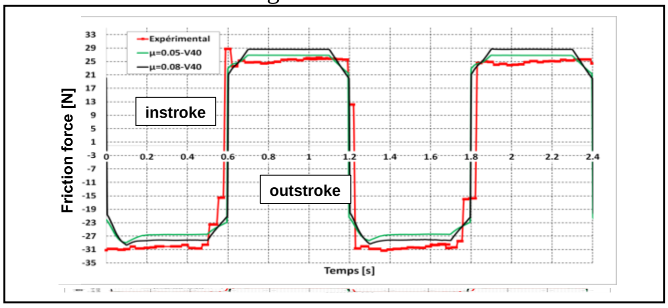

Fig.1 Variation in friction during two instroke/outstroke cycles at 40 mm/s

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CAVITATION IN A WAVY MECHANICAL SEAL

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KEYWORDS
Hydrodynamic Lubrication; Modelling in Tribology; Surface Topography, Mechanical Seal

ABSTRACT
Mechanical seals are sealing devices for rotating shafts. They are composed of two flat annular rings whose contacting surfaces ensure the fluid sealing. These surfaces, even with a good surface finish, always exhibit some residual surface waviness of typical amplitude of 1 micron [1]. The circumferential height variations due to these defects promots hydrodynamic pressure generation in the interface as well as cavitation in diverging areas. Payvar and Salant [2] proposed a well-known model for this type of problem. They highlighted the impact of the rotating speed on the extent of the cavitation zone in steady-state operation. However, in real configurations, both seal faces are wavy leading to a transient problem. In the present work, the behavior of a mechanical seal with two wavy surfaces is studied.

The cavitation model used in this paper was presented by Brunetière [3]. The transient lubrication model was developed by Cochain [4] and is based on the finite element method. The configuration of the problem is described in Table 1. Each seal ring has two waves of amplitude w_r, for the rotor and w_s for the stator. The resulting transient film thickness h is

$$h = h_0 + w_r \sin(2\theta + 2\omega t) - w_s \sin(2\theta)$$

θ is the angular position and ω the rotating speed. h_0 is the central film thickness. It is recomputed at each time step to ensure the axial forces balance.

Table 1 Configuration of the problem

Parameter	Value
Outer, inner radii	14.62 and 11.14 mm
Waviness w_r, w_s	0.5 and 1 µm
Outer, inner press.	1 and 0.1 MPa
Duty parameter G	$\frac{\mu\omega}{2\pi B \Delta p} = 6.3 \times 10^{-7}$

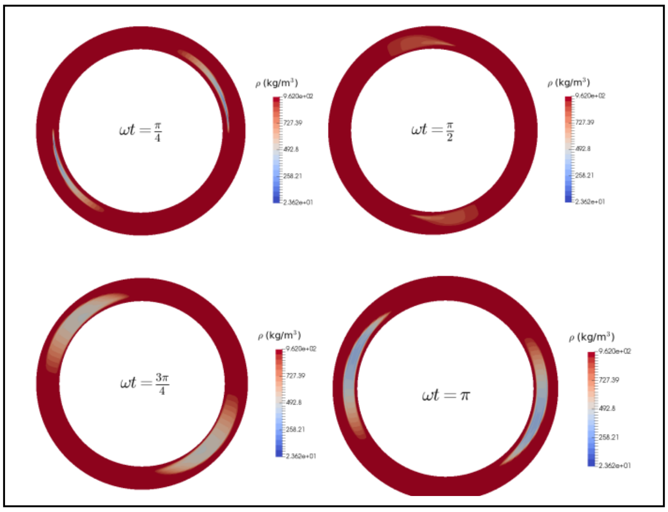

Fig.1 Fluid density of the film at different times

Figure 1 presents density distribution within the contact at different times. The cavitation zones extent and location change with time due to the evolution of the film thickness. The cavitation is due to the hydrodynamic effect promoted by the height variation and to the squeeze effect due to the change of h_0 with time.

ACKNOWLEDGMENTS
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FILM FORMATION AND TEMPERATURE DEVELOPMENT IN TEXTURED RECTANGULAR FACE SEALS

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KEYWORDS
Texturation; friction; film thickness, hydrodynamic lubrication, rectangular face seals

ABSTRACT

Rotary connections are used, inter alia, in automatic transmissions to transfer pressurized oil into actuators. For a proper function, sealing components are important in rotary connections. These usually seal axially. For this purpose, rectangular seal rings, which are a special type of face seal, are particularly suitable since they provide low leakage and high durability. Rectangular seal rings operate at high pressures and together with high speeds, significant friction losses occur, which also lead to a high thermal stress on seal and lubricant. Therefore, optimization of the seal rings in term of friction is particularly important to increase the efficiency in transmissions. One of the optimization methods of the seals is the reduction of the resulting normal contact force via hydrostatic or hydrodynamic load reduction. While the pressurized area on the seal contact surface can be decreased for hydrostatic load reduction, macro structures are used to enhance lubricant film formation in hydrodynamic load reduction [1]. The current project investigates rectangular face seals with pockets (hydrostatic load reduction) and macro structures (hydrodynamic load reduction) in terms of film formation and temperature development in the sealing contact. For this reason, friction torque and mean contact temperatures of a group of seals were measured. For detailed investigation, film thickness in the sealing contact was determined with fluorescence method and temperature development in the contact area was monitored via thermal camera.

To measure film thickness with fluoroscence method, an optical test rig, which was developed in previous works [2], is used [Fig. 1]. The visualization of the sealing contact area is realized with a counterface made of sapphire. The sapphire counterface provides high thermal conductivity and a similar surface roughness to an actual run-in steel counterface, therefore replicating the conditions of the real tribosystem more realistically compared to a glass counterface. An appropriate fluorescent dye dissolved in the lubricant emits fluorescence radiation when excited by light. By means of a microscope, the emitted light is forwarded to a CCD camera. Since both the excitation and emission wavelengths of the dye are known, optical filters are used to pass on the desired wavelength, so that the fluorescence is captured selectively. The emitted light is a measure of the dye concentration present in the sealing area and thus also the amount of lubricant. Thus, the lubricant film thickness distribution is obtained from fluorescence intensity. In addition, the contact temperature is also determined by replacing the microscope with a thermal camera. Experiments are carried out at different pressure and speeds.

Fluorescence method is described and film formation in rectangular seal rings is analyzed depending on macro and micro surface structure. The behavior of the seals with pockets to generate hydrostatic effects seems to be dominated by surface roughness effects and is thus stochastically distributed on the load carrying surface. The film formation and thermal behavior of the structured seals dominated by concentrating cavitation and pressure generation.

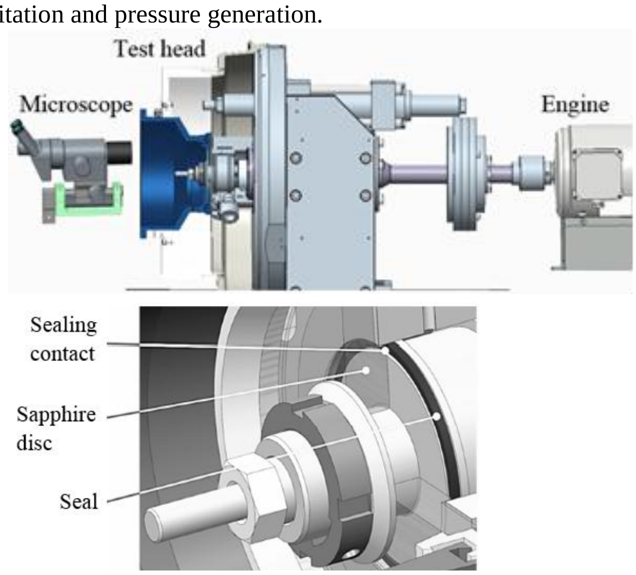

Fig. 1: Experimental set-up and the detailed view of the test head from [1]

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THIN FILM LUBRICATION OF A HYDRAULIC ROD SEAL EXPERIMENTAL STUDY USING ELLIPSOMETRY

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KEYWORDS
Hydrodynamic Lubrication; Fluid Lubrication; Experiments in Tribology; Seal

ABSTRACT
Hydraulic cylinders are widespread linear actuators and have become indispensable in daily life machinery. They are used under harsh conditions in a variety of industries like aeronautics, agriculture machinery, heavy industry, mining or medical technologies. One of the critical components of a hydraulic cylinder is the rod seal. If the rod seal fails, leakage is the result. Consequences are downtime and environmental damages. For these reasons the rod seal has to be well designed.

The variety of industries need individual and customized sealing systems, but all of them demand zero leakage, a low friction coefficient, little wear and a long lifetime. These requirements strongly dependent on the lubrication conditions in the sealing gap.

Simulation models to analyse the lubrication conditions of rod seals are subject of decades of research. In recent papers Salant simulated fluid film generation depending on sliding speed [1]. Further theoretical studies have been summarized by Nikas [2]. Analytical models do not completely explain the experimental data sufficient, since tribological mechanisms in the sealing gap are not completely understood.

After an outstroke there is always a thin oil film on the hydraulic rod, Fig 1. The oil film allows conclusions on the lubrication conditions and the gap height of the rod seal. Hörl has shown that this film is in nanometer-scale and that it can be measured precisely using ellipsometry [3]. Compared to other measuring methods, ellipsometry can be used to analyse fluid film generation on practical hydraulic sealing systems and operating parameters like stroking velocity, fluid pressure and temperature. Measurements can be made around the circumference of the rod. Due to high vertical and lateral resolution the ellipsometer allows the analysis of stick slip phenomena in axial direction, Fig. 1.

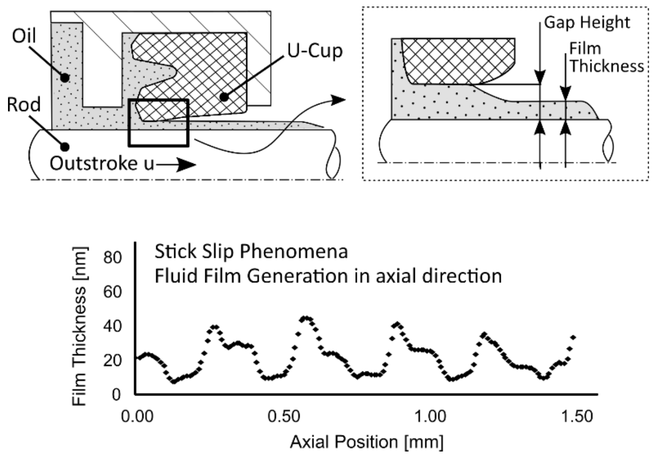

Fig.1 Film Thickness on a Hydraulic Rod

Ellipsometry is presented as a promising used measurement method to analyse the lubrication conditions of hydraulic rods. Experimental data show the correlation between the stroking velocity and the film thickness on the hydraulic rod. Furthermore the influence of the fluid viscosity on the gap height is shown. Final the gap height, the viscosity and the measured friction are discussed. The presented experimental data allow conclusions on the lubrication conditions in the sealing gap. Thus a deeper understanding of thin film lubrication is obtained.

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HYDRODYNAMIC LUBRICATION OF PARALLEL SURFACES WITH RANDOM ROUGHNESS AND GROOVES

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KEYWORDS

Oil control ring; cylinder liner; load carrying capacity

INTRODUCTION

For lubricated contacts, the component macro-geometry (radius of curvature) determines the pressure generation and the micro-geometry (i.e. roughness, texturing) alters it somewhat. However, for parallel surfaces, i.e. the oil control ring (OCR), the micro-geometry completely determines the hydrodynamic lubrication (HL).

For a smooth OCR-cylinder liner contact, the cross-hatched grooves provide a certain load carrying capacity (LCC). Furthermore, the surface (plateau) roughness can be an additional source of LCC. So, is the influence of grooves on the LCC of rough liner surfaces positive or negative?

The current paper studies the hydrodynamic pressure and LCC of parallel surfaces with random roughness and/or grooves. This paper extends the work by Biboulet et al. [1]. They developed an efficient global grid refinement solver of the Reynolds equation, which originates from [2], using a mass-conserving cavitation algorithm. The solver provides a fast and stable convergence for parallel surfaces with sinusoidal roughness or dimple texturing.

RESULTS

The dimensionless Reynolds equation with cavitation and Fischer-Burmeister equation are solved simultaneously:

$$\frac{\partial}{\partial X}(H^3\frac{\partial P}{\partial X})+\frac{\partial}{\partial Y}(H^3\frac{\partial P}{\partial Y})=\frac{\partial((1-\theta)H)}{\partial X} \quad (1)$$

$$P+\theta-\sqrt{P^2+\theta^2}=0 \quad (2)$$

where H is the gap; P is the pressure; θ is the cavitation fraction.

Two types of artificially generated surfaces were studied, illustrated in Fig.1. ‘R’ refers to a surface with only roughness; ‘R+G’ indicates that the rough surface contains grooves.

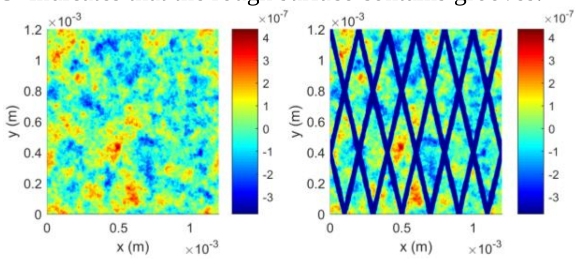

Fig.1 Cylinder liner surfaces: ‘R’ (left) and ‘R+G’ (right).

The surface roughness is randomly generated, with a Gaussian height distribution and an exponential autocorrelation function. The groove cross-section is sinusoidal. The pressure distributions for Fig.1 are shown in Fig.2. One can see that the grooves change the pressure distribution substantially.

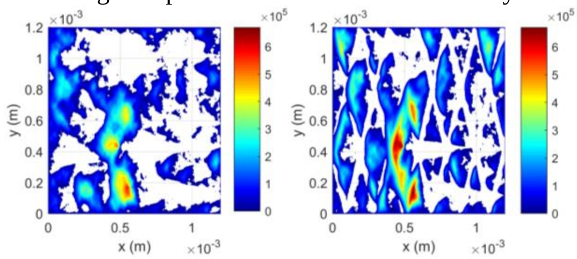

Fig.2 Pressure distribution for ‘R’ (left) and ‘R+G’ (right).

To find out if grooves are beneficial, we conducted many calculations. Fig.3 shows the variation of the LCC with the RMS for an ‘R’ and three ‘R+G’ surfaces.

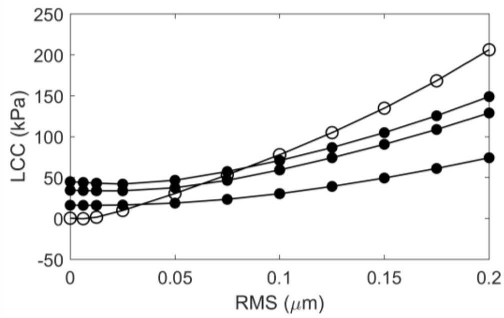

Fig.3 LCC as a function of the surface RMS roughness for ‘R’ (open dots) and for ‘R+G’ with a groove spacing of 0.1,0.2,0.3 mm bottom to top (closed dots).

We found that for increasing RMS (the surface roughness remains the same), the LCC increases for both the ‘R’ and ‘R+G’ cases. For ‘R+G’ cases, the larger the groove spacing, the higher the LCC-RMS curve. The curve for an ‘R’ surface intersects with those for ‘R+G’, showing that for small roughness, the introduction of grooves increases the LCC while for large RMS, grooves decrease the LCC. The grooves serve as channels for oil flowing from high pressure to low pressure zones. This results in a decrease in LCC, as was shown in [3].

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GAS FLOW VISUALIZATION ON DRY GAS SEAL WITH VIBRTION

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KEYWORDS
Seal; Fluid lubrication, *Experiments in tribology, Hydrodynamic Lubrication*

INTRODUCTION

Dry gas seals are widely used for high speed turbo machinery because of their high sealing performance, low friction and so on. In the dry gas seals, gas leakage can be protected by hydrodynamic gas film generated by high speed rotation. However, if the grooves are damaged by the vibration from the shaft rotation or the impact force from the outside, the function and lifespan of the seal will be drastically reduced. For this reason, as a research focusing on the influence of vibrations in dry gas seals, studies by experiments and analyzes are being conducted. However, there are very few examples that focus on the fact that the flow of the gas film changes under the influence of vibration. Therefore, in this study, a vibration exciter capable of giving arbitrary vibration to test dry gas seal was made and visualization experiment was conducted. In addition, we report velocity distribution by PIV analysis from the visualization results and investigate the relationship between the flow in the clearance due to frequency change and the leakage amount.

VISUALIZATION RESULTS

Figure 1 shows the results obtained by vibrating the test seal at 1 Hz and 3 Hz, subtracting the flow velocity from each other from the result that the seal clearance becomes the maximum and minimum, respectively, and the change in velocity is obtained. Fig. 1 (a-2), (b-2) downward when (a-1), (b-1) are ascending. From the results, the velocity boundary is confirmed in the region between the inner circumference and the outer circumference with all the results of different frequencies and displacement direction of the seal clearance. Also, an outline of the flow direction confirmed in the figure is shown. From the result, in the seal clearance, squeeze flow with the red line as the boundary is shown, and it is confirmed that the squeeze flow moves to the outer peripheral side as the vibration frequency increases. It is thought that the occurrence of the squeeze effect against the leakage amount of the dry gas seal from the leakage amount measurement result and the movement of the boundary promotes the inflow and outflow of the gas outside the clearance and deteriorates the sealing performance. Although the experimental oscillation frequency is low frequency as 1 Hz to 3 Hz, because the seal clearance is set to be large for visualization, if it is converted from the number of squeezes which is often used in dynamic characteristic analysis of the lubricating film. The same wave number corresponds to several hundred Hz. For this reason, the findings obtained the visualizations are useful.

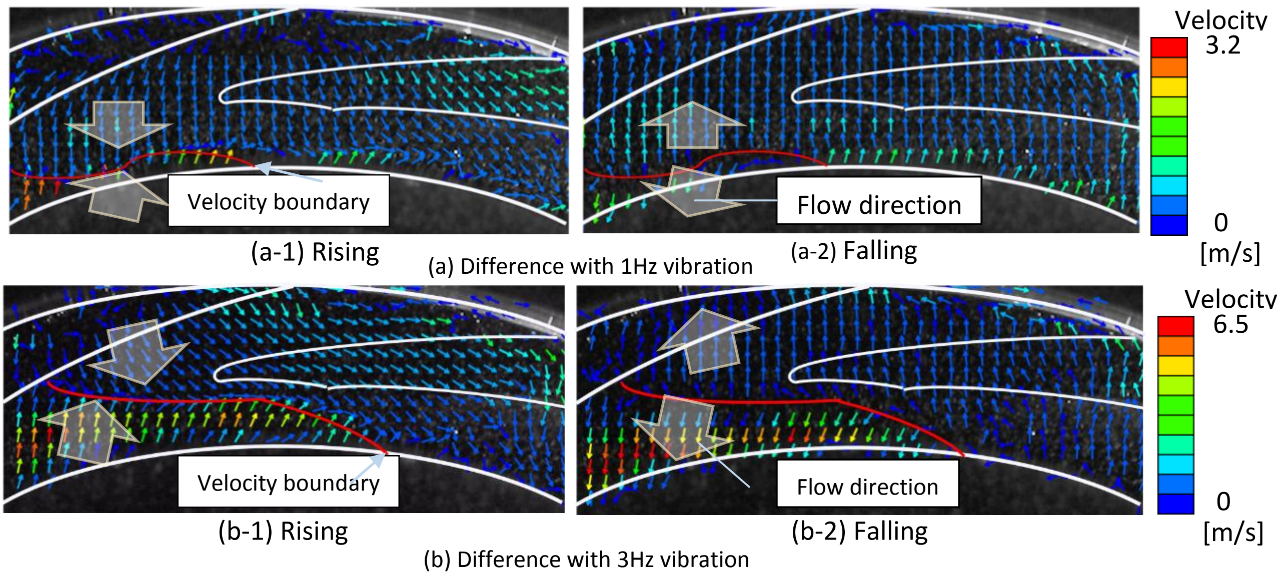

Fig.1 Visualization results under sinusoidal excitation

Tuesday

Sept. 3rd, 2019

46th LEEDS-LYON SYMPOSIUM on TRIBOLOGY
Lyon, 2-4 September 2019

Invited talk

Tactile perception and the role of friction-induced vibrations

By Francesco Massi

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In everyday life, our senses allow us for interacting with the surrounding objects and environment. While sight and hearing are largely understood and mastered, the sense of touch is far away from being fully achieved. We know the “signals” at the origin of the hearing (acoustic waves), which can be recorded and reproduced, as well the signals at the origin of sight (electromagnetic waves), recordable and reproducible. On the other hand, the signals at the origin of touch are still not clearly identified, and thus impossible to be recorded and reproduced. While cognitive psychology allowed for linking the mechanical stimuli with acoustic and optical perception on humans, the lack in the identification of the tactile stimuli is still a barrier to overcome.
Recent works focused on frictional forces and vibrations induced by the scanning of fingertip on a surface, investigating the role of friction-induced vibrations on the discrimination of surface textures. Being tactile perception at the bridge between several fields, from tribology to psychology, passing by neuroscience and engineering sciences, the research is developed within a research consortium (GdR TACT) interconnecting different research laboratories within the different disciplines.

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TRIBOLOGICAL INTERACTIONS RELATED TO THE TACTILE PERCEPTION OF DETERMINISTIC MICRO-TEXTURED SURFACES

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KEYWORDS
Everyday life tribology; Biotribology; Texturation, Tactile perception

ABSTRACT
In recent years, industrials paid a growing attention in qualifying and even predicting the tactile perception of their products. Surface texturing offers a reliable route to control surfaces tactile perception but relation between textured surface topography and tactile perception remains still unclear. Moreover, while tactile perception originates from the transmission of friction forces and friction induced vibrations to mechanoreceptors located in the dermis, a better understanding of the fingerpad/surface tribologic interaction is needed. Recently, many efforts were made to correlate friction forces to textures parameters on the one hand [1], and textures parameters to tactile perception on the other hand [2]. Nevertheless, few studies have been conducted to link together textures, fingerpad/surface tribo-response, and perception [3]. The current study aims at investigating both the tactile perception of micro-textured regular surfaces, and the *in vivo* mechanical interaction between the fingerpad and these surfaces. A panel of 52 polymeric textured surfaces were produced by the coupling of photolithographic and replication methods. All textures are defined by a regular hexagonal network of cylindrical micro-dots varying in diameter (from 12 to 905 µm), spacing (from 50 to 1,814 µm), and height (from 4 to 73 µm). Two subsequent tasks of texture perception characterization were conducted with 20 young volunteers. The first task resulted in subdividing the whole surfaces panel according to 3 perceptual categories: rough, slippery, and vibrating textures (Fig. 1). The second task led to quantify the level of perceived roughness, slipperiness and vibration of each textures. In parallel, *in vivo* friction tests were conducted with a young participant using a setup dedicated to active-touch experiments [4]. Measurements of friction coefficient and friction induced vibration were performed when participant's fingerpad rubbed the various textures under 0.4 N normal load and 30 mm/s sliding speed.

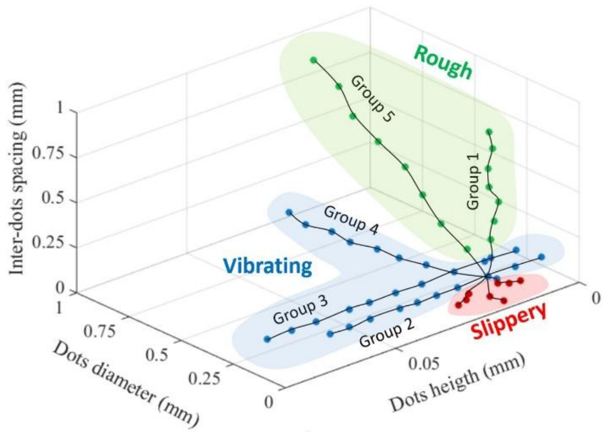

Fig.1: *Perception categories related to texture parameters*

For the 3 textures categories, results indicate significant relationships between (i) perception scores, (ii) friction coefficient and/or friction induced vibration levels, (iii) and surface texture parameters.

ACKNOWLEDGMENTS
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FINGERTIP FRICTION AND TACTILE PERCEPTION OF SURFACE STRUCTURE

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KEYWORDS

Friction; Everyday life tribology; Biotribology; Haptics

ABSTRACT

The haptic perception of materials is one of the key elements of everyday life in which friction plays an important role [1]. The structure of surfaces leads to a spatial and temporal modulation of friction forces and thus of strain in the skin which is sensed by our nervous system. Friction dynamics are of particular importance for the perception of structures which are small on the scale of finger ridges and of the characteristic distance between nerve endings. Here we report on experiments addressing the relation between fingertip friction and tactile perception for manufactured samples which have a well-defined surface microstructure.

For the first study, we have manufactured elastomer samples with a fibrillar surface structure. Hexagonal arrays of fibrils with 400 µm diameter and a varying height where produced by replica molding of different elastomer materials [2]. We found that fingertip friction decreases with increasing elastic modulus of the material, but depends only weakly on the fibril height. Study participants were asked to rate the similarity between samples as perceived by tactile exploration. Differences in both the fibril height and the elastic modulus were perceived by the participants through sliding contact with the fingertip. Multidimensional scaling analysis allowed to construct a map of perceived tactile distances between the samples. One dimension of this map was found to correlate with the bending stiffness of the fibrils (see Fig. 1), which will be discussed as a feature in tactile perception.

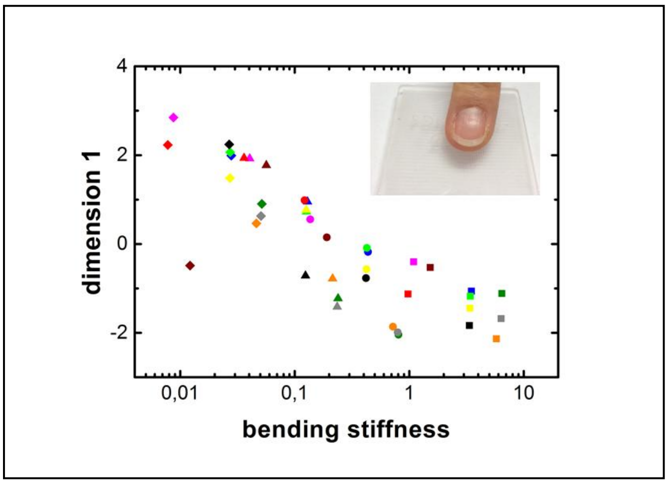

Fig.1: Results for an experiment on the tactile perception of micro-structured fibrillar surfaces, which were explored by sliding the fingertip over the surface. One perceptional dimension was found to correlate with the bending stiffness of the fibrils.

For the second study, randomly rough samples with a well-defined roughness spectrum were defined by a computer code [3] and produced by 3D printing. We will present first results for the relation between the roughness spectrum and fingertip friction, and discuss the role of roughness in the perception of similarity between the samples.

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LOADING RESPONSE TO FRICTIONAL STIMULUS APPLIED TO A FINGER SLIDING AGAINST GLASS SURFACES STRIPED WITH A MOLECULAR LAYER

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KEYWORDS

Biotribology; Everyday life tribology; Friction; Tactile perception

ABSTRACT

The frictional behavior between a finger pad and a solid surface is a common phenomenon in our daily life, such as in the process of touching, grabbing or browsing through a touch screen. Tactile perception is generated in these processes, which is believed to bond a strong connection between frictional phenomena. Thus, the study on frictional behaviors of a finger and dynamic responses to different frictional stimuli may provide us with vital information about the truth of tactile sensations.

The study on the correlation between finger friction and tactile perception often involves a friction test of a finger against solid surfaces with various surface features. In this study, glass surfaces coated with a self-assembled monolayer of octadecyltrichlorosilane (OTS-SAM) in different stripe-patterns were adopted as the specimen in three sets of friction tests with a total participants' number of 18. OTS-SAM has been proved to show a well friction modifying nature in previous studies [1,2]. Half of the surface on each specimen was coated with OTS-SAM, the widths, intervals or the orientation of the stripes being different. When the participants slid their fingers on the specimens, a change in friction force was recorded together with the change in normal load, a factor that quantifies the dynamic response to the frictional stimulus.

The first friction test involves specimen with striped molecular layers vertical to the sliding direction of the finger, with different stripe widths and intervals, yielding various molecular film coverage. Figure 1 shows that the rate of change (ROC) in interfacial shear strength caused by such molecular layers highly depended on the coverage of OTS-SAM, with a higher coverage inducing a lower friction. An increasing tendency of the normal load was observed with the decrease of shear strength, as the response to the frictional stimulus.

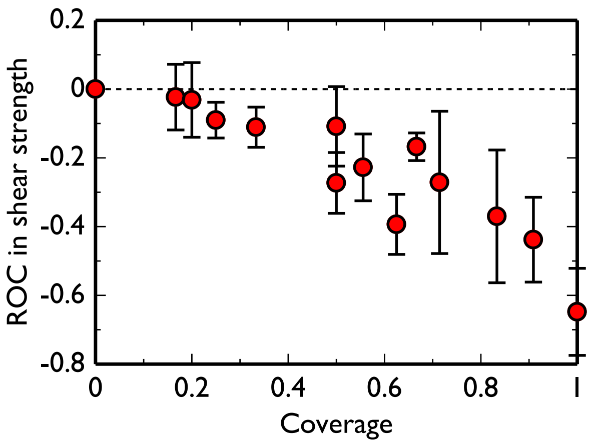

Fig. 1 Plots of ROC in interfacial shear strength against film coverage in patterned surfaces

ACKNOWLEDGMENTS

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

LOSS OF CONTACT OF A ROUGH SLIDER ON A ROUGH SURFACE UPON INCREASED DRY SLIDING SPEED

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KEYWORDS

Surface topography; Physics of friction; Experiments in tribology; Contact dynamics

ABSTRACT

We address experimentally the fundamental question of the vibrations induced in the direction normal to the interface when two dry rough solids slide on one another.

We consider a stainless steel slider in dry contact with a stainless steel surface, under its own weight. We investigate the vibration behavior of the slider during steady sliding at increasing velocities, using onboard accelerometers. We also monitor at high frequencies the contact voltage between the two surfaces, enabling detection of contact losses as a transient vanishing of the electric current through the interface. Macroscopic measurements of the sound pressure emitted by the interface and of the friction force are also performed simultaneously.

All types of measurements indicate a transition between a low velocity regime in which the two solids remain in contact at all times, and a high velocity regime where the slider moves through random bounces on top of the antagonist surface (Fig.1).

We will discuss (i) the scenario leading to such a transition, (ii) the statistical characteristics of the bouncing regime and (iii) a simple modelling framework. The latter is based on the classical Bouncing Ball model, used here with a correlated random excitation [1] obtained through a geometrical filtering of the contacting topographies [2].

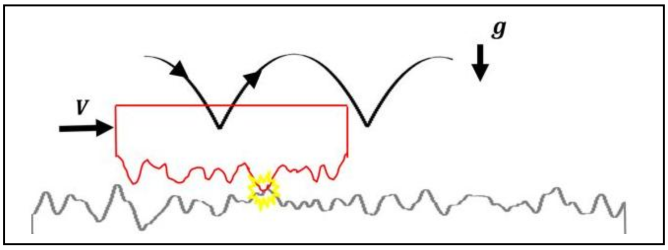

Fig.1 Sketch of the bouncing regime of rough slider (red) moving at constant velocity V on a rough surface (grey), under its own weight. Yellow: impact between two antagonist asperities.

ACKNOWLEDGMENTS

This work was supported by LABEX MANUTECHSISE (ANR-10-LABX-0075) of Université de Lyon, within the program Investissements d'Avenir (ANR-11-IDEX-0007) operated by the French National Research Agency (ANR).

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INTERFERENCE EFFECT OF LARGE AND SMALL GROOVES ON THE REAL CONTACT AREA GROWTH OF ONE-DIMENSIONAL REGULAR WAVY SURFACE

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KEYWORDS
Texturation; Surface topography; Experiments in tribology, Real contact area

INTRODUCTION

Engineering surfaces machined by a face milling or by a lathe are characterized by an array of tool marks. It would be worth considering the contact of regular wavy surfaces. In particularly, in soft solids, such as rubber, the behavior up to the nearly full contact could play an important role in the technological functions such as sealing. The authors [1] have examined in previous study the elastic contact of various types of one-dimensional and two-dimensional regular wavy surfaces shaped in the simple profiles such as sinusoidal, spherical asperities or spherical valleys arranged periodically on the surfaces. However, in general, engineering surfaces never have simple profiles and are formed in overlapping wave of various size of irregularities.

The objective of this study is to elucidate how the superimposed smaller irregularities affect the dependence of the real contact area on the load. In this study, as the first stage, the real contact area growth of one-dimensional regular wavy surface having large and small grooves is investigated in the light of comparing the effect of the bulk thickness on each groove.

EXPERIMENTAL PROCEDURE

Three types of surface profiles A, B and C are formed on blocks of silicone rubber having a shape of quadrangular prism with a base 16 mm x 7 mm. Fig. 1 shows the surface profiles of specimens. In specimen A, large cylindorical groove with a width w_L of 2.67 mm and small cylindorical groove with a width w_S of 1.33 mm are aligned alternately. The depth of large groove h_L and small groove h_S are the same and are about 90 μm. In specimens B and C, small groove with w_S = 0.8 mm is inserted between the large grooves with w_L = 3.2 mm and h_L = 130 μm. h_S = 32 μm for specimen B and h_S = 64 μm for specimen C. In the case for specimen B, the aspect ratio h/w of the small groove is the same as that of the large groove. These surfaces of blocks are pressed into the bottom surface of a right angle prism in decompression environments.

RESULTS AND DISCUSSION

Fig. 2 shows the variations of the observed contact images with increasing the mean pressure p. Here p is defined as the ratio of the normal load to the apparent contact area. When comparing specimens A and B for the thickness t of 10 mm, it becomes clear that in the case when the depths of both the large and the small grooves are the same, the large groove disappears first, then the contact images approach the complete contact. On the other hand, in the case when the aspect ratios are the same, the small groove disappears first. It was found from the real/apparent contact area versus mean pressure curve that when either the large or small groove disappears, the rate of increase in the real contact area shows sharp drop.

In the case for the specimen C, the large groove disappears first when the thickness of the specimen is larger than about 3 mm. On the other hand, when the thickness falls below about 1 mm, the small groove disappears first, because the decrease of the thickness make the extinction of large groove difficult which results in the increase of the contact pressure at the periphery of the small groove.

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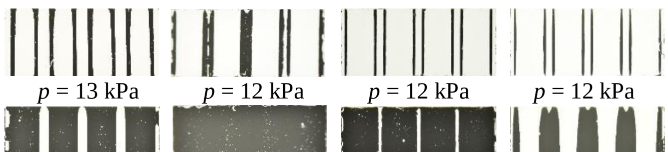
(a) Specimen A (b) Specimen B (c) Specimen C

Fig. 1 Cross-sectional shape of specimens



p = 32 kPa p = 53 kPa p = 54 kPa p = 53 kPa

(a) Specimen A (t = 10 mm) (b) Specimen B (t = 10 mm) (c) Specimen C (t = 10 mm) (d) Specimen C (t = 0.77 mm)

Fig. 2 Contact images of each specimen

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Wetting simulation on rough surfaces by lattice Boltzmann method

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KEYWORDS

Surface topography; Texturation; Contact and adhesion; Simulation.

ABSTRACT

The wettability of a surface may be changed for industrial or ergonomic needs. In order to increase or decrease the wettability, there are two main approaches: modifying chemically or topographically the surfaces. This work is interested in topography of a surface which will change the wettability by impacting the spreading dynamics. Natural surfaces like ginkgo biloba leaves are good examples of complex topographical multi-scale surfaces shape (Fig. 1). On a ginkgo leaf, we can see many asperities and they are obstacles for the liquid-gas and triple line motion.

The spreading of droplets is driven by dynamic effects which have to be taken into account for multi-scaled surfaces [1]. In order to calculate the shape of a droplet on those complex substrates, the Lattice Boltzmann Method is used and coupled with the Shan-Chen Model [2] to simulate two fluids. A model of wetting interaction is developed to reach a more realistic spreading and final contact angle. Because LBM is a statistical approach of molecular dynamics, it may be possible to handle both small scale and large scale geometrical effects. Fig. 2 shows the simulation of a droplet on a one-scale squared plot shape hydrophobic surface. The interaction model includes intrinsic hysteresis of the surface [3] and free energy barrier [4].

Simulation is first tested on a smooth and flat surface and then roughness is increased to reach a multi scale rough surface. Each numerical result is compared to the equilibrium contact angle and hysteresis of a real sessile test on the corresponding substrat.

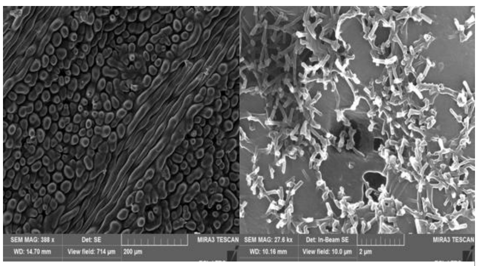

Fig. 2: Ginkgo Biloba Leaf multi-scale topography

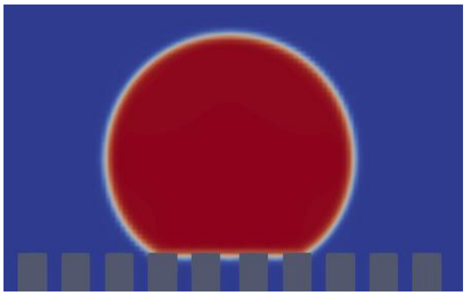

Fig. 1: Simulation of liquid (red) on a textured surface (gray)

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IN-LIQUID AFM OBSERVATION OF RUBBING SURFACE IN CVT FLUID

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Lubricant additives; Surface topography; Tribofilms; AFM

ABSTRACT

In the continuously variable transmission (CVT), the steel belt is stretched over two pulleys to transmit the power. Under the boundary lubrication, a tribofilm generated by tribochemical reactions between two steel surfaces achieves both the high friction coefficient and the wear resistance. In previous report, we revealed the pad-like tribofilm formed on rubbing surfaces of the steel pin increase the friction coefficient at the initial stage of sliding. In this study, we focused on the rubbing surface of steel disk under CVT fluid, and investigated the influence to the friction coefficient.

A carbon tool steel pin and a chromium steel disk were used for test pieces. All tests carried out under an isoparaffin base oil contains following additives; oleylamine, tricresyl phosphate, calcium sulfonate and succinimide. Pin-on-disk reciprocating friction tests and in-liquid AFM observations were carried out by the labo-made equipment as shown in Fig. 1.

We successfully observed the temporal changes in the rubbing surfaces under the additive oil. Figure 2 shows AFM images of the rubbing surface of chromium steel disk after 50 and 350 rounds under different oil temperatures. The microscopy images of rubbing surfaces of carbon tool steel pin after 350 rounds were also shown. Final friction coefficients of 25℃ and 60℃ tests were 0.144 and 0.188, respectively. As shown in Fig. 2, the rubbing surface of pin didn't show specific differences. On the other hand, a large number of particles generated in 25℃ disk surface, but much less in 60℃. Furthermore, as shown in Fig. 3, the rubbing surface of 60℃ disk indicated higher friction force than 25℃ by lateral fore microscopy. The results suggested the rubbing surface of chromium steel disk was covered with thin tribofilm that indicates high friction property. In our previous report, the total area of pad-like tribofilm generated on pin surface mainly affected to friction coefficient [1]. Additionally, we found that also the thin tribofilm formed on disk surface assumed to influence the high friction coefficient.

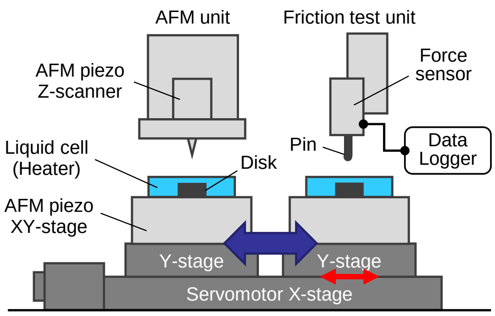

Fig. 1 Illustration of the experimental apparatus

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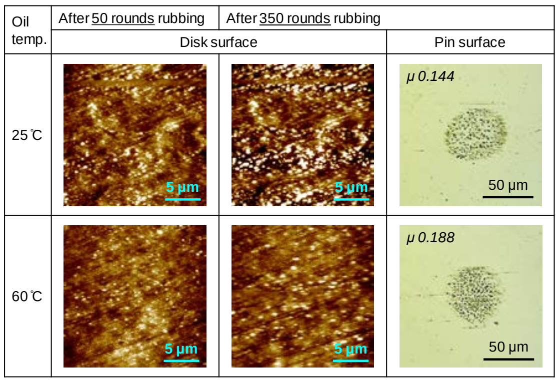

Fig. 2 AFM topography of the rubbing surfaces of chromium steel disk and optical microscope images of carbon tool steel pin tested under the additive oil

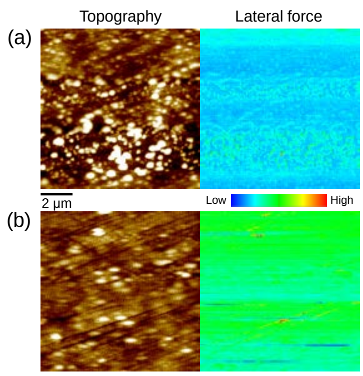

Fig. 3 AFM topography and lateral force images of chromium steel disk tested under the additive oil (a) 25℃, (b) 60℃

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IMPROVING PROCESSING QUALITY AND TRIBOLOGICAL BEHAVIOR OF LASER SURFACE TEXTURES USING OIL MASK METHOD

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KEYWORDS

Texturation; Surface topography; Experiments in tribology; Laser fabrication

ABSTRA

Rapid progressing of surface texturing technology has been widely witnessed within the past couple of decades [1]. In laser texturing technology, materials under irradiation spot of laser are partially vaporized and partially fused. Those highly heat fused materials, under the impact of successive laser pulsation, are pushed from the pool to splash along the rim edge of dimple, thus forming ridges/burrs [2]. Under wet lubrication condition, geometry of the splashed material accumulating along ridge/burr may be detrimental to tribological behaviors of the sliding friction pair [3].

The study allows the derivation of an effective oil mask method for improving the processing quality and the tribological behavior of laser textured surface. It goes on to investigate the influences of oil film thickness on formation of the coverage of oxides (Fig.1) and on the generated height of ridges/burrs (Fig.2). Analyses of experimental results suggest the possible reduction of the coverage area of metallic oxide and the average height of edge ridges/burrs around the rim edge of laser textured dimple. The possible mechanisms are summarized as mainly to be attributed to three effects: i) the cooling down effect of oil layer; ii) the shielding of oil film to reduce the laser ablation energy onto the base metal; iii) depleting effectively the oxidation and the adhesion of laser ablated melt on the irradiated surface of metal base. However, improperly too thick masking oil layer tends to reduce the laser ablation efficiency due to diminishing laser energy density or intensity on focal spot as it creates more severe refraction of laser beam. Tribological experimental tests confirm the favorable effect of textures obtain using oil mask method on reducing friction coefficient and wear.

Fig.1 Mean gray level changing with film thickness

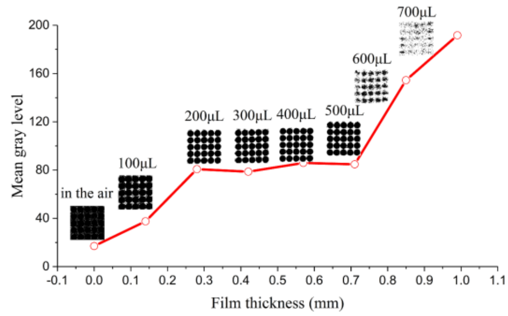
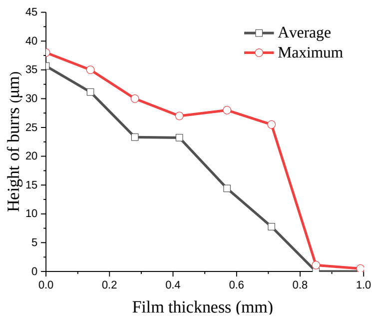


Fig.2 Dimple height of burrs changing with film thickness



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IN SITU OBSEVATION OF FRICTION INDUCED STRUCTURAL CHANGE IN HYDROGEN ATMOSPHERE

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KEYWORDS
Tribofilms and 3rd bodies; Coating; Friction; Hydrogen

ABSTRACT
The fundamental processes occurring with diamond-like carbon (DLC) sliding in hydrogen were studied. It is known that the sliding of DLC shows low coefficient of friction below 0.1 in hydrogen [1]. However, there is little precedent observed the structure of DLC during sliding in hydrogen.

Recently, we have developed an in situ system to observe the behavior of lubricant during friction by combining Raman spectrometer with the friction equipment in hydrogen as shown in Figure 1. Also, we have analyzed the tribofilm formed with the sliding by using the synchrotron XPS@KEK-PF-BL13B.

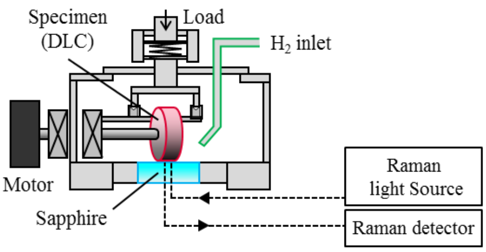

Fig.1 Schematic diagram of Raman in situ observation system

In this study, we will report the experimental data of structural change of DLC in hydrogen as measured using the in situ observation, and the synchrotron XPS.

Figure 2 shows Raman spectra obtained after test. We have assigned the bands of DLC with some papers. The spectra after test show the large change at ca. 1605 cm^{-1} corresponding to G-band and ca. 1350 cm^{-1} corresponding to D-band. The peak position of G-band and the coefficient of friction obtained by using in situ observation system are shown in Figure 3. The peak position was shifting with changing coefficient of friction lower.

The each component in C1s XPS spectra of DLC was obtained by the synchrotron XPS. The area of dangling bonds in the tribofilm was smaller than in the initial DLC, but the area of sp2 C-C band was larger.

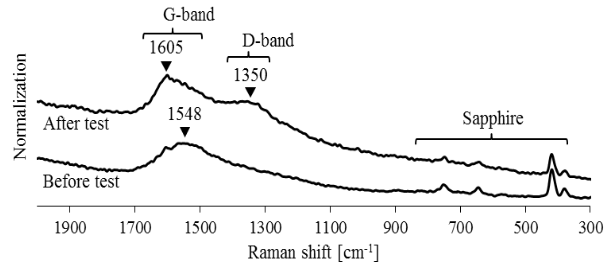

Fig.2 Raman spectra after test

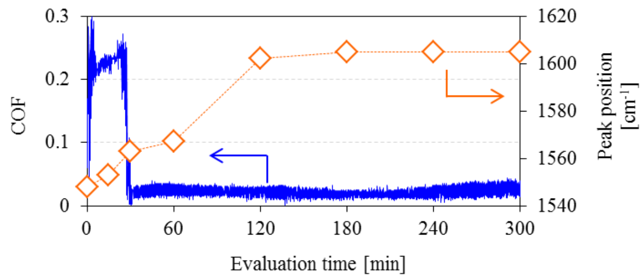

Fig.3 Time dependence of the peak position and COF

Based on these experimental results, it is suggested that the dangling bonds of DLC are changed to the sp2 (C-C) band structure with sliding in hydrogen, which induces low friction.

ACKNOWLEDGMENTS
We express our sincere thanks to Prof. Mase and the staff of PF for their support in conducting the performance evaluation of BL13B.

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THE ROLE OF TiC RENFORCEMENT ON THE FRICTION AND WEAR OF COLD SPRAYED Ti6Al4V COATINGS

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KEYWORDS

Coating; Tribofilms and 3rd bodies; Friction; Wear

ABSTRACT

Due to their high specific strength and excellent corrosion resistance, Ti alloys are useful materials in aerospace, automobile and marine applications [1]. However, their low resistance to plastic shearing and their non-protective tribo-oxides can result in high wear rates [2]. To improve the tribological properties of Ti alloys, reinforcing ceramic phases can be added to create a metal-matrix composite (MMC) [3,4]. In this study, Ti6Al4V-TiC MMCs were deposited as coatings using cold spray process. Composite coatings with two different TiC compositions 16 vol.% and 23 vol.% were deposited and their tribological properties were compared to Ti6Al4V coatings. Dry sliding wear tests were performed on the coatings at normal loads 0.5 N and 2.5 N using a WC-Co countersphere. Abrasive ploughing by the wear debris resulted in high wear of Ti6Al4V, whereas formation of protective tribolayers comprised of TiO_2 and fragmented TiC particles led to lower wear of composite coatings. Increased coverage and more rapid formation of the tribolayers was found to be tied to two factors: increased TiC in the initial coating and higher normal load for testing. Electron channel contrast imaging of the wear track cross-sections showed the formation of ultrafine grains and debonding of splats underneath the wear track in Ti6Al4V. For cross-sections of composite coatings, no splat debonding was observed and instead a coarse grain microstructure was found. The relationship between the coverage and mechanical properties of the tribolayers and the wear rate and subsurface microstructures will be discussed.

ACKNOWLEDGMENTS

The authors are thankful for the technical assistance from Maniya Aghasibeig and Jean-Francois Alarie at McGill Aerospace Materials and Alloy Design Centre (MAMADC). The authors gratefully acknowledge the contributions of Rene Cooper from Cristal Metals for providing the irregular Ti6Al4V powders.

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THE IMPACT OF BIOFUELS ON THE RUNNING-IN OF A THERMAL SPRAY COATING

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KEYWORDS
Friction; Wear; Mixed lubrication; biofuel

ABSTRACT

One approach to reduce the CO_2-impact of transportation is the fabrication and use of biofuels in internal combustion engines (ICEs). In the case of incomplete combustion, oil in the engine is diluted with the fuel. ICEs are operated in the ultra-low wear regime and running-in behavior is inherently connected with their operation and the desired long operating times. To ensure a reliable operation of the engine for the intended lifetime, the impact of biofuels on the engine's tribology is relevant.

We investigated the influence of the oil dilution with biofuels on the running-in of a thermally sprayed coating. A pin-on-disk tribometer operated in the ultra-low wear regime in combination with radionuclide technique was used for measurement of the running-in behavior with and without diluted oils. The expected impact of the viscosity reduction due to dilution on the stribeck curve was found. Results of the chemical analysis of the wear tracks after testing with and without diluted oil will be shown.

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EVALUATION OF THE CUTTING FORCES OF A THERMAL SPRAY COATING BY SCRATCH TEST IN DIFFERENT ORIENTATIONS

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KEYWORDS

Coating; Friction; Experiments in tribology, Abrasion

ABSTRACT

In internal combustion engines, the use of a full aluminum block to reduce engine weight and fuel consumption may lead to undesired tribological properties at the ring-cylinder contact. Coatings may be deposited on the cylinder bore to improve friction and wear behaviors. Iron-based coatings deposited by thermal spray process (TSP) are usually applied, given the enhanced ductility and properties similar to regular cast iron engine blocks [1-2]. TSP results in a coating presenting high porosity with large pore size distribution and an irregular surface finishing. After coating deposition, a honing process is used to improve surface quality. This work aims to evaluate the abrasion mechanisms and cutting forces when successive linear scratch tests are conducted on a 200 µm thick iron-based coating.

The scratch tests were carried out in a TI-950 triboindenter from Bruker Inc. using a cono-spherical diamond tip with radius of 100 µm and apex angle of 60º. The cutting velocity was 100 µm/min and the cutting depth was maintained constant at 400 nm. The samples were cross-sectioned and polished. Coating indentation hardness was 5.5 ± 0.8 GPa. A first scratch was initially conducted, followed by a second scratch with different orientations (10°, 20°, 30°) with respect to the first, as presented in Fig. 1. The specimens were characterized by scanning electron microscopy (SEM), optical interferometry and instrumented indentation techniques. After the scratch process, the intersection areas were analyzed for each condition by SEM to determine the deformation modes and micromechanisms.

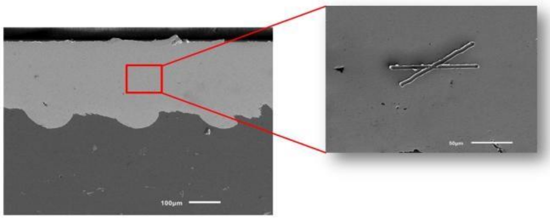

Fig. 1 SEM Image of the coating cross-section and scratches in the orientation of 30°.

Fig. 2 presents an example of the cutting forces along the scratch length. The forces decrease to a minimum value when the tip crosses the previously scratched area, which was at 60 µm in this case. Fig. 3 illustrates a comparison between three angles considering the friction coefficient (COF) minimum value. The angle between the scratches affects the friction coefficient. The case wherein the orientation was 20° shows the higher COF when the scratch crosses the scratched area. Results were also analyzed in terms of the influence of pores on the cutting forces.

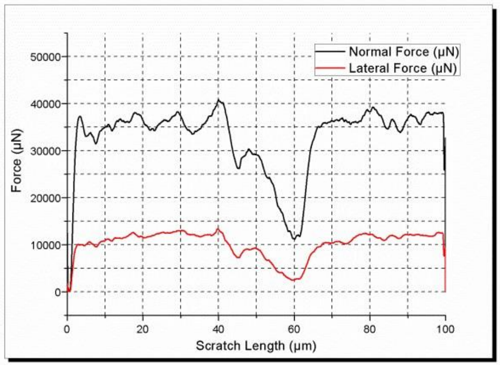

Fig. 2 Cutting forces along the scratch length

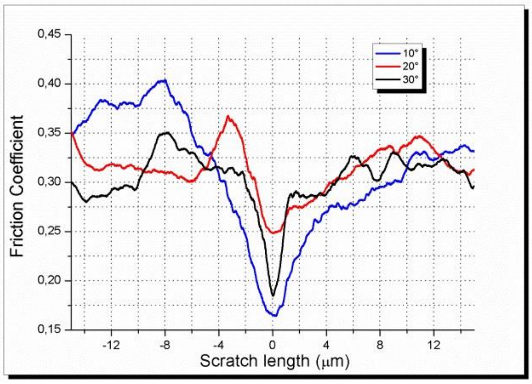

Fig. 3 Comparison of the friction coefficient in the three orientations (10°, 20° and 30°).

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AN ALTERNATIVE TO HARD CHROME PLATING BY USING THERMAL SPRAYING FOR VARIOUS TRIBOLOGICAL CONDITIONS

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KEYWORDS
Coating; friction; wear; replacement of hexavalent chromium.

ABSTRACT
Electrolytic hard chromium coatings are widely used for their good tribological performances. Confronted to more restrictive safety and environmental requirements, manufacturers need to find alternative solutions to the use of hard chrome plating. Among these, plasma projection techniques and HVOF (High Velocity Oxy Fuel) correspond to interesting candidates. Therefore, a contribution in this field is proposed by comparing the tribological performances of hard chromium with thermal spraying coatings by using different tribological tests to experimentally simulate different wear conditions.

First, the wear and friction behaviour of the coated specimens in the case of pin-on-disc friction tests have been compared (Figure 1 (a-b)). Even if the friction coefficient values are quite similar for the different specimens, it is shown that the four tested thermal spraying coatings present a much lower wear than the hard chromium spraying coatings.
Second, the abrasion wear resistance of the coated pins in the case of pin-on-plate tests were investigated. Indeed, in this test, the coated pin is sliding against a fresh abrasive paper. It is underlined that NiCrMo coating improves slightly the abrasion wear resistance compared to the hard chromium spraying coatings.
Third, complementary tests were performed to compare Al_2O_3 and WC thermal spraying coatings by using a reciprocating ball-on-plate test. It is shown that the WC coating presents a much lower wear and a much more stable friction coefficient than the Al_2O_3 coating.

This study enables to underline that thermal spraying coatings represent a good alternative to the use of hard chromium spraying coatings in terms of wear in particular. Moreover, thermal spraying has advantages in terms of productivity and can use a wide range of materials. Therefore, efforts are currently devoted to testing more optimised thermal spraying coatings by comparing different wear initial conditions.

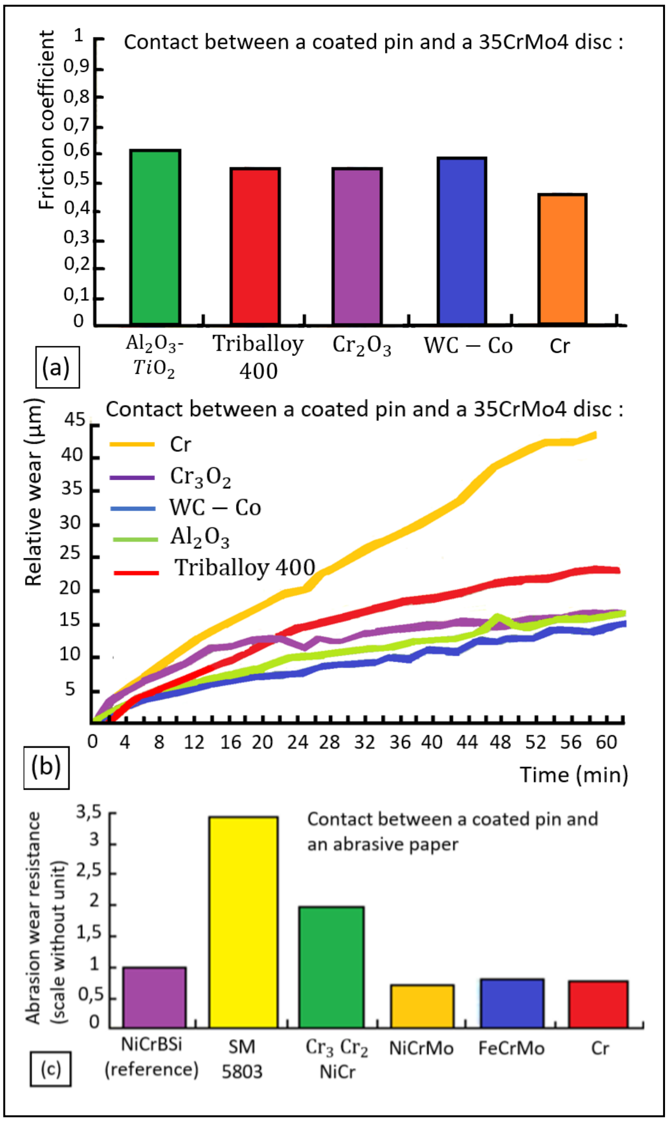

Fig.1 (a) Averaged friction coefficients and relative wear evolutions for the pin-on-disc test and (c) abrasion wear resistance for the pion-on-plate test.

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NANOTRIBOLOGICAL INVESTIGATION OF WEAR MECHANISMS ON TRANSITION METAL DICHALCOGENIDE THIN COATINGS

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KEYWORDS

Solid Lubrication; NanoTribology; Wear; Atomic Force Microscopy

INTRODUCTION

Thin amorphous solid lubricating films, based on transition metal dichalcogenides (TMD) have been known for their outstanding frictional properties, especially in vacuum. Their low coefficient of friction is only contrasted by average wear properties, due to poor adhesion and low hardness [1-2].

Atomic force microscopy (AFM) is a very powerful nanotribological tool for analysis of the tribological properties on the nano-scale and provides useful insight in the intrinsic frictional properties of the analyzed material. Here we utilize AFM to study nano-tribological properties of MoS_2 coatings after the tribotests, with the purpose of assessing nanoscale contributions to friction and wear behavior on the macro-scale.

EXPERIMENTAL DETAILS

MoS_2 coatings were deposited by non-reactive r.f. magnetron sputtering (AJA International, Inc., United States) from a single MoS_2 target on polished steel samples. Prior to the deposition, substrates were sputter cleaned for 45 min by plasma etching. Macro-scale tribotests were performed in a custom made vacuum tribometer (CTU, Czech Republic) at various loads and sliding speeds. 100Cr6 balls with a diameter of 6mm were used as sliding counter bodies. Wear-tracks were first analyzed by 3D optical profilometry, for an initial assessment of wear, which was followed by detailed topographical and frictional AFM analysis.

Atomic force microscopy (Agilent AFM5500, United States and Witec alpha300RAS, Germany) was performed in contact mode at environmental conditions. Probes with different spring constants were used, which allowed us to work with a wide range of contact loads (from nN to uN). Low loads were used to study nano-scale frictional properties of the wear tracks, while higher loads were utilized to analyze nano-scale wear mechanisms and provide an insight in the nano-frictional properties beneath the surface of the wear tracks.

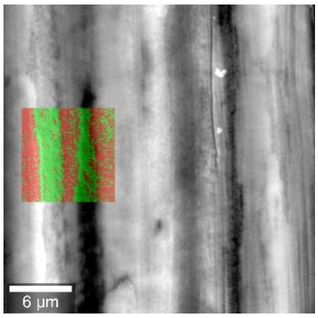

Fig.1 Overlay of the friction signal over the topography of the wear track; green region indicates lower friction

RESULTS

Macro-scale coefficients of friction as low as 0.025 and the reduction on the coefficient of friction with increasing load were observed, which is in good agreement with the literature [2]. We have identified regions with significantly different nano-frictional characteristics within the wear track (Fig. 1). The distribution of the observed regions presented on Fig. 1 is non-homogeneous across the entire wear track and indicates the formation of different compounds in the contact during sliding.

ACKNOWLEDGMENTS

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SUPERLUBRICITY AND SUPER WEAR: TRIBOCHEMICAL INTERACTION OF HYDROGEN-FREE TETRAHEDRAL CARBON COATINGS (TA-C) WITH OLEIC ACID

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KEYWORDS
Friction, Coating, Wear, Superlubricity

ABSTRACT
Since the first report of liquid superlubricity with ta-C coatings in the pioneer work of Kano et al. in 2005, the special interaction of lubricants with such coatings has sparked great interest. Despite several experimental and analytical findings adding puzzle pieces to the superlubricity phenomenon, a full understanding has not been obtained. Besides the superlow friction effect there is some scattering in reports on wear of ta-C coatings. Depending on the tribological conditions, wear of the coating is sometimes high, though the coating has much higher hardness compared to the uncoated counter body.

In this study we focus on the tribochemical interaction of oleic acid with ta-C coatings and show how tribological conditions can both cause high wear or superlow friction. Using a large parameter study we first investigated a tribochemical wear phenomenon and identified the role of sp^3-fraction, amorphicity, temperature, counterbody material, lubricant chemistry and contact pressure. In the second part of the study, we achieved superlubricity with no measurable wear by adjusting the tribological conditions. We studied the effect of lubricant chemistry and contact pressure, considering lubricant film thickness and tribo-induced rehybridization effects.

We found that a tribochemical wear process occurs for fattyacid based lubricants, which is unique to ta-C coatings, temperature activated and most likely catalyzed by the counter body [1]. Under such conditions that occur under very high contact pressures, wear can increase by several orders of magnitude.

When we studied effects outside high wear conditions, we could obtain superlubricity with both self-mated and single-side coated ta-C coatings. An accompanying study[2] revealed that the investigated system, opposed to other studies, was running in boundary lubrication conditions. Raman spectroscopy showed that a tribo-induced rehybridization of sp^3 carbon in the subsurface volume was not associated with superlubricity. However, DFT simulations found evidence of graphenization of the top surface atom layer, supporting recent analytical finding by De Barros Bouchet et al.[3]

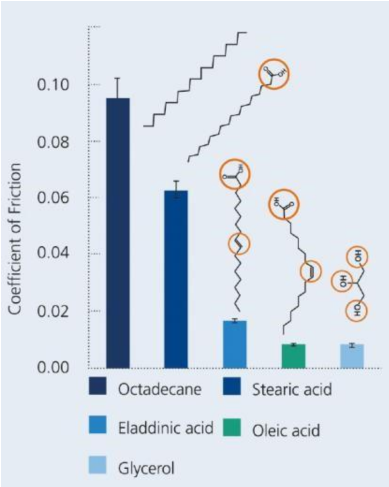

Fig.1 Superlubricity of self-mated ta-C coatings could be achieved with unsaturated oleic acid and glycerol. Saturated stearic acid has much lower reactivity and results in much higher friction common to boundary lubrication.

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LAB SCALE OPTIMIZATION OF DC MAGNETRON SPUTTERED C DOPED MoSe2 SOLID LUBRICANT COATINGS

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KEYWORDS
Coating; Solid Lubrication; Friction, Wear

ABSTRACT
The study involves the investigation of magnetron sputtered Mo-Se-C coatings for low friction tribological applications attributed to their excellent sliding properties in vacuum and humid environment conditions. Depositions were done using dc magnetron sputtering of seperate $MoSe_2$ and carbon targets, with and without the application of substrate bias voltage. Carbon content variation from 44-60 at. % was achieved utilizing different C target powers. Wavelength dispersive spectroscopy (WDS) showed a maximum Se/Mo ratio of 1.88 for the 50 at. % carbon coating deposited without substrate bias, while the ratio decreased with the application of substrate bias, possibly attributed to re-sputtering effects of Se during coating growth. Featureless and compact cross-sectional morphologies were observed in Scanning Electron Microscopy (SEM). X-ray diffractions utilizing grazing incidence mode depicted a broad amorphous diffraction pattern without any evidences of $MoSe_2$ platelets but Transmission Electron Microscopy (TEM) clearly depicted the presence of randomly oriented $MoSe_2$ platelets in amorphous C matrix, irrespective of substrate bias application. Crystalline $MoSe_2$ peaks in addition to characteristic G and D peaks for amorphous C were observed during Raman analysis. Nanoindentation hardness measurements displayed superior results for the coating deposited with 90 V substrate bias. Lowest friction coefficient of 0.05 in humid environment while 0.025 in dry nitrogen environment for 90 V substrate bias coatings were observed during reciprocating sliding tribotests, performed under 30 N load. Much improved and superior results than literature were achieved during this research [1,2]and it paves way as a first step towards industrial implementation of the system.

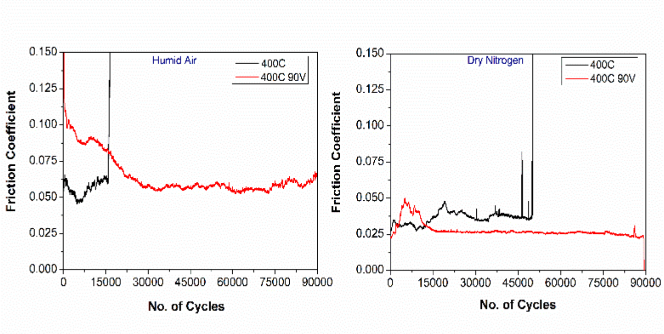

Figure 1 Friction curves of coatings deposited with and without substrate bias

Table 1 Chemical composition of the coatings

Coatings	C (at. %)	Mo (at. %)	Se (at. %)	O (at. %)	Se/Mo
330C	44	19	34	3	1.79
400C	50	16	30	4	1.88
500C	60	13	24	3	1.85
400C(50V)	55	15	25	5	1.67
400C(70V)	51	17	28	4	1.64
400C(90V)	51	18	28	3	1.59

ACKNOWLEDGMENTS
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II. ATRITO-0 [co-financed via FEDER (PT2020) POCI-01-0145-FEDER-030446 and FCT (PIDDAC)].

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TRIBOLOGICAL BEHAVIOR OF CrN COATINGS DEPOSITED BY RAAMS UNDER LUBRICATED RECIPROCATING RING ON PLANE CONDITION

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KEYWORDS

Coating; Friction; Experiments in tribology, Sliding wear

ABSTRACT

Ceramic coatings are designed to improve friction and wear behavior for tools, gears and engine components, but some deposition processes may lead to an increase on surface roughness mainly by the presence of coating defects [1]. In a lubricated system under high contact loads and boundary lubrication regime, those defects can promote surface/subsurface damage of the material, leading to premature failure of the system [2]. In addition, fully formulated lubricants are designed to operate under metal contacts, with the possibility of losing performance under nonmetal or ceramic coating contacts [3]. In this work, an innovative reactive deposition process called Remote Anode Assisted Magnetron Sputtering (RAAMS) was used to produce 4 µm thick CrN coating on polished AISI H13 tool steel substrates, which were previously quenched and tempered. Fig.1 shows SEM image (JSM 6010-LA from JEOL Ltd.) and 3D roughness evaluation (CCI AMETEK Inc.) of the as deposited CrN. The roughness parameter Sa was 0.026 µm for coated and uncoated samples.

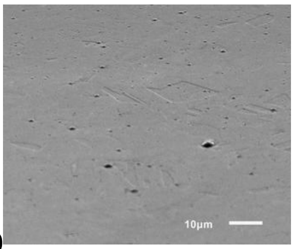
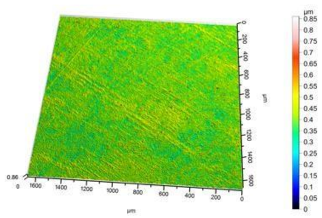
a)  b) 

Fig.1 SEM images of surface (a) and cross-section (b) of the CrN deposited by RAAMS technique.

The tribological behavior was analyzed using a reciprocating test rig (SRV v4 from Optimol Instruments Prüftechnik GmbH) on a ring on plane configuration. The ring was a commercial nitrided cast iron with a diameter of 75 mm. Ramping normal loads were tested (5 N to 50 N in steps of 5N for 10 min.) with a stroke of 4 mm and frequency of 10 Hz.

Both coated and uncoated samples were tested using SAE 0W20 fully formulated synthetic oil (FFSO) at 120ºC. Also, SAE PAO-8 was used with an uncoated sample to stablish a

base line case.

Fig. 2 shows time average COF behavior based on 3 replicas for each condition. In this figure, CrN lubricated with FFSO presented lower friction results compared to uncoated sample with PAO-8 case for a wide range of normal loads (5 to 30 N), approaching similar friction results for higher loads. The lower friction results for uncoated sample lubricated with FFSO may be promoted by the presence of oil additives designed to work with metallic surfaces, suggesting a non-reactive tribochemistry system between oil additives and CrN coating.

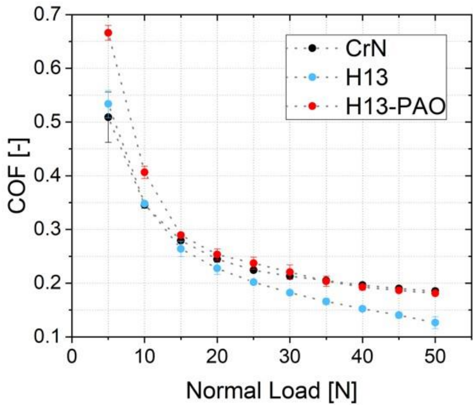


Fig.2 Coefficient of friction behavior during the reciprocating tests for CrN (black) and uncoated (red and blue) samples.
Black and blue circles were tested with fully-formulated oil while red circles were tested with PAO-8.

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TRIBOLOGICAL BEHAVIOUR IN DIVERSE TESTING ENVIRONMENTS OF A SELF-LUBRICANT W-S-C COATING DEPOSITED BY CFUBMS

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KEYWORDS
Friction; Coating; Solid lubrication; Magnetron sputtering

ABSTRACT
Transition metal dichalcogenide based coatings alloyed with carbon show very promising tribological behavior, providing reduction of friction and wear in various testing environments (normal air, dry nitrogen, vacuum) [1,2].Coatings providing good tribological response presented in the literature were often deposited in a laboratory scale deposition units by RF magnetron sputtering [2]. In this study W-S-C coating was deposited by closed field unbalanced magnetron sputtering (CFUBMS) in a semi-industrial deposition unit (Teer UDP 650/4) equipped with 4 magnetrons. The coating had ~40 % at. of carbon with a S/W ratio of 1.47. Cross-sectional imaging was performed using field-emission scanning electron microscope (FESEM). The coating had dense and featureless morphology, with a thickness of ~2.3 µm including a ~400 nm Cr interlayer. The hardness of the coating was ~5.7 GPa. Tribological studies were performed at normal laboratory air (RH=30-40%) with 2 different loads, elevated temperatures (up to 400°C), vacuum ($p<10^{-3}$ Pa) and dry N_2 environments. Unidirectional pin on disk apparatus was used for performing the tests. The counterbodies were 100Cr6 bearing steel balls and the sliding speed was set at 0.1 m/s, unless otherwise noted. Tests performed at normal laboratory air with 5 N of load resulted in coefficient of friction (COF) of 0.15-0.2 with specific wear rates of ~$3x10^{-7}$ mm^3/Nm. Raman spectroscopy performed on the tribolayers formed on the bearing steel balls showing presence of graphitic carbon. Testing with 35 N of load resulted in reduction of COF (~0.06). Raman spectroscopy performed on the tribolayers showed presence of well oriented WS_2 on the sliding interface. Testing at elevated temperatures was marked with significant reduction of COF, with average values of ~0.01. Specific wear rates were an order of magnitude higher for the higher temperature tests compared to RT tests with values of ~$3x10^{-6}$ mm^3/Nm. Raman spectroscopy performed on both sliding partners showed well defined peaks related to WS_2, peaks that are not observed on the coating in the as deposited state. Vacuum tests were initially performed against 100Cr6 balls, and the friction was high, reaching values up to 0.7-0.8. Further tests were done with the ball being coated using the same coating. Friction was much lower during the first 1000 cycle (<0.01), with presence of friction spikes (COF=0.4) during the remaining time of the test (10000 cycles). Same testing conditions were used for testing under dry N_2 environment. COF response was much more stable (no presence of frictional spikes), with a slightly higher average value (0.02-0.03) compared to the vacuum tests if the friction spikes are not considered.

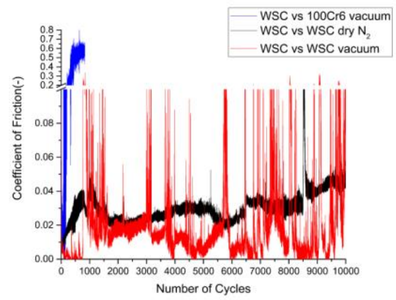

Figure 1 Tribological response in vacuum and dry N_2 environments

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TRIBOLOGY OF AMORPHOUS METALLIC ALLOYS: TRIBOCHEMICALLY OR MECHANICALLY DRIVEN?

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KEYWORDS

Friction, Wear, Tribofilms and 3rd bodies, Amorphous Metallic Alloys.

ABSTRACT

Amorphous Metallic Alloys (AMA), also known as metallic glasses, have exceptional mechanical properties compared to their traditional crystalline counterparts: yield strength close to theoretical limit, high hardness, high elastic deformation capacity, high fatigue strength [1]. Despite their interesting mechanical properties, tribological studies conducted over the last two decades showed that AMAs exhibit erratic tribological behaviour, often mediocre but sometimes excellent, and especially unpredictable or even often contradictory [2-5]. Thus, a better understanding of the "composition / friction condition / tribological behaviour" coupling is necessary in order to make the tribological performance of AMAs more reliable. The compositions of AMAs tested for tribological application in which sliding occurs, are alloys mostly based (main element in weight%) on Cu, Zr, Ni, Fe, or Ti [3,5-6]. The Cu, Ni, and Zr-based materials are displaying among the best performances.

Consequently, 4 different alloys (Cu-based, Zr-based, CuZr-based, and Ni-based) were chosen for this study. They were tested in reciprocating ball-on-plate pure sliding configuration with a ± 1 mm stroke. They are studied in terms of friction coefficient evolution over 10,000 cycles of friction, estimation of damaged volume at the end of the test, and wear track morphologies and compositions using SEM and EDX analysis. To study the impact of the initial contact conditions on their tribological behavior, AMAs are tested under two different initial contact pressures (310 and 680 MPa).

Results show that the Cu, Zr and CuZr-based alloys exhibit very similar friction coefficient under both conditions, but the Ni-based alloy exhibit a dramatic change in friction coefficient when the contact pressure increases (Figure 1). In the latter case, the volume of damaged material only slightly variates and most importantly remains almost null! This peculiar behaviour is due to selective tribochemical reactions leading to the creation of a specific 3rd body. Interestingly, selective tribochemistry takes place in all the contacts studied. In some case it protects the AMA and deteriorates the crystalline ball, some the opposite, leading to high or low wear.

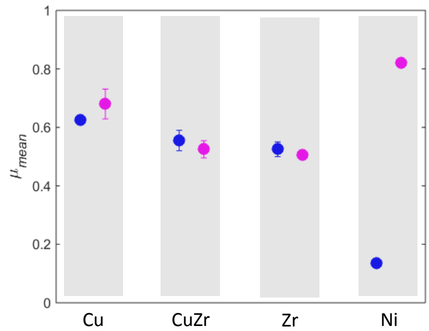

Figure 1 - Mean friction coefficient of AMAs at 2 different contact pressures: 310 MPa (Blue) and 680 MPa (Pink)

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46th LEEDS-LYON SYMPOSIUM on TRIBOLOGY

Lyon, 2-4 September 2019

Invited talk

From fibre coating to Hair cosmetic properties: Tribology in daily hairy life

By Dr. Judith Wollbrett-Blitz

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Hair that emerges from the human scalp is a highly organized fiber. It is a unique composite material, with a rather well-characterized microstructure. It is well known that the hair surface and structure of both cuticle and cortex can be altered by chemical treatments and daily-life routines (combing, brushing, UV exposure….). Many of the sensorial aspects concerning hair relate to friction. The condition of the hair surface is crucial in terms of cosmetic product applications and sensorial appraisal. Coating or damaging the surface can lead to very different surface states and hence to non-negligible differences in surface properties.

These changes clearly impact the sensory feeling. Predictive evaluation by a rapid scanning of different coating can be very useful but it is previously required to understand the relation between different scales (from microscopic to nanoscopic) and between morphology and tribology. In the present study, we aimed at understanding the link between the tribological behaviour and surface properties in terms of topography. Multi-scale tribological, mechanical and topographic methods were used, to deal with some issues such as biologically induced heterogeneities and fiber geometry. Coupling very different technics helps at addressing the following questions: Is the roughness linked to friction parameters? What is the contribution of nanoscale roughness to large scale tribological measurements? How does the surface (bio)chemical composition impact surface adhesion? Can we predict the mechanical behaviour by a surface scanning?

Several techniques, such as friction measurements and mechanical surface properties were used to investigate tribological properties of hair/hair interactions. Novel techniques derived from hair wettability measurements were also used to bring new mechanical insights into fiber /fiber interactions by measuring hair / hair adhesion forces.

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NEW INSIGHTS IN THE PHYSICS OF ICE SKATING

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KEYWORDS
Physics of friction; Everyday life tribology; Experiments in tribology; Ice friction

ABSTRACT

A liquid water layer is commonly believed to lubricate sliding friction on ice. Pressure melting, frictional heating and premelting have been proposed as mechanisms by which this lubricating water layer forms. Our recent experiments however provide an alternative explanation for the slipperiness of ice: weakly bonded surface water molecules diffuse over the ice surface in a rolling motion that facilitates the sliding [1].

The friction coefficient of steel-on-ice over a large temperature range reveal very high friction at low temperatures (−100 °C) and a steep decrease in the friction coefficient with increasing temperature. Only for a limited temperature range typical for ice skating, low friction is found. Remarkably, the strong decrease in the friction coefficient with increasing temperature exhibits Arrhenius behaviour with an activation energy of $E_a = 11.5\ kJ/mol$. Molecular dynamic simulations of the ice-air interface reveal a very similar activation energy for the mobility of surface molecules. The microscopic molecular mobility indicated that slippery ice arises from the high mobility of its surface molecules.

These sphere-on-ice model experiments did not probe the effect of slider geometry. Using spheres but also pieces of a real skate, we see that far from the melting point, similar frictional behaviour is observed for various slider geometries. However, close to the melting point we find that the plastic deformation of the ice depends on the geometry. We predict the ‘ploughing’ force based on the geometry of the slider and the independently measured hardness of the ice and find reasonable agreement with the friction measurements [2].

The slipperiness of ice then results from a layer of very mobile water molecules, combined with the fact that the ice remains very hard up to temperatures close to melting. This differentiates ice from other solids, and thus explains why skating is possible on ice, but not on other materials.

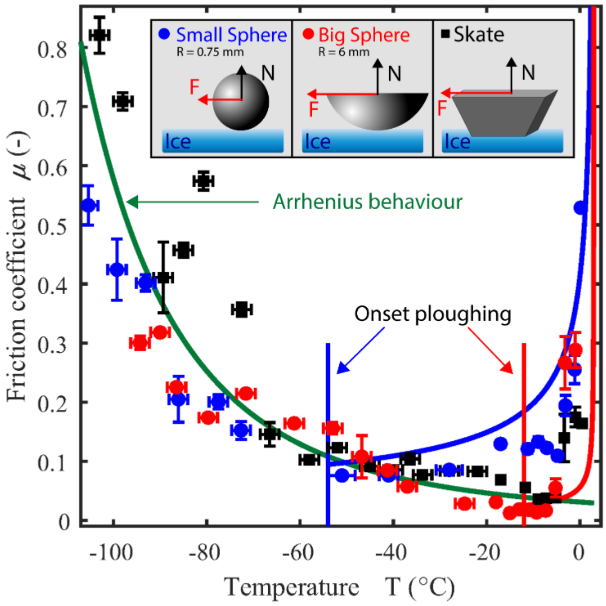

Fig.1 Friction coefficient as a function of temperature measured at a constant sliding speed (0.38 mm/s) for sliding a small sphere (blue, R = 0.75 mm), a big sphere (red, R = 6 mm) and a model skate (black) over ice. At low temperatures, the friction displays an Arrhenius temperature dependency which is independent on the geometry. Close to the melting point, plastic deformation occur which increases the friction; ploughing through ice can be modelled based on the temperature-dependent hardness of the ice and the geometry of the slider.

ACKNOWLEDGMENTS

We thank Shell for financial support (PT 67354).

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

EXPERIMENTAL EVIDENCE OF FRICTION EFFECT INVOLVED IN PLAYING FRENCH BILLIARD

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KEYWORDS
Friction; Everyday life tribology; Third body; Visualization.

ABSTRACT

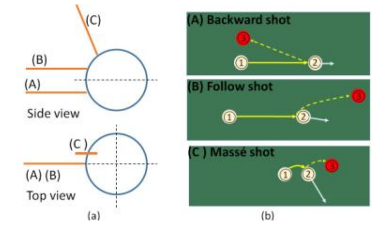
Billiard games involve collision between balls and friction phenomena between ball and ball, ball and table, ball and cue. In the literature, few studies are found on dynamics of billiards. From a theoretical point of view, it implied the collision of two rigid balls with spins or not [1, 2]. Others present some experimental results using high-speed camera to study ball-cushion collisions [2, 3] in the case of snooker or pool.

In this study, focus is made on French billiard game, involving 3 balls only (no table pockets). The basic rule is that the ball ① stroke by the player should strike the two others balls ② and ③ consecutively. In order to accurately place the balls on the table, the player has to control the force (consequently the velocity) applied on the cue-ball and its direction and motion. Those imply to choose the right impact location on the ball by the cue and thus which effect must be imposed. In this study three specific effects, backward, follow and Massé shots (fig. 1), are analyzed from a mechanical and tribological point of view.

The system can be described according to the tribological triplet. Multi contacts occurred and they involve the following elements:

- balls (first body), in phenolic resin, 61.5 mm of diameter,
- cue tip (first body), single layer of leather, 3 mm thick,
- cloth (first body),
- chalk (third body) put on the cue tip before each shot,
- cue (wood, 1.5 m of length), slate plates (billiard table) and player (mechanism).

In this study one focus on the impact by the cue tip on the ball ① (cue-ball), the motion and velocity of the ball ① until and after its collision with the ball ②. Nevertheless, it was verified that the ball ③ was contacted to validate the strike. A "Phantom® Miro® eX4" high-speed camera, with a 55 mm Nikon lens, was used to track the movements and velocity of the cue-ball. The sample rate was 1900 frames per second. Image tracking and processing algorithms were developed to extract from the recorded videos the cue ball speeds and accelerations function of time. The cue tip, balls, chalk and cloth were analyzed by optical and scanning electron microscopies in the aim to highlight the cleaning conditions of the cloth and the chalk distribution on the cue tip and transfer on the ball.



(a) Schematics strike location of the cue on the ball, function of the targeted shot: (A) Backward, (B) Follow, (C) Massé.

(b) Schematics of the balls displacements - Top views.

Fig.1 Displacements of the balls, as a function of the effect

Backward and follow shots allow to apply a spin rotation about a horizontal axis perpendicular to the direction of the displacement of the ball. Results showed different consecutive motions steps for the backward and follow shots: pure sliding (just after the first contact impact tip-ball ①), rolling and sliding, pure rolling (just after the impact ball ①-ball ②), rolling and sliding again. The phase depended on the applied effect, the presence or not of the chalk on the cue tip, and the cleaning conditions of the cloth. This highlighted different contacts involved and friction ratio. The Massé shot is more complex as it imposes spin about an axis not mandatorily horizontal neither perpendicular to the direction of the displacement of the ball. The spin rotation given to the ball ①, coupled with the friction between the table and the ball ends up curving the path of the ball ① (fig.1), involving significant Corriolis acceleration effects.

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A MODEL TO PREDICT THE FRICTION FORCES GENERATED DURING SKIING ON ARTIFICIAL SKI MATTING

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KEYWORDS

Friction; Modelling in tribology; Everyday life tribology, skiing

ABSTRACT

Skiing is a popular pastime and competition sport enjoyed by amateurs as well as professionals across the globe. While many people ski, access to snow is limited in many countries. This issue is commonly addressed through the use of specially prepared artificial matting which can provide a skiing surface in warmer climates when it is lubricated with water.

The sliding contact is formed between the ski base and an ensemble of matting fibres in which each individual fibre may operate in one of several contact modes. Each of these modes gives rise to a different contribution to the overall friction force resisting sliding of the ski. Contact modes are considered to be either: dry contacts (leading to contributions to friction due to adhesion or abrasion) or water film lubricated contacts. The ends of the fibres are rounded, as illustrated in figure 1. Consequently, the presence of water precipitates liquid film lubrication on some of the fibre tips leading to contributions to friction due to viscous shear. (An additional contribution to friction is also due to elastic deformation at each fibre to ski interface.) The total friction, F_T, at the interface due to contact at each fibre can, therefore, be represented by a multi term equation of the form:

$$F_T = N\,(Af_{ab} + Bf_{ad} + Cf_{lub} + Df_{\mathrm{def}})$$

Where: *N* is the total number of fibres in the contact, f_{ab} and f_{ad}, are the friction forces due to one fibre in either abrasive or adhesive contact, f_{lub} is the friction force due to one fibre in fluid lubricated contact and f_{def} is the friction force due to elastic deformation caused by a single fibre contact. *A*, *B*, *C* and *D* are the proportions of the fibres at the interface operating in each contact mode. A multi-term model, based on this principle has been developed to predict friction at the ski to matting interface.

The model includes the use of appropriate elastohydrodynamic (EHD) equations to allow an estimation of lubricating film thickness and the friction forces arising due to water film shear at lubricated contacts. (Established using an EHD regime map.) It also incorporates equations to describe the adhesive and abrasive contact friction components along with the contribution to power loss arising from the work required to overcome elastic deformation at fibre contacts.

The model is used to predict overall friction between samples of ultra-high molecular weight polyethylene, a material commonly used for ski bases, sliding against typical matting fibres. This data is compared to previously published experimental data for friction at this interface over a range of sliding speeds from about 5 km hr^{-1} to 25 km hr^{-1} [1]. Using this approach, an attempt is made to estimate the likely relative contributions to the overall friction force due to the differing proportions of fibres in fluid lubricated and dry contact, thus permitting friction forces during skiing on artificial matting to be estimated as a function of matting design parameters.

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SCRATCH RESISTANCE OF FLOOR COVERING SURFACES

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KEYWORDS
Wear; Coating; Contact and adhesion; Scratch resistance

ABSTRACT

Floor covering are daily submitted to various mechanical solicitations: walking, rolling chairs, furniture feet indentation, sliding objects, cleaning devices etc. All these solicitations are liable to cause wear of the product, which negatively impacts its visual aspect. A wear mechanism which is particularly severe is the scratch.

The aim of this project is to identify which kinds of scratches have a high optical influence and to prevent them. The final objective is to optimize the material (rheology, structure…) to increase its scratch resistance.

Scratch tests have been performed on a material composed with a plasticized PVC substrate covered by an anti-scratch polyurethane coating. These tests are observed in situ thanks to a microscope coupled to a camera.

Depending on the scratch test conditions (tip radius, normal force, temperature…), different deformation regimes (elastic, elastoplastic, plastic) and 3 different failure mechanisms are observed (figure 1).

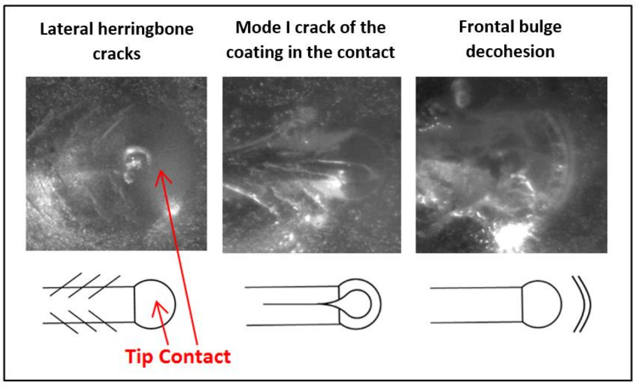

Figure 1 : In situ photos and schemas of 3 different failure mechanisms that may appear together.

These mechanisms do not have the same optical influence: for example a ductile scratch is almost invisible by naked eye, even with the shallow and short lateral cracks (1st mechanism), whereas a scratch with delamination (3rd mechanism) is very visible because of a whitening of the material.

In order to understand the local mechanical conditions during these tests, a numerical model of scratching has been developed. As shown in figure 2 the case of high load/indentation depth is clearly similar to failure mechanism 2. A variety of scratching conditions will be presented and analyzed, the strain and stress fields correlated with the corresponding failure mode.

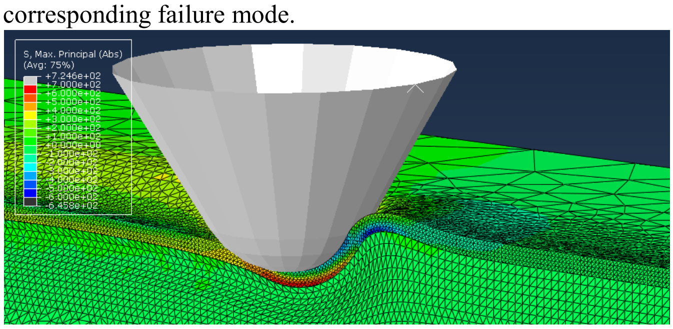

Figure 2 : Numerical simulation of a scratch test, max principal stress (MPa).

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INVESTIGATION ON THE WEAR RESISTANCE OF GEOCORAIL: A NEW NATURAL CONCRETE

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KEYWORDS
Wear*;* Experiments in tribology*;* Everyday life tribology*;* *Abrasion*

ABSTRACT
The purpose of this study is to characterize the wear response of a new material named Geocorail. Electrochemical process drives the growth of this natural material directly in the sea. In fact, the natural calcareous deposit [1,2] is developing between natural grains of sand, sediments and debris of sea shell. After few months, a solid aggregate may be used as a mechanical reinforcement in order to consolidate the coastline and protect the maritime constructions.

The main goal of the Geocorail start-up is to understand how the growth of the aggregate can be optimized in terms of mechanical behaviors, as well as the mechanical resistance in static loading and wear response. Then an experimental design with different electrochemical parameters and sand granulometry was conducted in the Geocorail laboratory based in Fos/Mer to obtain different samples from 3 months to 1 year living and growing in seawater (Fig1). Mechanical tests were defined in order to qualify and maybe quantify the mechanical properties, and the characterizations were done in MSMP laboratory in Aix-en-Provence.

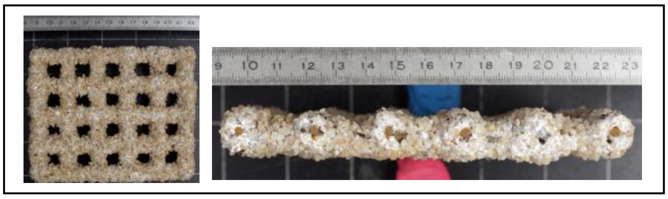

Fig.1: Geocorail's sample after 5 months (Top view on the left, cross section on the right)

As the other mechanical tests, the tribological behavior of the aggregate is difficult to investigate in standard conditions used for "industrial concrete" [3], mainly due to the small size and heterogeneity of the samples. The samples were too small to quantify the abrasive response using standard for natural stones [4]. Then, our first goal was to determine a significant experimental approach to quantify the wear response. After few months in the seawater, the average thickness of the samples is about 10 to 30 mm. Furthermore, the shape of the aggregate all around the steel stem is not very regular (Fig. 2).

Fig.2: 10 months' Specimen for wear test

In order to perform the wear test, resin is used to form samples with quite equivalent area of friction surface and with the same position of the steel stem. Response of different samples are obtained in water lubricated wear test under constant pressure with SiC counterpart. To complete the analysis, other materials such as normalized mortar (sand granulometry and dosage of the cement) and a natural stone "Pierre du Pont du Gard" (sedimentary natural stone) are characterized using the same protocol.

The first results obtained show that Geocorail specimens:

- are much more resistant than this natural stone,
- present the wear resistance level quite equal to the normalized mortar.

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SCRATCH DAMAGE OF ALUMINIUM SURFACES – ASSESSMENT OF DAMAGE MECHANISMS ON DIFFERENT SCALES

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KEYWORDS
wear; modelling; surface topography; scratching

ABSTRACT

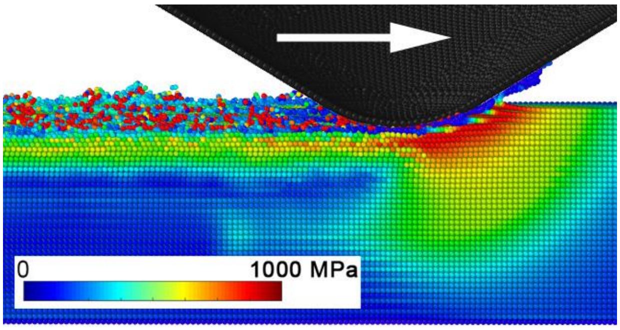
Aluminium is an important material for many industrial applications and often used in daily life for decorative reasons. In both cases scratch damage is an unwanted phenomenon reducing the quality of the product. In order to assess the scratch damage induced by a hard indenter, an experimental and numerical approach was chosen in this study. Topographies and microstructural changes resulting from experimental scratches are analyzed in detail, while numerical simulations were used to investigate the stresses within the material leading to these changes.

Scratch experiments were carried out on a conventional aluminium alloy with a diamond indenter of Rockwell C geometry at various loads. Numerical scratch simulations made use of the mesh-free Material Point Method (MPM) implemented in the open-source code LAMMPS, which is well suited for simulating scratch phenomena [1]. We applied a Johnson-Cook visco-plastic material model, parametrized it according to [2], and refined it based on the experimental scratch results.

A strong focus of this paper lies in the analysis of the microstructural changes. For this, cross-sections of the scratches were prepared for nanoindentation and EBSD analysis to investigate the hardening and grain refining behaviour of the aluminium under abrasive load. The results were compared to the stresses calculated with the numerical model.

The numerical results suggest that stresses up to 1,000 MPa occur during scratching. An exemplary stress distribution is shown in Fig. 1. These stresses are believed to lead to the hardening behaviour detected using nanoindentation.

Fig.1 Modelling of stress distribution during scratching



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CHARACTERIZATION OF VARNISH / NYLON FIBRE ADHESION

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KEYWORDS
Coating; Contact and adhesion; Friction, Scratch test.

ABSTRACT

The adhesion of varnish on different type of materials has caught significant attentions in the past few years. Indeed, varnish is used in many domains medical, textile, mechanical, electronic or electric…

To characterize the tribological behaviour of varnish on any type of surface, a scratch test is used.

The scratch process test is defined as mechanical deformation process where a controlled force or displacement is exerted on a hard-spherical tip to indent onto a substrate and move across its surface at a prescribed speed.

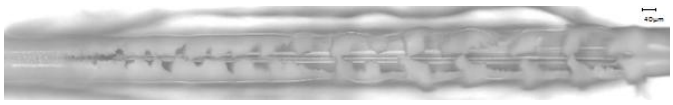
There are mainly two main types of damage found in materials: ductile damage (e.g., shear yielding and ironing) and brittle damage (e.g., crazing and cracking); their occurrence depends on the material characteristics and applied stress state and magnitude [1;2]

To characterize the adhesion between varnish and a mono fiber of nylon, a series of scratch tests on coated fibers with different type of varnish were performed.

The scratch damage features were characterized by optical microscope. Brittle damages were identified for the majority of samples. Studying the effect of this manipulation shows that the magnitude and the shape of the cracks depend on the load applied to the fiber surface.

A comparison between the different prints was discussed to characterize the effect of varnish type on the scratch resistance.

Fig.1 A scratch test on mono fiber of nylon coated with varnish



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ABRASION WEAR RESISTANCE OF MODIFIED HADFIELD STEELS

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KEYWORDS
Wear; Experiments in tribology; Hadfield Steel

Hadfield austenitic manganese steel are widely used in industrial applications that include rock crushing and railroad crossing due to their high toughness, excellent wear resistance and high work hardening ability. The traditional chemical composition of Hadfield steel alloys containing approximately 1.0–1.4% C and 10–14% Mn. It is known that increase in carbon content results in an improvement of abrasion wear resistance [1,2]. Nevertheless, the addition of this element compromises the toughness caused by grain boundary carbide precipitation [3]. Moreover, avoid the carbides precitate phases is achieved by dissolution of carbides by a suitable heat treatment, addition of elements that delay carbide formation such as Mo, or reduction of carbide-forming elements such as C [3]. Additionally, adding nitrogen (includes nitrogen in solid-solution and in precipitate form) has received a lot of interest to steel because improves its mechanical strength without change in ductility [4].

In this study, the abrasive wear behavior and mechanism of a standard Hadfield steel (1.1%C, 13%Mn, 1.5%Cr) and a modified austenitic manganese steel with lower carbon content and nitrogen addition (1.05%C, 13%Mn, 2.5%Cr and 0.05%N) were investigated. Abrasive wear tests, using a rubber wheel abrasion tester, were carried out applying normal loads up to 200 N with abrasive size of 0.2 mm for 600 s. The steels were: (i) standard Hadfield steel, (ii) Class C Hadfield steel with 2.5%Cr and (iii) modified Hadfield steel with nitrogen. The microstructure of these modified austenitic manganese steel alloys was studied thoroughly using optical microscopy (OM), scanning electron microscopy (SEM) and X-ray diffraction (XRD) and was compared to the standard Hadfield steel. The worn surface and the wear debris were analyzed by SEM and XRD. Macro and microhardness were measured before and after the wear tests in order to analyze the strain-hardening effects beneath the abraded surfaces. The surface topography of the wear scars was examined by a non-contact 3D profiler in order to measure the depth of the abrasive penetrations. Microstructural results showed that varying the carbon content in the Hadfield alloys can affect the abrasive wear resistance which leads to considerable changes of the mechanical properties. The wear results showed that the traditional Hadfield steel had a higher wear resistance than modified Hadfield steel, as shown in Fig. 1. This is associated with a higher hardness of the traditional alloy, as observed in the hardness profile realized below the worn surface, where the traditional steel presented a hardened layer with a hardness value higher than 100 HV. The deformed layer below the abraded surface was also analyzed by EBSD. Some regions close to the top of abraded surface was not fully identified due to high deformation, but for the traditional alloy was possible to observed high density of twin formation in comparison to the modified alloys which explains the higher hardness for this alloy, as shown in Fig. 2.

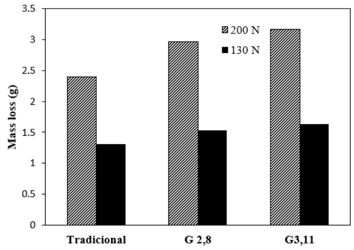

Fig.1 Mass loss as function of normal load

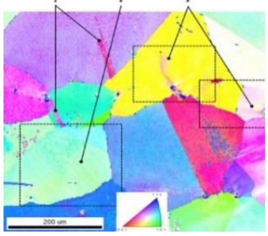

Fig.1 EBSD-IPF of deformed layer.

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EFFECTS OF MUCIN ON MEDICAL GLOVE TRIBOLOGY AND PERFORMANCE

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KEYWORDS
Friction; Fluid Lubrication; Biotribology; Medical Gloves

ABSTRACT
Medical glove use has changed over recent years. Despite allergy fears, the leading preference of material is still natural rubber latex but, synthetic alternatives have been introduced, such as nitrile [1]. It has been shown that all glove materials can affect the grip, dexterity and the tactile feedback of medical glove users. Some of these materials have been assessed in previous studies, but questions still remain as to the effects of them in different user conditions [2]. Many of the current glove test methods do not include the specific tasks and conditions used within medical procedures. For instance, many test do not consider the bodily fluids that could be present during glove-surface interactions. This study aims to assess how mucin (found in saliva and mucus, around organs) affects the sensitivity and dexterity of latex and nitrile medical glove users. This study also seeks to assess how the frictional behavior of the gloves change in the presence of such fluids.

15 subjects took part in the dexterity assessments whilst 10 took part in the sensitivity assessment. Sensitivity was assessed using a "bumps" perception test, which is described in Mylon *et al* [4]. Gross dexterity was measured using the Purdue Pegboard test whilst fine dexterity was measured using the Crawford Small Parts Dexterity Test. Five gloving conditions were used for the assessment: bare hand, latex, nitrile (both dry), and latex, nitrile (both with a 10mg/ml concentration of porcine gastric mucin applied). Frictional properties were assessed by having one participant run their finger over a polished steel strip (Ra 0.11µm) with a normal force ranging from 1 to 5N. Latex showed a decrease in sensitivity and gross dexterity with a higher friction coefficient at lower loads when mucin was applied. Nitrile, on the other hand, showed an increase in dexterity when mucin was applied across the sensitivity test and both dexterity tests. The friction coefficients at all loads used were lower when mucin was applied to the nitrile gloves. As mucin is a protein, it undergoes conformational changes and this particular protein has the ability to form muco-adhesive films, which appeared to be more pronounced at higher loads as the friction increased over time, as seen in Figure 1. This was more evident in the latex over the nitrile material. The results of this study show that bodily fluids having an effect on glove user's dexterity and sensitivity and this is linked to change in tribological behaviour.

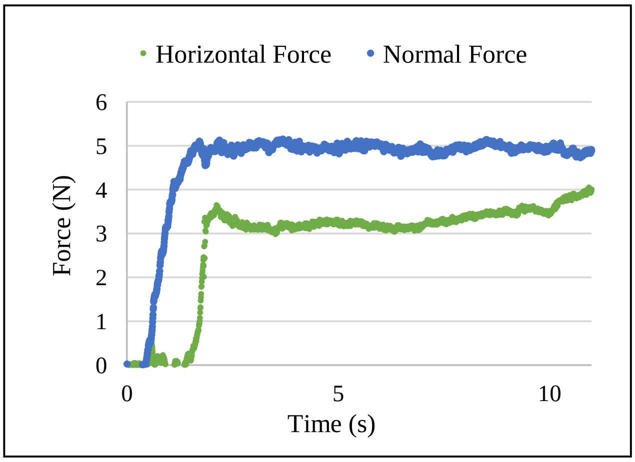

Fig 1. Example of raw data from sliding of latex glove across steel strip with mucin present.

ACKNOWLEDGMENTS
This research was funded by the Engineering and Physical Science Research Council (EPSRC) though the integrated Tribology Centre for Doctoral Training (iT-CDT) with additional support from Synthomer (UK) Ltd.

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

NANOTRIBOLOGY OF PEARLS – INFLUENCE OF THE ORGANICS' CONTENT ON THE FRICTIONAL DISSIPATION OF SHEET NACRE

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KEYWORDS:

Biotribology ; Nano Tribology ; Tribofilms ; Sheet nacre

ABSTRACT

Sheet nacre is a hybrid biocomposite with a multiscale structure, including nanograins of $CaCO_3$ and two organic matrices [1] : (i) the *interlamellar,* mainly composed of β-chitin and proteins, and (ii) the *intracrystalline* composed by silk-fribroin like proteins. This material is currently studied for the manufacture of small prostheses – *eg.* rachis or dorsal vertebra prostheses [2] – which can be subjected to *slip* or fretting motion at the nanoscale. In a recent work, it has been demonstrated that the tribological behavior of sheet nacre is completely controlled by the organic matrices on a large range of frictional dissipated powers. Besides, various dissipative mechanisms are involved within the contact as function of the injected power. Thus, an interesting lubricant effect [3] due to the presence of an organic tribolayer generated by the organic *interlamellar* phase can be observed in association with some very long recovery-time viscoelastic deformations of the organomineral tablets [1, 3]. However, the influence of these organic matrices on the frictional behavior is not completely understood yet.

In order to address this issue, the role of the organic phases in the dissipation process will be investigated in the present work by controlling the organics' content within the nacre specimen. This content is varied by using pearls created by freshwater bivalve mollusks *Hyriopsis cumingii* displaying a polymorph sheet nacre in the same pearl sample – *ie*, *lustrous* aragonite area *vs*. *milky* vaterite area with a lack of *lustrous*. Besides a different crystallographic structure (hexagonal *vs.* quadratic) the *milky* vaterite area own at least 20% more organics with respect to the *lustrous* aragonite area [4, 5].

In this work, evolution of friction laws of the *lustrous* and *milky* pearls are both studied as a function of sliding amplitude and velocity by using a AT-cut quartz crystal resonator (QCR, 10 MHz) which is in contact with the both pearl area at constant normal load (8 mN). The surface displacement amplitudes of the AT-cut QCR – *ie,* the sliding amplitude – is controlled by means of a Vector Network Analyzer (VNA *R&S ZNC 3*) [6-8]. In order to study the interaction between the QCR and pearl's asperities, experiments were performed over a wide amplitude range – from 0 to 40 nm – by changing the drive level provided by the network analyzer [7]. Thus, induced sliding velocity lies from $mm.s^{-1}$ to $m.s^{-1}$ which corresponds to an injected mechanical power from nW to mW.

When the pearl is applied at constant normal load on the QCR, the network analyzer sweeps the frequency across the resonance and measures the resonator's electrical admittance [8]. At the resonance frequency, the real part of the latter forms the well-known resonance curve which is characterized by its quality factor Q. Hence, any variations of resonance frequency (dF) and dissipation factor ($dD = dQ^{-1}$) can be studied over time as function of the sliding amplitude or sliding velocity [9].

As a result, friction laws, static and dynamic contact parameters can be extracted using parametric identification of *emerging* frictional behavior on various scales [10, 11]. Thus, the frictional behavior can be accurately studied – for strong bonding conditions – by fitting the evolution of *slip-time (ie. dD/dF) vs.* amplitude by power-laws [10]. Hence, the power-law exponent continuously changes *vs.* amplitude. Since this evolution is equivalent to those of friction force *vs.* velocity [10], friction laws can be accurately extracted for the both *lustrous* and *milky* area and then, studied as function of the organics' content and the injected power within the contact.

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

The Tribological Properties of Methyl Cellulose as a Model Oviductal Fluid

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KEYWORDS
Friction; Rheology; Biotribology, Experiments in tribology

ABSTRACT

As a medical issue, infertility affects approximately 186 million women from all parts of the world, consequences are varied and can include societal repercussions and personal suffering [1]. The viscosity of the oviductal fluid may provide important information regarding the success rate of the spermatozoa reaching the oocyte and subsequent fertilisation. As the sperm needs to traverse against the oviductal flow gradient, also known as rheotaxis, a higher viscosity of the oviductal mucus presents an obstacle for the sperm. It also decreases the frequency and wavelength of the sperm flagellar wave. The transport of an oocyte from the ovaries along the fallopian tubes can be described as a tribological process, as traction forces experienced by cells are crucial to various biological processes such as wound healing, angiogensis and metastasis. To understand the influence of the physical properties of the mucus on the tribology of the system, there is a need to formulate a model fluid that closely replicates the oviduct mucus. A Methyl Cellulose (MC) based model mucus was developed, which has previously been reported as an ideal in-vitro sperm motility fluid [2]. Understanding the behaviour of the mucus under various dynamic conditions, allows a correlation on the effect of MC concentration on the tribology of the system. Physical properties including the density, viscosity, surface tension and the contact angle were evaluated. Further to which, a mini-traction machine (MTM) was employed to obtain a fully automated traction mapping of different concentrations of the model mucus. The experimental conditions consisted of a 19.05mm PDMS ball (E= 0.7GPa, ν=0.5) loaded onto a 46mm diameter silicone elastomer disc (E= 6.9MPa, ν=0.5) (figure 1a), which were independently driven in order to simulate the interactions between the mucus, fallopian tube wall and the oocyte, the temperature was set to 37˚C to simulate the body temperature. Stribeck curves were formed for all samples by measuring traction from 0-100mm/s with a scaled-up 2N normal force. As the viscosity of the model mucus is increased with higher concentrations of MC, a reduction of the traction coefficient is observed (figure 1b). This is a favourable condition for oocyte transport, however may negatively affect sperm rheotaxis. These results suggest that a balance in the physical and tribological properties of the mucus is essential to provide the favourable conditons for successful fertilisation.

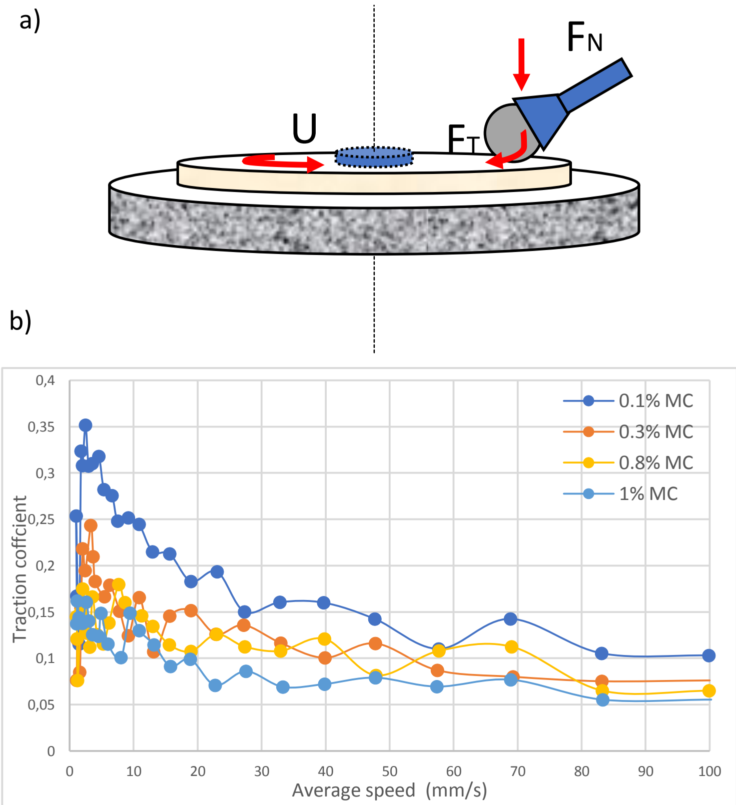

Fig.1 a) Schematic of Mini traction machine (MTM) b) coefficient of traction versus speed of 0.1-1% Methyl Cellulose.

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SUSTAINED RELEASE OF AGAROSE-HYALURONAN HYDROGEL WITH ANTI-FRICTION PERFORMANCE

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KEYWORDS
Biotribology, artificial hip joints, EHL, friction

ABSTRACT

Hyaluronic acid (HA) as a major constituent of bionic synovial fluid (BSF) has significant role in lubrication of human body hip joints. Those who mostly suffer from joint related disease prefer to try injections of synovia after total hip arthroplasty (THR). However affection of Metabolism process to the injected synovia is able to destroy prolonging the life time of the prostheses. In this study injectable, thermosensitive agarose hydrogel as a carrier for hyaluronic acid has been investigated to extend the life time of the artificial hip joints. Experimental evidences reveal bioactivity, superior viscoelasticity and naturally amorphous network structure of the HA in combination with the large molecules of agarose is able to create the three dimensional polymeric network to separate the conterminous surfaces and improve the lubrication with more than 30% reduction rate in coefficient of the friction. Role of mechanical and rheological properties of designed polymeric network in cumulative of the release has been widely investigated. Novelty of the present work provides a survey to the long-term lubrication of artificial hip joints.

ACKNOWLEDGMENTS

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Protein film formation and its protective role on dental tissues under tribological and acidic conditions

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Introduction

Dental erosion (chemical degradation, corrosion) and tooth loss due to wear is an area of concern in modern dentistry, with growing interest in preventative and restorative measures. Acidic and high sugar diets are linked to being one of the leading causes of this. Pathological conditions, like Xerostomia (dry mouth syndrome), that reduce salary flow also have an effect on this [1]. A reduction of saliva in the oral cavity reduces its buffering capability and the amount of proteins suspended in the saliva which would adhere to dental and oral tissues to form a protective film known as the pellicle [2]. This film serves as a protective diffusion barrier against chemical attack and can reduce the dental and oral surface friction considerably [3-4]. If the film is not adequately formed, it can easily be removed due to the mechanical action of mastication. Once underlying enamel is exposed by this, chemical dissolution may take place in acidic conditions. This combination of mechanical and chemical interactions gradually wear teeth down over time.

While some studies have examined the components of this protein film formation and others have examined effects of tribology of surfaces in salivary mediums, it is not fully known how the pellicle's composition and structure influence its tribology under normal and acidic conditions. It is also not known what conditions can aid in maximizing the protective capabilities of this protein film, specifically looking at its composition and structure. This knowledge is essential for improved artificial saliva substitutes and other preventative therapies to reduce the effects of tooth erosion. This study therefore aims to examine the formation of these protein films on the surfaces of hard dental tissues and their protective roles under combined erosion and masticatory conditions.

Methodology

Tribological experiments were conducted by immersing bovine enamel and steatite (magnesium silicate) samples in solutions of different pH and ionic concentration, with and without the addition of porcine gastric mucin (PGM). A nanotribometer (Anton Parr, NTR^3) was used to simulate sliding of teeth after impact using a reciprocating ball on flat configuration against a Ø3 mm Yttria stabilized tetrahedral zirconia polycrystalline (Y-TZP). Friction was monitored by the tribometer and wear data was collected post-test using vertical scanning interferometry (Bruker, NPFlex) for wear scar analysis and Atomic Absorption Spectrophotometry (Agilent, 200 series AA with SIPS) for quantifying calcium dissolution into the immersing solutions.

The nanomechanical properties of the adhered mucin films was quantified using Atomic Force Microscopy, AFM, (Bruker, Multimode 8). Utilizing the Peakforce QNM imaging mode in liquid conditions, nano-indentations were performed over the enamel and steatite surfaces after immersion in a particular mucin solution for a given time period. Height data as well as elastic modulus, adhesion, dissipation and deformation would be determined for each pixel. A quartz crystal microbalance with dissipation monitoring, QCM-D, (Qsense, UK) was used to assess protein absorption kinetics. QCM experiments were conducted for these solutions to monitor the rate of growth, film thickness and viscoelasticity.

Results & Discussion

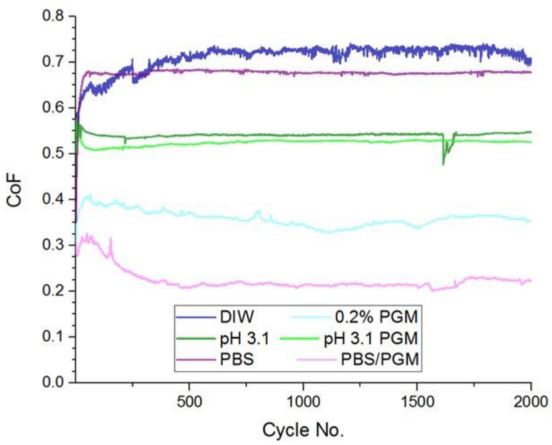

Figure 1 – Mean coefficient of friction for enamel samples. Deionised water (DIW), phosphate buffered saline (PBS), pH 3.1 citric acid (pH 3.1) and solution with mucin in (-PGM).

DIW and PBS mucin solutions give a much lower CoF compared to their non-mucin counterparts while the pH 3.1 mucin solution has had little influence on the friction, shown in Figure 1. The lower CoF in the PBS mucin solution was linked to the ionic content and the subsequent interactions with the mucins. This is supported in the QCM-D tests where the mucin's film thickness and elasticity of 26.4 nm and 22.2 kPa differ compared to the DIW mucin solution of 18.6 nm and 38.2 kPa. The presence of ions has been shown to influence the way in mucins modify friction as a result of the underlying film properties.

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INFLUENCE OF CONTACT LOAD ON TRIBOLOGICAL BEHAVIOR OF POLY(VINYL ALCOHOL) HYDROGELS AS ARTIFICIAL CARTILAGE MATERIAL

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KEYWORDS
Biotribology; Everyday life tribology; Friction; Hydrogel

ABSTRACT

1. Introduction

Poly(vinyl alcohol)(PVA) freezing-thawing (FT) gel, cast-drying (CD) gel, lamination-type hybrid gel composed of FT and CD gels (Hyb-LM), and composite-type hybrid gel as composite cross-linking networks of FT and CD gels in single layer (Hyb-CP) were developed as artificial cartilage material. Hyb-CP showed low friction and wear[1,2] and its friction coefficient has no sliding-speed dependency[3]. In daily activities, not only sliding speed of articular joint surface but also applied load varies, so artificial cartilage materials have to show excellent tribological properties under varying sliding conditions. In this study, the influence of contact load on friction property of PVA hydrogels was evaluated.

2. Methods

15 wt% solution of PVA (average polymerization degree: 1,700, saponification degree: 98.0~99.0 mol%) was used as raw material for PVA hydrogels. FT gel was prepared by repeated freezing-thawing method with the same condition in previous study[1]. CD gel was prepared by cast-drying method with drying temperature of 60ºC and humidity of 80%RH (CD-HT) or 8ºC and 50 %RH (CD-LT). For the preparation of Hyb-CP gel, FT gel was firstly prepared in polystyrene dish by single FT treatment. Then, the sample was dried in the temperature and humidity controlled chamber (60ºC, 80%RH). After the drying process, the samples were treated by single FT process. The sample was dried in the temperature and humidity controlled chamber (8ºC, 50%RH) and the dried sample was swollen in pure water and Hyb-CP gel was obtained.

The sliding pairs of flat PVA hydrogels and an alumina ceramic ball (φ = 26 mm) were tested in reciprocating friction test. The applied load was 0.98, 4.9, 9.8, 14.7 and 24.5 N. The sliding speed was 30 mm/s and the total sliding distance was 2.5 m. Pure water was used as a lubricant for friction test. All friction tests were conducted in room temperature.

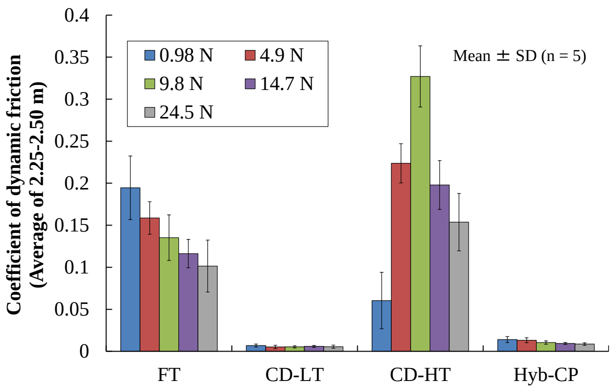

Fig.1 Coefficient of dynamic friction of PVA hydrogels

3. Results and discussion

FT and CD-HT gels showed load-dependency of coefficient of dynamic friction (CoF) and CoF of FT gel decreased with increase of applied load. Cof of Hyb-CP gel slightly decreased with increase of applied load, but CoFs of Hyb-CP and CD-LT gels were nearly constant. In previous studies, CoFs of Hyb-CP and CD-LT gels showed no sliding speed-dependency[3] but wear resistance of Hyb-CP gel is superior to CD-LT gel[1,2]. These results indicated that Hyb-CP gel has superior tribological property under varying sliding condition expected in articular motion.

ACKNOWLEDGMENTS

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QUANTIFICATION OF CORROSIVE MATERIAL LOSS FROM COCRMOTI6AL4V FRETTING CONTACTS

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Introduction

Modern Total Hip Replacements (THR) frequently feature modular taper connections, particularly in between the femoral head and stem. Under cyclic loading as a result of patient gait, these taper connections undergo fretting. *In vivo* they can also rapidly form an electrochemical crevice resulting in synergistic degradation referred to as mechanically assisted crevice corrosion or fretting-corrosion [1]. Recently several studies have measured the micromotion taking place at the taper interface and noted a range of amplitudes from as low as 2 µm up to approximately 50 µm depending on seating conditions [2-4]. The aim of this study was to quantify the corrosive degradation taking place under these parameters and beyond into 'gross-slip' and to correlate corrosive material loss with dissipated energy.

Methods

A simple configuration sphere-on-flat fretting tribometer was used to recreate different fretting regimes under contact conditions commonly found in THR modular tapers, as reported in the literature [2-4]. The contact consisted of a CoCrMo pin with domed surface (r = 25 mm) and a Ti-6Al-4V plate. The pin was loaded such to give an initial contact pressure of 300 MPa (P_{mean}). The lubricant used was Foetal Bovine Serum (FBS) diluted to a total protein concentration of 30 g/L with deionized water and made to 1x Phosphate Buffered Saline (PBS). Sodium Azide (0.03%) was added in order to retard bacterial growth. The couple was articulated for 10,000 cycles at 10, 25, 50, 100 and 150 µm displacement amplitudes. Tangential force and displacement was recorded to calculate the dissipated energy per cycle.

The fretting tribometer was instrumented with a threeelectrode electrochemical cell in order to measure the corrosive material loss *in situ* during fretting. A connection was taken from the pin and thus the working electrode (WE) consisted of the immersed surfaces of both the pin and plate. A combination Reference Electrode (RE, vs. Ag/AgCl) and platinum Counter Electrode (CE) was used to complete the cell. The Open Circuit Potential (OCP) was monitored throughout the experiment and sampled at 0.1 Hz. Periodically the WE was polarized to +50 mV vs. OCP and the resultant anodic current sampled at 10 Hz. The charge transferred as a result of the overpotential was calculated which is linked to the corrosive material loss.

Results

The charge transferred as a result of fretting articulation can be seen in Figure 1. During fretting the measured charge transferred increased from approximately 3.8 µC at 10 µm amplitude to approximately 17.2 µC at 150 µm amplitude. This increase did not occur linearly however and was highly dependent on the fretting regime as it transitioned from 'stick' at 10 µm to 'stick-slip' and finally 'gross-slip' at 150 µm.

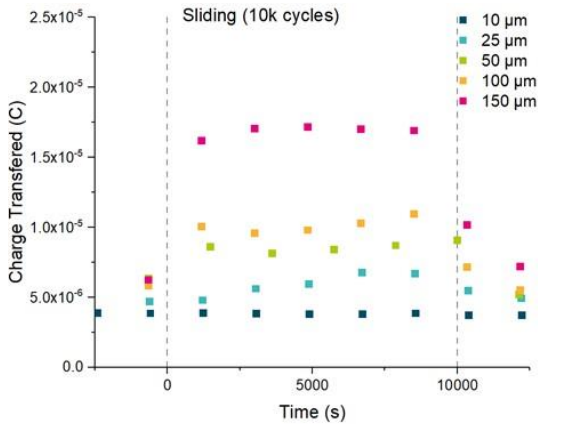

Figure 1: Charge Transferred during 10,000 cycles of fretting under 'stick' (10 µm), 'stick-slip' (25 & 50µm) and 'gross-slip' (100 & 150 µm) fretting regimes.

Discussion

In modular tapers the total degradation is dependent on both the mechanical fretting processes and corrosive material loss, as well as their synergistic effects. The mechanics of the contact correlate with the electrochemical degradation. With increased fretting amplitude, dissipated energy and different fretting regime the charge transferred increased.

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STRUCTURAL AND LUBRICATION PROPERTIES OF THE HYDRATION LAYER OF ARTICULAR CARTILAGE

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KEYWORDS
Biotribology ; Friction ; Everyday life tribology ; Articular cartilage

ABSTRACT

[Introduction]

Previous studies indicated that a hydration layer is formed an articular cartilage surface with proteoglycan molecules protruding from cartilage surface. The hydration layer contributes to excellent lubrication property of articular cartilage[1~3], but its detailed structure – function relation has not been clarified yet. In this study, we investigated structural and lubrication properties of the hydration layer to elucidate its lubrication mechanism.

[Method]

Cartilage specimens were harvested in a cylindrical shape from the load-bearing area of the distal femur of immature porcine knees. In addition to intact cartilage samples, rubbed cartilage samples were prepared in which the hydration layer of the samples was removed by rubbing against a flat glass plate with a friction distance of 60 m. Surface morphology of cartilage samples was observed using an amplitude-modulation atomic force microscope, and the cross-sectional imaging of hydration layer was conducted using a frequency-modulation atomic force microscope. Friction test was performed for the cartilage samples against an alumina ceramic ball of 3 mm in diameter with a friction speed of 0.5, 1.0, 5.0 and 10 mm/s. The load was 0.9 N (maximum surface pressure : 2.25 MPa), and the total friction distance was 1.0 m.

[Result and Discussion]

Surface morphology revealed that the hydration layer was removed with 60 m-rubbed cartilage. Cross-sectional imaging revealed that a hydration like layer with a thickness of approximately 6 μm was confirmed on intact cartilage surface (Fig. 1). The coefficient of dynamic friction of intact cartilage was lower than that of 60 m-rubbed cartilage, and the coefficient of dynamic friction of intact cartilage tended to decrease with the increase of friction speed (Fig. 2). These findings suggest that the hydration layer contributes to improvement of the lubrication property of articular cartilage.

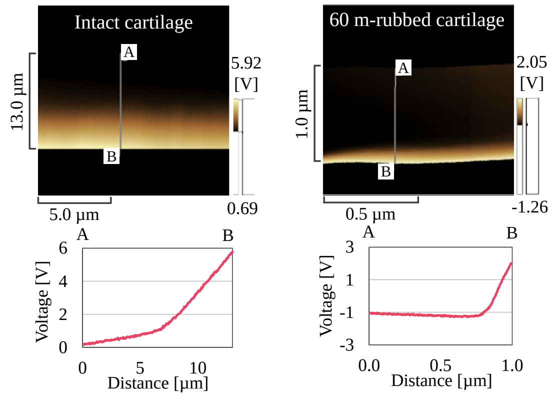

Fig. 1 Z-X mapping images (upper) and voltage profile in arbitrary section (lower) of hydration layer on cartilage

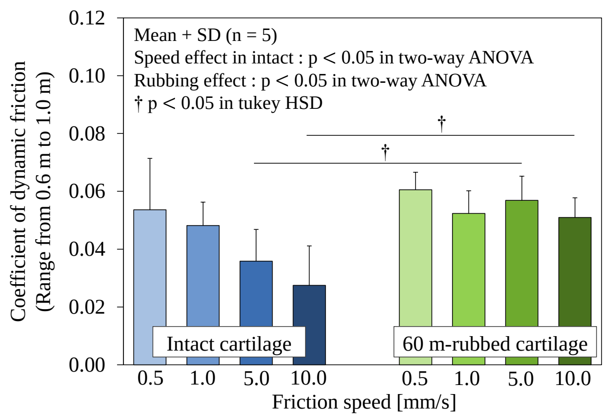

Fig. 2 Coefficient of dynamic friction of intact and 60 m rubbing cartilage

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INFLUENCE OF COLLAGEN STRUCTURE ON THE MECHANICAL PROPERTY OF ARTICULAR CARTILAGE

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KEYWORDS
Biotribology; Friction; Modelling in Tribology, Polyvinyl alcohol hydrogel

ABSTRACT

[Introduction]

Articular cartilage shows excellent mechanical properties with unique structure formed mainly of collagen fiber. However, it is difficult to discuss the relationship between the collagen network and mechanical property in detail using actual cartilage specimens since the factors affecting the mechanical properties are diverse and complicated. In this study, using of fiber-oriented poly(vinyl alcohol)(PVA) hydrogel mimicking articular cartilage structure, we clarified the influence of changes in collagen structure change due to tissue maturation on the mechanical property of articular cartilage.

[Method]

As shown in Fig. 1, oriented PVA fibers were placed in acrylic mold. Twenty five wt% aqueous solution of PVA (polymerization degree: 1,500-1,800, Saponification degree: 98.4-99.4 mol%) was poured into the mold. And then, this sample was treated by 4-times repeated freezing-thawing method (freezing process: -20°C for 8 hrs, thawing process: 4°C for 16 hrs). Considering the collagen content[1)] and density[2)] of immature and mature cartilage, the interval of PVA fibers were 0.4 and 0.8 mm for the immature and mature models, respectively. In addition, fiber-free PVA hydrogel was prepared as a comparative control. Unconfined compression test was performed on the cartilage model at a compression rate of 5, 30, and 100 μm/s. Friction test was performed on the cartilage models against an alumina ceramic ball of 6 mm in diameter with a friction speed of 5.0 mm/s. The load was 0.7 N (maximum contact pressure: 0.28 MPa), and the total friction distance was 2.4m. Two friction directions were selected; perpendicular (⊥) and parallel (//) to the fiber orientation inside cartilage models.

[Result and Discussion]

The elastic modulus of mature model showed a tendency to be higher than that of immature model. In contrast, the coefficient of dynamic friction of mature model showed a tendency to be lower than that of immature model when sliding parallel to the fiber orientation (Fig.2). These findings suggest that changes in collagen structure due to maturation contribute to improvement of the mechanical property of articular cartilage.

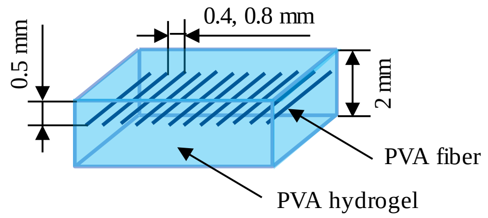

Fig. 1 Schematic drawing of a fiber-oriented PVA hydrogel as a cartilage model.

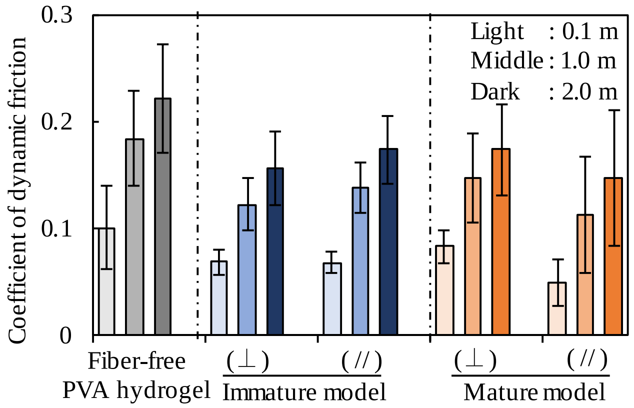

Fig. 2 Coefficient of dynamic friction of Fiber-free PVA hydrogel and cartilage models (Mean ± SD (n = 5), *: $p < 0.05$ in Tukey's HSD test).

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

ORIENTATION BASED FRICTIONAL PERFORMANCE OF MICRO-GROOVE CROSS HATCHED TEXTURES FOR METAL-ON-CERAMIC HIP IMPLANT

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KEYWORDS
Friction; Biotribology; Wear; Micro-groove cross hatched texturing

ABSTRACT
Surface texturing is the latest technology in bio-tribology field to improve tribological performance of an articulating interface. Texture produces micro-hydrodynamic pressure at the contact, acts as lubricant reservoir and also entraps onsite wear debris. Circular, elliptical and triangular texture shapes were investigated for improved tribological performance under conformal contact [1]. The influence of texture shape and geometrical parameters have also been investigated extensively to improve tribological performance [2]. The perpendicular and parallel orientation of micro-groove textures showed a significant impact on the tribological performance of sliding surfaces under different loads [3]. However, the influence of texture orientation still needs to be explored for micro-groove cross hatched textures to improve the tribological performance for hip implant application. Hence, this study investigates the tribological behavior of micro-groove cross hatched surface texture over Metal-on-Ceramic contacts with 0° and 45° texture orientations under bio-lubricated condition. Micro-groove cross hatched textures with 5μm depth and 25% area density were fabricated precisely over Ti6Al4V block samples using Laser Surface Texturing (LST) technique. 3D images of these textures with different orientation were obtained using non-contact type optical surface profilometer as shown in Figure 1. All the textured and untextured Ti6Al4V samples were tested for their friction and wear performance against cylindrical alumina pins for two different loads under bio-lubricated condition using linear reciprocating tribometer. Dimple texture with similar depth and area density was also fabricated and tested for the friction and wear performance using same testing conditions. Tribology results for micro-groove cross hatched and dimple textured samples will be statistically analyzed and compared with untextured samples. Worn-out samples were examined for their surface interaction and wear mechanism using Scanning Electron Microscopy (SEM).

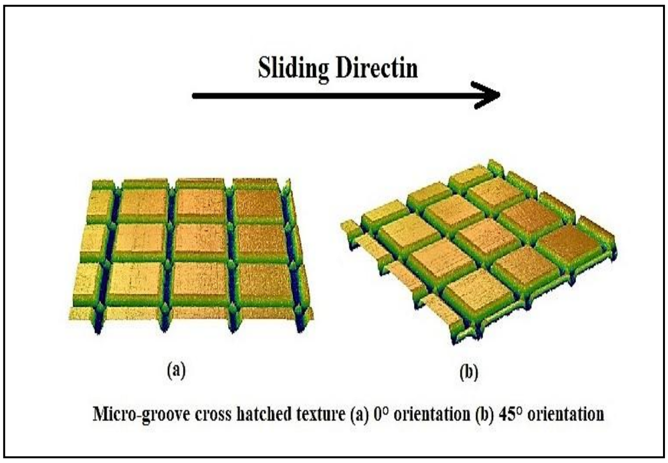

Fig.1 3D images of Micro-groove cross hatched texture with different orientations

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46th LEEDS-LYON SYMPOSIUM on TRIBOLOGY
Lyon, 2-4 September 2019

Invited talk

Neutron and AFM Studies for Understanding of Boundary Lubrication

By Tomoko Hirayama

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Boundary lubrication is one of the most interesting topics in the field of tribology, and a lot of studies have been conducted from the past for understanding the characteristics of boundary lubrication layers. General boundary lubrication layers are formed by the adsorption of additives mixed into lubricant, and then the tribological performances are drastically improved in many cases. However, there is still room for discussion on the 'actual' structure of adsorbed additive layer at the solidliquid interface. This talk will introduce the recent approaches using neutron reflectometry (NR) and frequency-modulation AFM (FM-AFM) for in-situ and operando structural analysis of adsorbed additive layer, and the relationship between the structure and friction coefficient under boundary lubricated condition will be discussed, especially for advanced development of products for daily use.

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FAST TRACTION PREDICTION IN ROLLING/SLIDING EHL CONTACTS

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KEYWORDS

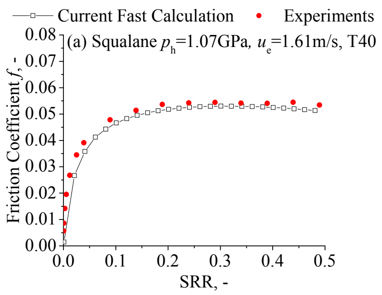
EHL; Fluid lubrication; Rheology; Traction

ABSTRACT

There are several non-Newtonian fluid models in EHL area describing the film behavior under high pressure, high shear, and possible high temperature conditions. However, traction prediction in EHL lubricated rolling/sliding contacts is still challenging. Solving EHL problems with measured fluid rheological properties and appropriate non-Newtonian fluid models is thus of great importance for the quantitative understanding of EHL traction behavior.

Numerical methods, including FDM (e.g. multigrid [1]) and FEM (e.g. with Comsol Multiphysics [2]), could solve EHL problems accurately. However, full numerical methods are usually time consuming for practical applications and may fail to converge under high pressure and some extreme conditions. In this work, a simplified fast traction prediction approach was built for highly loaded point/elliptical EHL contacts based on measured fluid properties (free-volume viscosity model and Carreau shear thinning model). Thermal effects were also included by solving both the oil and solid energy equations considering temperature and pressure influences on the thermal properties of the lubricant.

The proposed fast traction approach is validated by the experimental results of Squalane (a well-characterized reference liquid, see Ref.[3]). The predicted traction curves show agreements and reasonable accuracy with the experimental results over a wide range of running conditions.



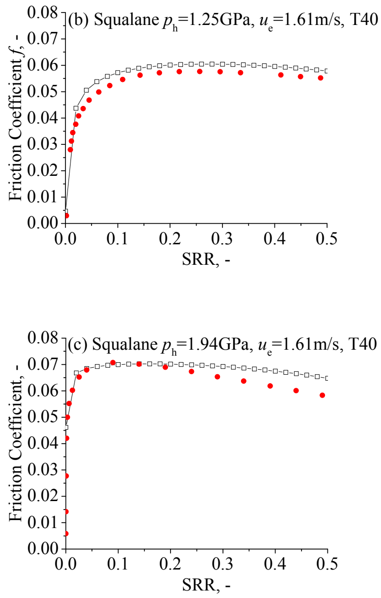


Fig.1 Comparison of the traction curves between calculations and measurements for three Hertzian contact pressures (Squalane, $u_e = 1.61$ m/s, $T = 40$°C)

ACKNOWLEDGMENTS

The authors appreciate Dr.Björling from Lulea University of Technology, Sweden, for providing the experimental results. This research was partly funded by FVV association, Germany.

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EHL MODELING OF ANISOTROPIC MATERIAL FOR POINT CONTACTS

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KEYWORDS

EHL; Fluid lubrication; Modeling in tribology; Anisotropic material

ABSTRACT

Due to increasingly strict performance requirements, rolling bearings usually operate in very demanding conditions. In order to have a better understanding of the fatigue life of rolling bearings, the effect of lubricant pressure and material topology (e.g. surface roughness, inclusion, anisotropy) on subsurface stress distribution should be investigated [1][2]. On a macro scale, the bearing material can be considered as isotropic. However, on the scale of the elastohydrodynamic lubrication (EHL) contact region, the anisotropic feature which originates from crystals rotation may not be ignored. Detailed description of material anisotropy requires dense meshes, which results in huge computational effort and is therefore hard to employ in practical cases. In this work, the multigrid method [3] is applied to the coupled EHL modeling of anisotropic material for point contacts. The results show that the developed multigrid algorithm can solve the problem efficiently and accurately.

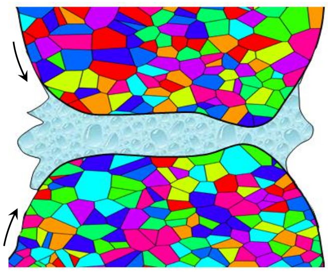

Fig.1 Schematic graph of an EHL lubricated conjunction with anisotropic material

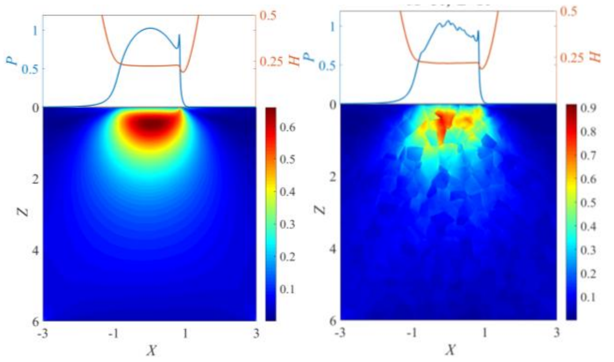

Fig.2 The influence of isotropy and polycrystalline anisotropy material on EHL pressure, film thickness and subsurface Von Mises stress distribution (Newtonian fluid, L=10, M=50)

ACKNOWLEDGMENTS

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LUBRICANT VISCOELASTICITY: IS IT OF ANY RELEVANCE TO QUANTITATIVE EHL FRICTION PREDICTIONS?

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KEYWORDS
EHL; Friction; Rheology, Viscoelasticity

ABSTRACT

From the earliest works on EHL friction [1], lubricant viscoelasticity has often been invoked to justify the use of rheological models that are not supported by primary measurements. It is claimed that the transit time of the lubricant through an EHL contact is too short for a purely viscous behavior to be exhibited, according to which shear stress τ would be related to shear rate $\dot{\gamma}$ and the generalized lubricant viscosity η as follows:

$$\dot{\gamma} = \frac{\tau}{\eta}$$

Instead, viscoelastic behavior is claimed, whereby an elastic component is added to the shear stress-shear rate relation, which is written according to the single mode Maxwell model as:

$$\dot{\gamma} = \frac{\tau}{\eta} + \frac{d}{dt}\left(\frac{\tau}{G_\infty}\right)$$

The property G_∞ corresponds to the limiting high rate value of the lubricant shear modulus. However, too low a value has been used for G_∞, compared to the actual known measured value, leading to an overestimation of the elastic effect.

The current work aims at showing that, when measured values of G_∞ are employed in EHL friction calculations, the elastic response of the lubricant may be ignored and a purely viscous behavior can be assumed [2]. For this, a lubricant is selected, for which the rheology is well characterized and for which the real value of G_∞ is known: di(2-ethylhexyl) phthalate (DOP) [3]. Then, friction calculations are carried out for TEHL line contacts operating under steady-state conditions, using the finite element full-system approach [4]. The results reveal that viscous and viscoelastic predicted friction coefficients are virtually the same and that elastic creep of the rollers has a significantly greater effect on friction than the elastic response of the liquid film. This can be clearly seen for instance in Figure 1, which reports friction curves for a steel-steel line contact with an inlet temperature T_0=50°C, a mean entrainment speed u_m=3m/s and a Hertzian contact pressure p_h=1.3 GPa.

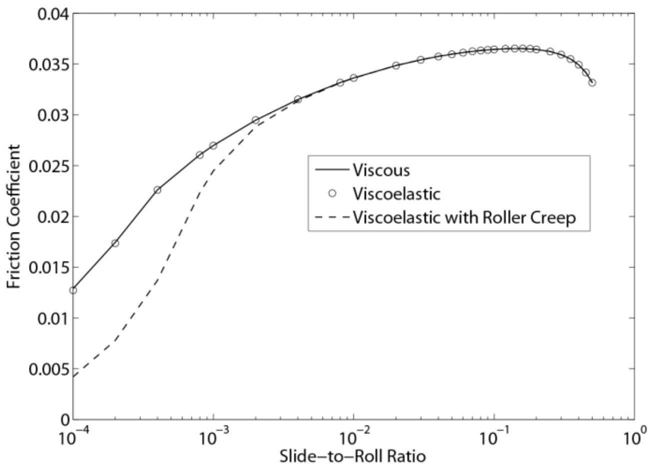

Figure 1: Friction curves for a steel-steel line contact (T_0=50°C, u_m=3m/s p_h=1.3 GPa)

To conclude, the answer to the question raised by the title is a definite no.

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Engine Tribology in Daily Life

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I/c engines will be part of 'daily life' to 2050, as sole or hybrid prime movers. The targets are 50% reduced emissions and 100% increased fuel efficiency. Many engineering disciplines contribute to 'light weighting', increased thermodynamic efficiency, reduced Cd values and more efficient tyres. Internal engine friction from in-bore components is a major energy loss from 'fuel tank' to 'road wheel'

Conventional wisdom was that the lubricant at the piston/bore interface was the same composition as the sump but at a higher temperature. However, a standing lubricant ring was demonstrated in the piston ring zone; later, sampling inter-ring gas found very degraded lubricant. Analyses of bore wall lubricant samples at top ring reversal from diesel engines showed extensive degradation. Degradation of bore wall samples was so extensive that different grades could not be differentiated. Lubricant internal sampling from the ring pack gave insights into degradation of additives and base oil components, improving commercial lubricant formulations. Samples from the second ring groove, intermediate land, top ring groove and crown land showed progressive degradation of base oil and additives components at different rates as lubricant is transported up the piston face. Sequential degradation of ZDDP through several intermediates was shown to lead to the alkyl sulphide as final product.

Continuous gas and oil sampling transport rates plateaued between 40-75% engine of the speed range for varying loads. Ring pack design changes showed differing oil and gas rates, reducing hydrocarbon emissions without increased wear. An engine lubricant transport model based on two, interconnected, Continuous Flow Stirred Reactors, was developed, with the Sump as a large reactor in equilibrium with a much smaller reactor, the Ring Zone. Relative rates of additive and base oil degradation were measured. The concept of a *'residence time'* for a lubricant particle in the Ring zone was developed as a measure of how the ring pack controlled lubricant flow, measured for both small and large diesel engines and at different sampling positions within the ring pack.

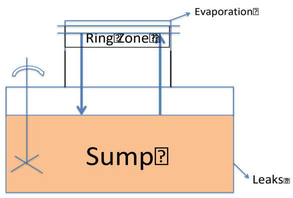

Figure 1. Lubricant Transport Model Between the Engine Sump and the Ring Zone

'Laser-Induced Fluoresence' measured lubricant film thickness in the ring zone for new and used lubricants, finding significant differences between them. 'In-Bore' friction loss measurements showed reductions by added friction modifier to a petrol engine fuel. Alternation between plain fuel and fuel containing individual organics gave up to 4% reduced fuel consumption. Different friction reduction effectiveness was found between organic types and individual within those groups. This effect reduces ring zone friction of domestic and transport, to reduce consumption, in every day life.

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EXPERIMENTAL STUDY OF THE MIXED-ELASTOHYDRODYNAMIC TRANSITION WITH LOW VISCOSITY LUBRICANTS

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KEYWORDS
Mixed Lubrication; EHL; Lubricant additives

ABSTRACT
The friction in passenger car engines plays a crucial role in fuel overconsumption. To minimize friction and reduce these energy losses, new surface coatings and new low viscosity lubricants were developed and their combined use needs to be evaluated. The contacts in engines cover all lubrication regimes and, therefore the Stribeck curve appeared as the appropriate tool for this evaluation. Even if this curve exhibits the three main lubrication regimes, the transition between the mixed (ML) and the elastohydrodynamic (EHL) lubrication must be determined accurately with additional traction experiments. We attempted to find how surface coating and low viscosity lubricants shift the onset of ML.

We performed Stribeck and traction experiments at moderate speed (10^{-3} – 1 m/s) and pressures (0.1 – 1 GPa), for three lubricants of viscosity ranging from 30 to 50 mPa.s at 22°C (base oil, base oil + viscosity index improvers and fully formulated oil) and several surfaces (quartz, sapphire, steel with or without DLC coating). Two ball-on-disc tribometers were used: the IRIS tribometer and the Mini-Traction-Machine (MTM). The surface speeds were controlled independently, and the normal and tangential loads were measured simultaneously. Also, the IRIS tribometer was equipped with an interferometry system allowing the measurement of the contact area and the lubricant thickness distribution. The experimental conditions for the traction experiments were carefully chosen to completely separate the surfaces and minimize the temperature increase. For the Stribeck experiments, a moderate Sliding-Rolling Ratio (SRR = 25%) was chosen to avoid surface wear at low speed. Materials and methods were detailed in [1].

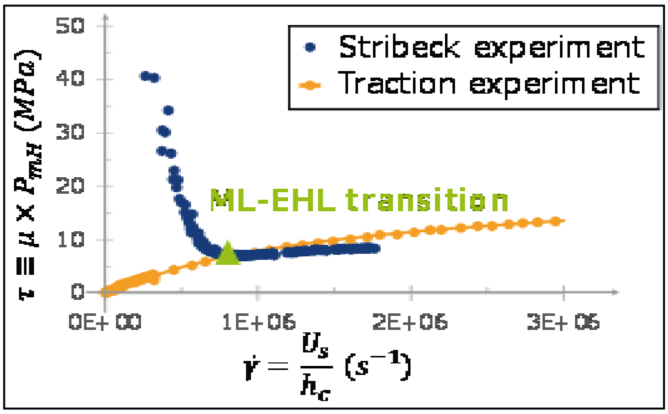

Fig.1 Stribeck and traction curves allowing to define the mixed-EHL transition (example with a low viscosity base oil: steel/steel, mean Hertz pressure 440MPa, Stribeck SRR 25%, inlet oil viscosity 23 mPa.s at 27°C)

The transition was defined as the intersection of the Stribeck curve with the traction curve presented in Fig 1. At this point, the friction becomes higher than the viscous shear stress. The influence of parameters such as the pressure or the sliding will be commented and finally, the role of our surfaces and our lubricants on the ML-EHL transition will be explained.

ACKNOWLEDGMENTS
This study was carried out as part of the IMOTEP project within program ’Investissements d’Avenir’ operated by ADEME.

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CHANGES IN CAVITATION AND CONTACT OIL FILM DUE TO INCREASE IN PERIPHERAL VELOCITY IN TRACTION DRIVE UNDER HIGH LOAD

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KEYWORDS
EHL, Fluid lubrication, Experiments in tribology, Cavitation

ABSTRACT

Traction drive is a device that have the transmit power by rolling contact via lubricating oil. Compared to gears, traction drive has the advantage of being low vibration and noise. Therefore, traction drive is expected to be used for speed reducers for robot joint (control) systems and automotive drive systems.

However, cavitation occurs when the gas in the lubricant oil has been precipitated by the negative pressure in the rear of contact part. The cavitation is considered to affect the flow of the rear part of an oil film and it also causes various problems. For example, in the case of planetary type traction drive that has multiple contact parts, there is a risk of overlap with traction contact parts for the cavitation which is formed at the back of certain contact part[1]. It causes direct solid contacts when the cavitation overlaps. It is also conceivable that the rear part of an oil film is ruptured when the cavitation connects with the atmosphere[2]. This phenomenon decreases the amount of re-supply lubricating oil to the traction contact part[3]. Therefore, it is necessity to understand the characteristics of cavitation in the traction drive. However, in previous researches, observation of cavitation is only performed under low load or low peripheral velocity conditions. The changing of cavitation when the operating conditions is approximately the same with practical range has not actually been confirmed.

In this research, two experiments have been carried out under high load and high peripheral velocity operating conditions. The first experiment is measurement of the size of cavitation as the peripheral velocity is increased under the condition of multiple loads. Another experiment is to visualize the oil film rupture under each load condition. Incidentally, in these experiments, the direction of rotation is also changed to observe the changing cavitation. As a results of the experiments, the following was confirmed. Fig.1 shows that the experimental cavitation length with peripheral velocity at each load. In the measurement of the size of cavitation, it was confirmed that the cavitation extend with an increasing in peripheral velocity. However, under the peripheral velocity more than certain peripheral velocity, cavitation began to shrink. In the visualization of oil film rupture, it was confirmed that the atmosphere, which is sucked from the rear part of an oil film, is connect with the cavitation, cause the oil film ruptures even there is an oil film around the cavitation.

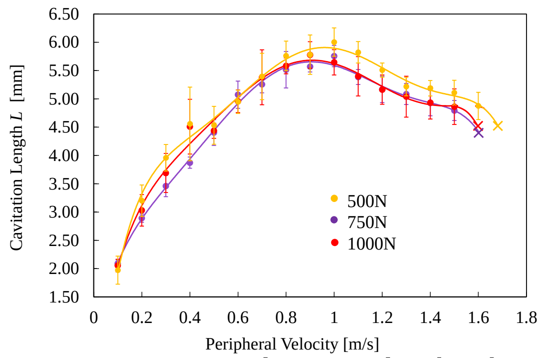

Figure1. Experimental cavitation length with peripheral velocity at each load

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FUNDAMENTAL ASPECTS OF FRICTION IN STARVED EHL CONTACT

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KEYWORDS
EHL, Fluid lubrication, Friction, Rheology

ABSTRACT

Present machine design is driven by demand to increase machine components efficiency to fulfil a vision of sustainability society development. For successful engineering design, it is necessary to predict friction in lubricated concentrated contact. Despite large amount of research made on friction, our capabilities of fluid film friction modelling are still limited.

Common assumption is that main part of sliding friction is produced in the central zone while contact inlet has practically no significant effect on friction. Nevertheless, it was already shown that friction at starved contact is significantly increased. Severe starved contact represents a situation when size of contact inlet is limited, therefore, film thickness is thinner. Under rolling-sliding conditions, lubricant inside contact are exposed to higher shear rate.

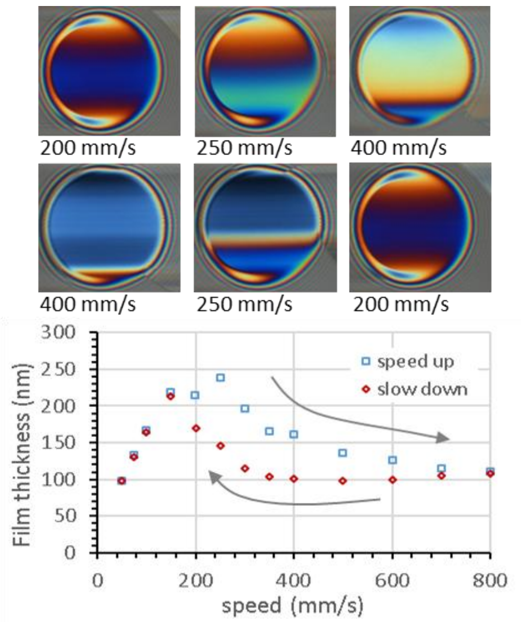

Fig.1 Film thickness and several interferograms from ramp up and down experiments.

Figure 1 shows results of film thickness and several interferograms obtained by thin film optical interferometry technique under 10% slide/roll ratio and 0.6 GPa of Hertzian pressure. The speed was ramped up and down. The film thickness exhibits hysteresis due to starvation which is depends not only on speed but also on time. In Figure 2, there is plotted coefficient of friction depending on shear rate which was derived from measured film thickness. It can be seen that data of friction for speeds up and slow down phases forms single curve.

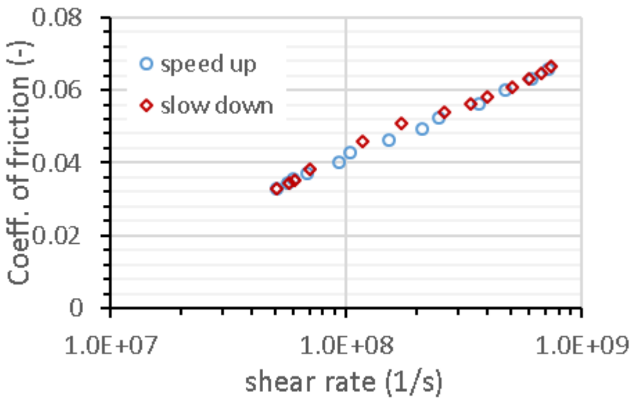

Fig.2 Friction data of measurement in Fig. 1

In this paper the friction of starved contact is analyzed in more detail. Film thickness and friction are measured in-situ. Experimental data for starved and fully flooded contacts are compared for different speeds, slide/roll ratios and loads. Such comparison could depict possible effects of lubricant temperature rises, universality of limiting shear stress and role of conditions in contact inlet on friction produced in central zone. This contributes to better knowledge of lubricant in-contact rheology and lubrication of elastohydrodynamic contact.

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FRICTION OF PEEK WITH STEEL COUNTERPARTS IN EHL AND MIXED LUBRICATION

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KEYWORDS
Friction; EHL; Mixed Lubrication

ABSTRACT
Poly-ether-ether-ketone (PEEK) has better mechanical properties and higher thermal stability than other conventional polymers and therefore it is becoming a preferred material in many tribological applications. PEEK can be used unlubricated but lubrication has the potential to further reduce friction and wear [1]. However, previous reports have mainly focused on wear, and little is known on friction in EHL and mixed lubrication as found in gear and bearing applications. The aim of this study is to elucidate the friction behavior of PEEK with steel counterparts in EHL and mixed lubrication.

A poly−α−olefin oil (PAO) and a naphthenic base oil were used as lubricants. Their properties at the tested temperature of 25 °C are shown in Table 1. Tribological tests were carried out on a mini traction machine (MTM) in a ball-on-disc configuration. The disc, covered with a PEEK sheet, and the steel ball are driven independently to create a mixed rolling/sliding contact with slide-roll ratios of 50 %. The applied loads were tested at 10 N and 50 N. The Ra surface roughness of the smooth steel balls was approximately 0.01 µm, and the semi-rough steel balls were shot blasted to Ra of approximately 0.1 µm.

The friction coefficient values as a function of Uη which is the entrainment speeds (U) multiplied by the dynamic viscosity (η) are shown in Fig. 1. It is expected that the lubrication regimes of our MTM tests were mainly EHL with smooth steel balls and EHL and mixed lubrication with semi-rough steel balls. The friction coefficient of PAO was load dependent only in the mixed lubrication regime. Interestingly, the naphthenic base oil showed almost the same friction as PAO at 10 N, but significantly higher friction than PAO at 50 N, throughout all the lubrication regimes. The literature indicates that the high pressure-viscosity coefficient (α) base oils have increased friction in full EHL regime [3]. By plotting the friction coefficient values of our MTM tests as a function of Uη emphasizes the effect of α which becomes noticeable at higher loads. It can also be seen that the influence of α on friction extends to the mixed lubrication regime with semi-rough steel balls.

Table 1 Properties of test lubricants at 25 °C

		Poly-α-olefin	Naphthenic base oil
Dynamic viscosity (η)	Pa s	0.11	0.44
Pressure–viscosity coefficient (α) *	GPa⁻¹	22	33

* Calculated from kinematic viscosities according to [2]

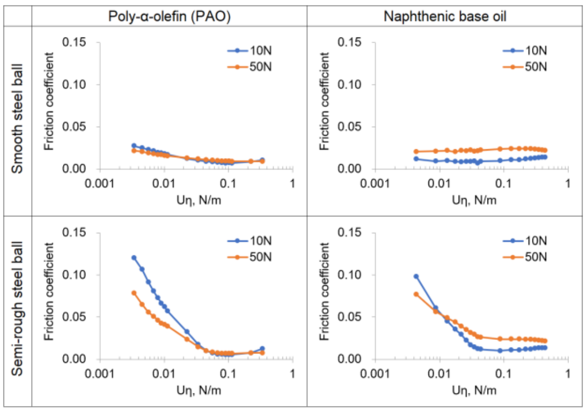

Fig.1 Friction coefficient as a function of Uη

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LUBRICATION CHARACTERISTIC OF SURFACE TEXTURING UNDER RECIPROCATING MOTION

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Keyword Texturation; Hydrodynamic Lubrication; Friction; Numerical analysis

INTRODUCTION

Surface texturing is known as one of the approaches for the improvement of lubrication characteristic[1]. The lubrication characteristics on the sliding surface may vary depending on the shape, size, and arrangement of surface texturing. There are a few studies on lubrication characteristics of surface texturing during sliding movement of reciprocating machines[2]. However, how much these elements affect the characteristics have not been fully understood. This study focus on the arrangement of surface texturing under reciprocating motion to reduce friction loss. Numerical analysis of the lubrication characteristics is conducted in order to examine the optimum arrangement of surface texturing.

ANALYSIS CONDITION AND METHOD

Figure 1 shows the analysis model. Figure 2 shows the textured slider. Table 1 shows the dimension of the slider and texturing. Numerical analysis is performed by solving the Reynolds equation using the finite element method. As the boundary conditions, ambient pressure and negative pressure are assumed to be atmospheric pressure.

RESULT

Figure 3 shows a relationship between reduction ratio of friction loss with ratio of separate length. The friction loss reduces due to the texturing compared with the no texturing. Both of the groove type and the dimple type shown in Fig.2(a) and (b), it is found that the optimum ratio of separate length, *s/L* of texturing exist.

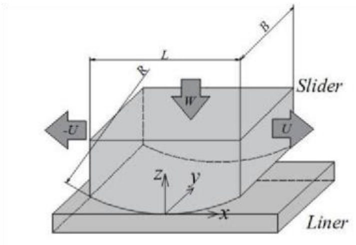
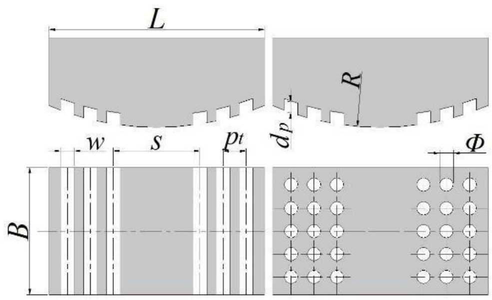


Fig.1 Analysis model



(a) Groove type (b) Dimple type

Fig.2 Textured slider

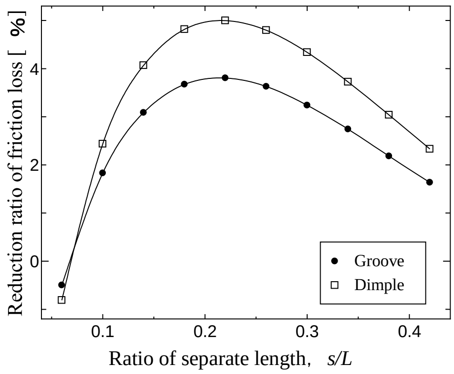


Fig.3 Reduction ratio of friction loss compared with no texturing versus separate length, *s/L*

Table 1 Dimension of Slider and Texturing

L/B	1.0
Area density of texturing, *A*	0.3
Ratio of Pitch, p_t / L	0.06
Ratio of Depth, d_p / L	0.004
Ratio of Separate length, *s/L*	0.06~0.42

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EFFECTS OF DIMPLE SHAPE AND ARRANGEMENT PATTERN ON OIL FILM PRESSURE BETWEEN TWO SLIDING SURFACES

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KEYWORDS
Texturation; fluid lubrication; physics of friction; fluid lubrication analysis

ABSTRACT

Dimple improves supplying the lubricating oil and it reduces friction of the sliding surface. Its effect varies depending on the dimple shape and arrangement pattern, therefor generic design method of dimples has not been clarified. The purpose of this study is to propose a design method of dimples based on fluid pressure under fluid lubrication.

We analyzed maximum load carrying capacity and fluid pressure using the TED/CPA when a single dimple was applied load and sliding velocity in oil lubrication. Figure 1 shows an analytic model, and Table 1 shows analytic conditions. Lubricating oil is compressible viscous fluid, and elastic deformation and surface roughness of materials is not considered. Furthermore, material A slides against material B with dimples. Figure 2 shows a dimple pattern model. We changed the diameter of dimple, depth, curve. The function of curve is denoted by $z = (2/D)^a \cdot d \cdot x^a$ and D, d and a being the diameter of dimple, the depth of dimple and the curve factor, respectively. Dimple becomes flat bottom and cylindrical with increasing the curve factor.

Figure 3 shows the fluid pressure distribution. The oil film pressure reached the maximum pressure on the right side from the center of the dimple. Figure 4 shows the maximum load carrying capacity vs. diameter, depth and curve factor. The maximum load carrying capacity increases with increasing the dimple diameter, and maximum load carrying capacity decreases with increasing the depth of dimple. There is an appropriate curve degree dependance on the depth of dimple. As a result, we proposed the method to investigate the influence of dimple shape on maximum load carrying capacity and fluid pressure.

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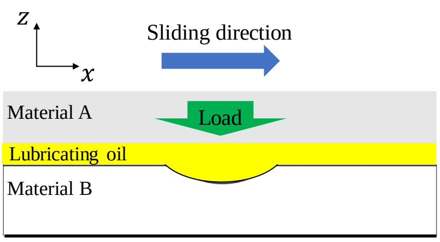

Fig. 1 Analytic model

Table 1 Analytic conditions

Sliding speed, m/s	10
Viscosity, MPa·s	4.6×10^{-9}
Density, g/cm^3	1.0
Film thickness, µm	1.0
Analysis area, mm^2	1.5×1.5

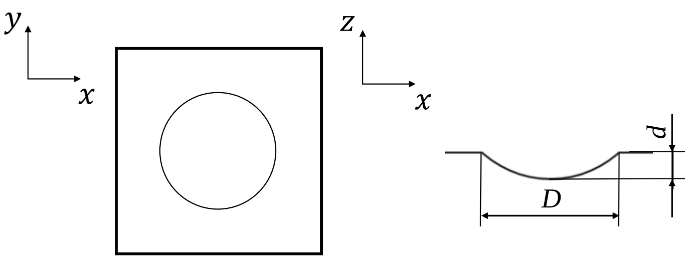

Fig. 2 Dimple pattern model

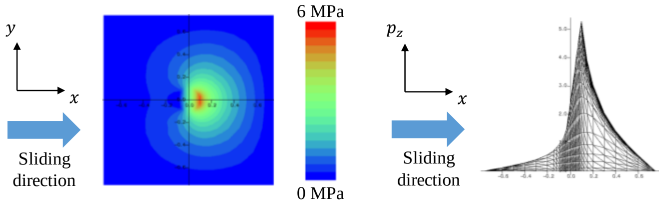

Fig. 3 Fluid pressure distribution

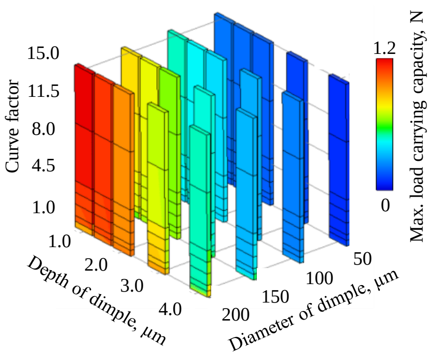

Fig. 4 Analytic result

Effects of thermal deformations on textured thrust bearings optimally designed by isothermal and THD calculation methods

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KEYWORDS
Modelling in tribology, Artificial surface texturing, Fluid lubrication, Parallel surface thrust bearings.

ABSTRACT
In the present work, two numerical optimisation problems have been setup and solved, aiming at evaluating the optimal texture geometry of a sector pad thrust bearing with rectangular dimples. In the first optimisation problem, isothermal lubricant flow has been considered, whereas in second one, a THD modeling approach has been followed. The resulting optimal geometrical configurations have been evaluated with the use of a thermoelastohydrodynamic (TEHD) model, in order to quantify the effects of thermal deformations on the tribological characteristics of the textured bearing. After the TEHD evaluation, four optimal designs have been selected, and a sensitivity analysis has been performed, varying the independent geometric parameters around their optimal values, in order to identify their proximity to a local optimum.

1. INTRODUCTION
Many studies have been conducted aiming at optimising texture design and evaluating the effects of texturing on the tribological characteristics of thrust bearings. In most of the studies, the conclusion drawn was that, for each application, the optimal texture parameters differ (in terms of texture region, shape, depth), thus individual studies need to be performed on a per-case basis [1]. On the other hand, the optimised textured parameters have shown to improve the performance characteristics of the bearings in a narrow range of operating conditions, but both computational [2] and experimental studies [3] have pointed out that, for high values of specific pressure, the positive effect of textures decreases dramatically, whereas, in some conditions, even a parallel thrust bearing exhibits better tribological characteristics than a partially textured thrust bearing optimised for different operating conditions [3]. At high values of specific pressure, mechanical and/or thermal deformations of the bearing geometry become significant, therefore more advanced modelling procedures are required, in order to evaluate the optimal texture geometry of the bearings.

2. METHODOLOGY
To CFD models of a textured thrust bearing (isothermal and THD) have been generated, following modeling techniques proposed in the recent literature [1-2]. Two different optimisation problems have been solved, one for each model. Two sets of optimal parameters have been selected from each optimisation process. The four sets of optimal parameters, obtained from the isothermal and THD optimisations, have been evaluated by a TEHD model. A parametric analysis has been performed for each set, in a range near the optimal parameter values, in order to identify if this set can be characterised as optimal for operation under a thermoelastohydrodynamic regime.

The ThermoElastoHydroDynamic (TEHD) model has been generated utilising a commercial code (Ansys CFX and Ansys Mechanical). A two-way FSI modelling approach has been utilised for the fluid-pad interface. The CFX and FE solvers exchange data for the domain interface (Fluid-Pad). Temperature and pressure field data are transferred from the CFD to the FE solver, and mesh displacement and heat flux of the interface from the FE to the CFD solver. The bearing pad geometry is able to deform due to (a) the temperature gradient, and (b) pressure generated within the thin lubricant film. In the present simulations, lubricant properties and operating parameters are considered to be the same as those in [3].

The bearing geometry is characterised by a parallel sector pad configuration, consisting of 8 pads with 24 rectangular dimples on each pad, being 4 and 6 in the radial and circumferential directions, respectively. The optimisation parameters for both problems are: (a) textured length (as a percentage of the pad length), (b) texture depth, and (c) textured width (as percentage of the pad width). The runner is made of steel and the slider of bronze, both characterized by a thickness of 20 mm.

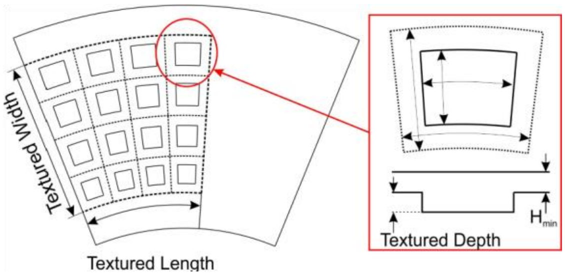

Fig1. Texture geometric parameters.

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BEARING CHARACTERISTICS OF JOURNAL BEARING APPLIED BIOMIMETICS

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KEYWORDS
Friction; Fluid lubrication; Texturation, Biomimetics

ABSTRACT

There will be times when we were walking on a rainy day and we slipped and fell down. Very small friction is realized while supporting a load by merely slight fluid intervening between shoes and the ground. This phenomenon is called fluid lubrication. Those using fluid lubrication are journal bearings used in engines and turbochargers. Journal bearings maintain extremely low friction even under high surface pressure or high-speed rotation because of fluid lubrication. This bearing has evolved for development of high-quality machineries. Especially, friction of bearings used in automobiles is concerned with fuel consumption, so friction reduction is strongly required. In response to that request, various methods have been developed, such as applying a groove-like texture to the engine bearings[1]. However, innovative friction reduction technology is necessary in order to meet the demands of the world. Therefore, author focused on biomimetics. Biomimetics is science and technology that helps new technological development by imitating the excellent functions and structures of organism. However, no research applied to journal bearing has been found.

The organism that the author attracted attention is a dragonfly. Dragonfly has excellent flight ability. In particular, long-distance flight of 7,100 km is possible by using gliding[2]. One of the factors that realizes this flight is micro spikes with a height of about 100 μm present on the wing surface as shown in Fig. 1. It has been clarified that this spike has a resistance reducing effect[3]. From the viewpoint of size effect, the residential environment of the dragonfly is governed by the viscosity like the fluid under fluid lubrication. Therefore, author considered whether it can be applied to friction reduction of fluid lubrication.

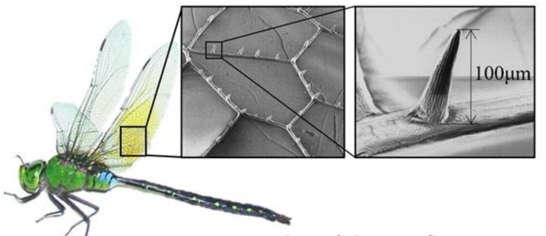

Fig.1 Micro spike of dragonfly

In this study, the structure simulating the micro spike of the dragonfly as shown in Fig. 2 was provided on the sliding surface of the journal bearing, and the effect by spike was considered by measuring the friction torque. As a result, as shown in Fig. 3, the friction torque decreased when the micro spike was positioned on the entire surface and the edge side of the lower half part of the bearing at 4000 rpm and 5000 rpm. Also, when the axial locus was measured, the runout of the shaft was suppressed at the rotational speed which the friction torque was reduced.

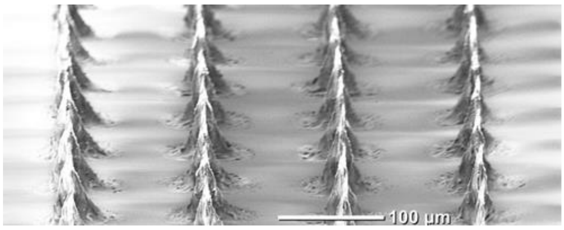

Fig.2 Micro spike of test apparatus

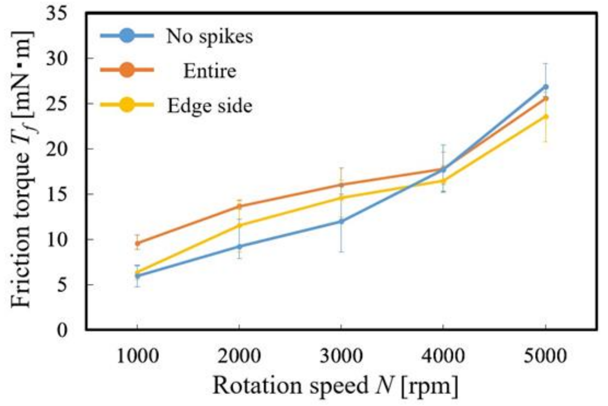

Fig.3 Experimental result

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NUMERICAL AND EXPERIMENTAL OPTIMIZATION OF SURFACE TEXTURES THROUGH THE ADJOINT METHOD

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INTRODUCTION

Among the several numerical optimization tools for engineering problems, the discontinuous adjoint method represents a promising and versatile technique, which can also be applied to the field of tribology[1,2]. In particular, the design of complex engineered surfaces, *e.g.* as textured ones, can thoroughly benefit from this method, as it allows dealing with a large number of degrees of freedom at low computational costs. In order to assess the applicability of this technique on the optimization of an actual tribo-system, this work investigates surface texturing in a twofold approach. Pin-on-disc experiments hereby complement numerical simulations, so that the effects of optimized textures can be compared to traditional texture designs and other numerical methods[3].

Adjoint method; Reynolds equation; Surface textures.

NUMERICAL APPROACH

The cornerstone of the adjoint method is represented by the computation of the sensitivity function, which relates the increment of the aim function (*e.g.* the load carrying capacity) with respect to the variation in the design parameters (*e.g.* shape and location of texture elements and operative conditions). Such computation is based on the governing equation, in our case the Reynolds equation with mass conserving cavitation[4]. Once the sensitivity function is known, it can be used to iteratively update the initial geometry until the desired (optimum) performance is achieved.

The optimization may run also under user-defined constrains in order to exclude trivial solutions or to account for possible manufacturing restrictions. Figure 1 shows, for example, the optimized textured surface of a pin. Due to the different values of gap height and pressure, texture elements in different positions also have a different optimal shape.

EXPERIMENTAL SET-UP

The numerically optimized surfaces are tested on a pin-on-disc tribometer with particular attention to the manufacturing precision of both the texture and the shape of the pin. For this reason, the textured pins are prepared through laser surface texturing, so that every texture element can have a different shape (see Figure 1). The so optimized surface will be subsequently compared to other ones resulting from traditional parametric optimization[3].

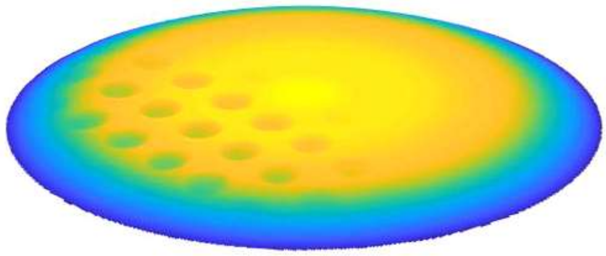

Fig.1 Zoom on the optimized textured surface of the pin. The texture elements consist of dimples (with prescribed circular area) whose depth distribution has been optimized in order to obtain the maximal load carrying capacity. In color is the gap height distribution.

CONCLUSION

The adjoint method can be successfully used in the field of tribology for the optimization of surface textures, allowing to fine-tune each single texture element individually rather than through a trial and error approach with dimples having all the same geometry. The effectiveness of the adjoint method will be also discussed using experimental support from pin-on-disc tribometer results and compared to textures obtained with traditional optimization processes.

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COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS OF THE SKEW ANGLE IN TAPERED ROLLING BEARINGS

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KEYWORDS
Friction; Modeling in tribology; Tapered roller bearing; Roller skew; Contact

ABSTRACT

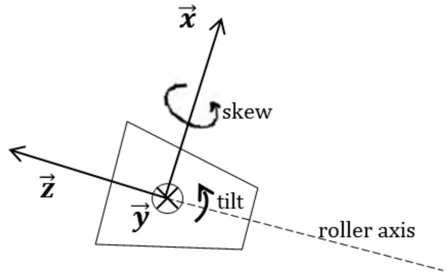
The evaluation of the roller skew has a prime significance for bearing designers and manufacturers. Skewing is presented as the motion of a roller as it rotates about an axis normal to the roller-axis (Fig.1).

This work reports the roller skew of a tapered roller bearing. A numerical analysis for kinematic equilibrium at each rolling element in tapered roller bearings [1] permits to calculate the roller skew angle in tapered rolling bearings. In order to validate the numerical skew values, an experimental setup is built. It allows measuring the roller skew in tapered roller bearings thanks to two Contact Potential Difference (CPD) probes.

The main objective of this work is to compare the numerical skew angles to the experimental values for a tapered roller bearing. Moreover, the effect of the load, shaft speed, temperature, and viscosity of the lubricant are examined.

The primary numerical results are qualitatively in a good agreement with the literature [2, 3]. Results show that the roller skew angle strongly depends on the friction at the rib-roller end contact.

Fig.1 Skewing about the x-axis and tilting about the y-axis of a tapered roller



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INVESTIGATION OF SUBSURFACE MICROSTRUCTURAL ALTERATIONS IN STEEL BEARINGS DUE TO ROLLING CONTACT FATIGUE

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KEYWORDS
Rolling Contact Fatigue; Experiments in Tribology; Wear; Steel Bearings

ABSTRACT
Rolling Contact Fatigue (RCF) in steel bearings can manifest through subsurface microstructural alterations known as dark etching regions (DER) and white etching bands (WEB) under medium-high stress cycles. These features have been researched intensively for decades yet the formation mechanism and how these features contribute to bearing failure remains unknown. DER was reported to be randomly scattered deformed patches of ferrite [1] while WEBs form later in the bearing life and are parallel three-dimensional ferrite discs, which are found to be parallel to the contact surface in the axial direction and inclined to the surface in the circumferential section towards the rolling direction at 20-35° (known as low angle bands or LAB) or 65-85° (known as high angle bands or HAB). The aim of this study is to investigate the formation mechanisms of DER, LABs and HABs by analysing these features formed at different stages of bearing life. A number of angular contact ball bearings (ACBB) subjected to RCF testing under two maximum contact pressures of 2.9 GPa and 3.5 GPa at stress cycles ranging from 151 million to 4141 million are examined. The bearings have been cross-sectioned and metallographically analysed performed using light optical microscopy (LOM), Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy; while nano-indentation tests and Electron Backscatter Diffraction were used to obtain the mechanical properties of different regions within the WEBs.

For the first time, a 3D-model of multiple HABs is established based on multiple LOMs obtained at 5 μm intervals through serial sectioning procedure that has confirmed the structure of the parallel bands in three dimensions (Figure 1). Similar to a previous study [2], analysing LABs and HABs at the very early stages of their formation has revealed that they consist of three main constituents 1) globular equiaxed ferrite grains, 2) elongated ferrite grains and 3) carbon-rich areas as shown in Figure 2.

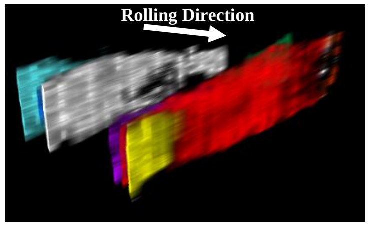

Fig.1 3D-model of HABs in ACBB inner ring

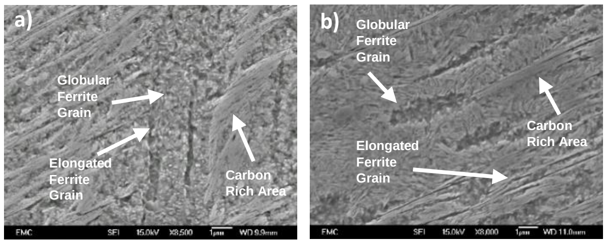

Fig.2 SEM images of a) HAB b) LAB

Based on the observations over multiple experimental results, it is proposed that the formation of WEBs initiates with the growth of globular equiaxed ferrite grains due to martensitic decay. The accumulation of plastic deformation during operation causes the globular grains to deform and elongate across the band which leads to the development of carbon-rich areas surrounding the elongated grains of the LABs. For the early stages of HABs it appears that, the globular regions of LABs transform into grains for the HABs where the direction of grain growth changes from about 30° to about 80°.

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

OPTIMIZATION PERFORMANCE OF PLAIN JOURNAL BEARINGS WITH PARTIAL WALL SLIP ZONE

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KEYWORDS

Hydrodynamic Lubrication; Modelling in tribology; Coating; Wall Slip

ABSTRACT

Coatings have been widely used in bearings nowadays due to its helpfulness to improve the tribological performance, prolonging the serving life. For heavily loaded hydrodynamic journal bearings under high speed, wall slip is easier to occur at solid-fluid interfaces for some hydrophobic coatings of lubricants. It will decrease the bearing load carry capacity for the full slip configuration on the bushing, but an appropriate partial slip zone could improve the performance of the bearing [1]. In this work, in order to optimize the partial slip zone for heavily loaded bearing conditions, an isothermal hydrodynamic model considering wall slip occurring at oil-bushing interface is built. Two-Component Slip Model is used to calculate slip velocity. The optimal slip parameters are chosen by considering the effects on the hydrodynamic behavior, such as hydrodynamic pressure, load bearing capacity, flow rate, friction/friction torque.

MODEL AND RESULTS

In order to shape the slip zone, we define three coefficients of $\alpha=B_s/B_1$, $\lambda=L_1/L_{s1}$, and $\gamma=L_{s1}/L$ as shown in Fig.1. Note that B_1 is the length from attitude angle φ to the minimum film thickness position. Dimensionless pressure is $P=p/(\mu\omega/\psi^2)$. μ is fluid viscosity, ω is shaft velocity, $\psi=C/R$. Usually, in order to improve the bearing performance, α is less than 1. The present model is validated by the data in Ref.[2]. Fig.2 shows the effects of coefficient α on the hydrodynamic behavior with the constant parameters of eccentricity ratio $\varepsilon=0.5$, length to diameter ratio $L/D=0.8$, $\lambda=0.5$ ($\beta=3.64°$), $\gamma=0.8$. The pressure distribution is obviously affected by the relative slip zone length. Fig.3 shows for $\alpha=0.85$, the partial slip zone can best improve the load bearing capacity with a gain of about 6%. For this configuration, the friction coefficient can be reduced by 7%.

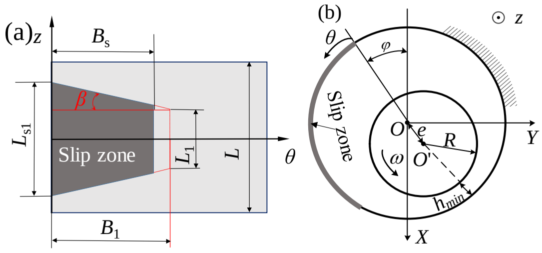

Fig.1 The slip zone at fluid-bush interface

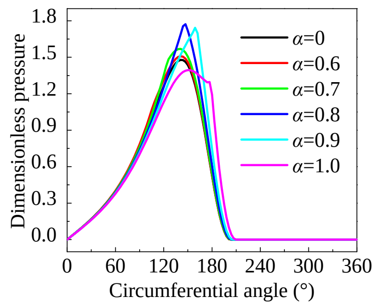

Fig.2 Mid-plane dimensionless hydrodynamic pressure

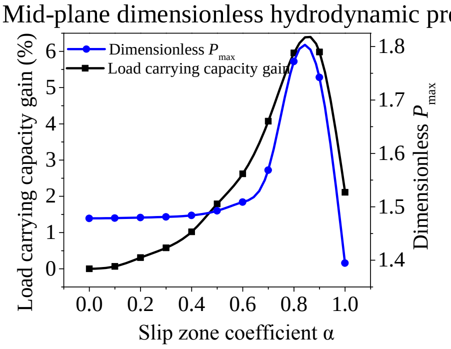

Fig.3 Dimensionless maximum pressure and load gain versus the relative slip zone length

CONCLUSIONS AND PERSPECTIVES

Furthermore, the effect of slip zone is largely influenced by working conditions of journal bearings. We will further analyze and discuss the influence of partial slip zone characteristics with bearing operating conditions. The optimal results would provide a good introduction for future experimental study.

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LUBRICANT FORMULATION: A DRIVER FOR EARLY BEARING DAMAGE ASSOCIATED TO WHITE ETCHING CRACKS?

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KEYWORDS
Mixed Lubrication; Lubricant additives; Rolling Contact Fatigue, Experiments in Tribology

ABSTRACT
Early bearing damage associated to White Etching Cracks (WECs) has been extensively studied in the past decade [1, 2]. Several hypotheses have been formulated on the role of the lubricant and tribochemistry under mixed lubrication and high slip conditions, based on tests of 81212 bearings on FE-8 rigs [3-6]. It has been suggested that WECs develop in points of high frictional energy accumulation [5], promoted by specific additives. Some suggest that certain oils will lead to hydrogen ingress and subsequent weakening of the material [6]. Others suggest that specific stress profiles and history profile can prevail over oil formulation [1, 7]. The aim of this study is shed light on the assumption that certain oil chemistries can accelerate bearing damage and to discuss the relevance of the findings.

Tests have been performed on 81212 bearings as proposed in the literature [3-6]. To enable a systematic post analysis the number of test variables has been reduced to: 2 oils formulated specifically for these experiments A and B (same viscosity) and 2 temperatures (90C and 70C). The tests are suspended after 120% of the estimated lifetime or stopped on vibrational level. Subsequently, components are inspected: raceway microscopy, wear profiles, SEM-EDX and metallographic sections in specific locations across the contact. Similar tests have also been performed on 6207 bearings.

Analyses show that oil A and B lead to similar mechanical stresses but that only oil A leads to WEC-associated damage, thus suggesting that oil formulation is a driver for WECs under such conditions. The results further enable to identify the frame of contact conditions at risk and cannot confirm some statements from the literature (influence of water contamination, friction energy accumulation, etc.). Depending on the conditions, WEC can be generated more due to stresses (as such oil formulation becomes secondary), or more due to chemical influences (e.g. under mixed lubrication and high slip) [1, 2, 7].

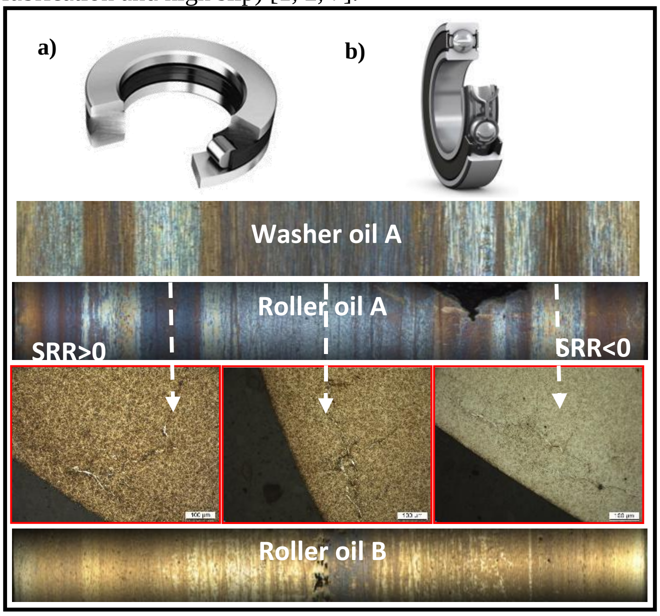

Figure 1 : Type of bearing tested, CRTBs (a), DGBBs (b) and typical WECs only observed for oil A and not B.

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Experimental investigations on REB thermal behaviour

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KEYWORDS
Friction; EHL; Experiments in tribology, Rolling Element Bearing

ABSTRACT

Temperature prediction is a major issue in the analysis of modern transmission systems. Rolling Element Bearings (REBs) are one of the essential components. In high speed REBs, power losses are mainly generated by: i) the contact between rolling elements and races; ii) the aerodynamic drag force generated between rotating parts and the oil-air mixture. Heat generated is evacuated through lubricant, inner and outer rings. The REB thermal equilibrium depends on many parameters such as rotational speed, applied load, lubricant properties and the surrounding environment.

In the present study, some measurements of REB thermomechanical behaviour are conducted on a dedicated test rig. Power losses for a specific REB are measured through the resistive torque. Some thermocouples are located on fixed parts (housing, REB outer ring) and other on rotating parts (REB inner ring and shaft) via a telemetry system. A deep groove ball bearing (DGBB) with a pitch diameter of 85 mm is tested under oil jet lubrication for different operating conditions. Measurements show a sudden increase of resistive torque for high speeds (figure 1).

An extended thermal network of the test rig was established to enable a closer understanding of the inside REB thermal behaviour. Based upon the first principle of Thermodynamics for transient conditions, the studied system is divided into lumped elements at uniform temperature connected by thermal resistances which account for conduction and convection. This model also allows the estimation of power losses and its distribution within REBs. This coupled analysis (thermal behaviour and local power losses) is compared with temperature measurements in order to analyse heat sources which generate this sudden increase.

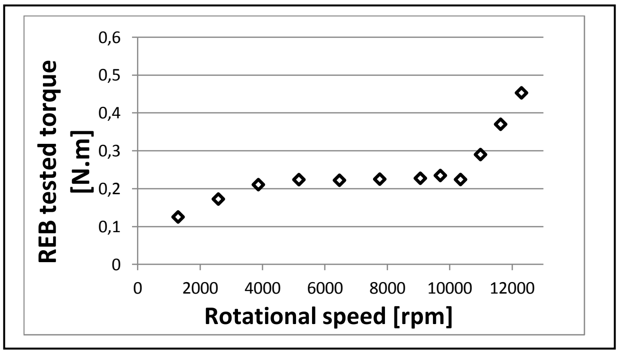

Fig.1: REB resistive torque
(radial load 400N, oil injection temperature 70°C, oil flow 25 L/h)

ACKNOWLEDGMENTS

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Tribological optimization of single and double slope marine stern tube bearings: A case study

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ABSTRACT

In the present study, the optimum geometric parameters of a double slope aft stern-tube bearing are sought, for (a) maximizing the contact area between the bearing and the propeller shaft, and (b) minimizing the maximum local pressure exerted on the bearing surface. Apart from generic geometric parameters (L/D, D, clearance, misalignment angle), additional design parameters are the two slope angles of the bearing surface and the longitudinal length of each sloped region. The computational approach used, evolves from the solution of the Reynolds differential equation in the oil domain between the shaft and the bearing. A general purpose optimizer based on genetic algorithms is utilized.

1. INTRODUCTION

High efficiency ship designs have reduced significantly the shafting system reliability of newbuild vessels according to Devanney and Kennedy [1]. Murawski [2] has studied the effects of hull flexibility and deformations on the shaft line, demonstrating a substantial effect regarding the stern tube bearing. Several failures of the shafting system have been reported and emphasis has been put on the severity of the stern tube bearing failures in modern VLCCs and ULCCs, as the one reported by DNV in [3]. Thereof, ABS and BV introduced the Elastic Shaft Alignment in [4]-[5], in order to improve the Shaft Alignment standards. ABS supports that the maximum absolute bearing-shaft misalignment allowed is 0.3 mrad, beyond which point, slope boring should be applied at the stern tube bearing.

2. METHODOLOGY

In this study, a single and a double slope optimum design of the stern tube bearing of a large container vessel were calculated and compared in terms of their tribological performance. The dimensionless bearing-shaft misalignment (Ψx) was set to 0.3 mrad in both cases and the loading condition was identical. A parametric model of the lubricant film thickness domain between the sloped housing geometry and the bent shaft was developed. The shaft curvature, for the given loading condition, was evaluated. The models were coupled to a shaft alignment calculation tool, to seek equilibrium between the externally loaded bent shaft and the required curvature of the bearing, in order to achieve optimal lubrication. The process was followed by optimization of the single and double slope geometry for the given load distribution. For the slope bearing design, the two slope angles and the respective region lengths were identified utilizing a genetic algorithm and a multiobjective Pareto Front optimizer. The results were compared with those of a single slope bearing design and the tribological performance of the two bearings were assessed.

3. CASE STUDY - RESULTS

In the present case study, the following input data were used:
Bearing Geometry: *Bearing length = 1.05 m , Bearing diameter = 0.52 m, Diametrical clearance = 0.0009 m*
Bearing loading: *Aft protruding edge = 0.407m, Fore protruding edge = 0.5412 m , Moment (aft end) = 409948 Nm , Force (aft end) = -202598 N , Force (fore end) = -107261 N*
Operational data: *RPM = 90, Lubricant Temperature = 40°C*
The design parameters for single and double sloped housing, optimised using the bent shaft model are:
Single slope non-dimensional parameters: *Slope = 0.3*
Double slope non-dimensional parameters: *Slope_Aft = 0.31 , Length_Aft = 0.61 , Slope_Fore = 0.11 , Length_Fore = 0.39*

In **Table 1** and **Figures 1 & 2**, the results of the comparison between: No Slope (NS), Single Slope (SS) and Double Slope (DS) housing models for Linear Shaft (LS) and Bent Shaft (BS) modeling are presented.

Slope Modeling	No Slope	No Slope	Single Slope	Single Slope	Double Slope	Double Slope
Sh. Model	Linear	Bent	Linear	Bent	Linear	Bent
h_{min} [μm]	79.1	**2.25**	175	**80.8**	145	**156**
p_{max} [GPa]	1.56	**16.1**	1.22	**1.13**	1.42	**1.28**
Angle of p_{max}	39.2	**53.7**	22.1	**26.5**	27.9	**27.2**
Ploss [kW]	2.40	**2.56**	2.34	**2.35**	2.35	**2.33**
*Ds.p. * [m]*	0.0744	**0.170**	0.00	**0.0315**	-0.0417	**-0.0162**
Ecc ratio	0.594	**0.506**	0.346	**0.301**	0.141	**0.106**
Att angle	48.31	**38.45**	37.34	**35.41**	30.90	**30.29**

Table 1. Computation results for: S = 0.0618 and Ψx = 0.3
** Ds.p. = Distance of Support Point from L/2 [m]*

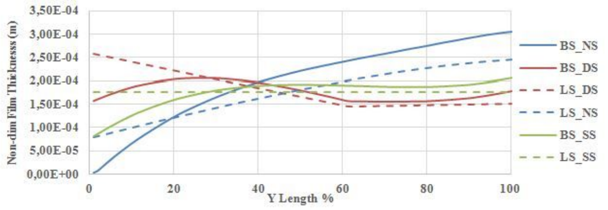

Fig1. Non-dimensional Film Thickness on the longitudinal direction, for (a) no slope, (b) single slope and (c) double slope bearing design.

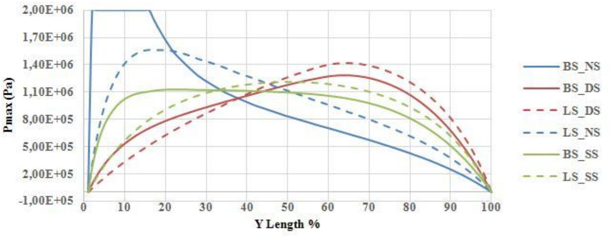

Fig2. Maximum pressure on the longitudinal direction, for (a) no slope, (b) single slope and (c) double slope optimized bearing design.

4. CONCLUSION

The effect of bent shaft modeling, in comparison to linear shaft modeling, was significant. Both the single and the double slope optimum designs improved the performance of the bearing by increasing the minimum film thickness and decreasing the maximum pressure. The double slope design altered the longitudinal location of the H_{min} position, by increasing significantly the pressure distribution towards the fore end of the bearing. The distance of the actual, one-point, support location from the bearing center was small in absolute size but positive for the double slope design (fore direction) and negative for the single slope one. Last but not least, a slight decrease on the lift of speed was observed in the double slope model.

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Wednesday

Sept. 4th, 2019

46th LEEDS-LYON SYMPOSIUM on TRIBOLOGY

Lyon, 2-4 September 2019

Invited talk

Tribocorrosion of biomedical implants

By Stefano Mischler

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The increase in life expectancy has meant that more and more elderly people require substitution of degraded natural joints with implants. Every year nearly 2 millions patients worldwide require a hip joint replacement. In US one elderly person over seven bears a knee or hip implant. Thus joint implants have entered in the daily lives of older people and an increasing number of younger patients. The primary function of hip and knee implants is of tribological nature and consists in ensuring the mobility of the articulation while carrying the person weight.

Not surprisingly, tribologists have been involved in the R&D on hip and knee joints that, despite their clinical success with survival rate in excess of 90% after 17 years, still require improvements and understanding of the responsible degradation mechanisms. Tribology related research was focussed in the past in establishing solid test protocols, designing appropriate material and surface combinations and assessing and quantifying the lubrication regime. Understanding the complex physical and chemical interactions between contacting surfaces and the surrounding body fluids constitutes nowadays a new research line in the tribology of artificial joints. In particular, the role of interfacial reactions in the degradation of joint and junction surfaces by combined wear and corrosion (tribocorrosion) is investigated by a number of laboratories.

In this talk we will discuss recent progress in the field of tribocorrosion of biomedical implants including mechanistic multiphysics models and their applicability to predict in-vivo hip joint wear rates. Further, the failure of large head MoM hip joints will be retrospectively analysed in an attempt to identify what went wrong, in particular in research and knowledge transmission.

46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

Velocity-dependence of tribologically-induced oxidation of high-purity copper

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KEYWORDS
Friction; Wear; Experiments in tribology; Tribo-oxidation

ABSTRACT

Tribochemical reactions are an often observed phenomenon during friction and wear processes, ranging from daily life applications such as medical implants to industrial applications such as fretting corrosion. Among various tribochemical reactions, tribo-oxidation is a far from fully understood mechanism, taking place by tribochemical reactions of the tribo-partners or the surrounding medium. Our research aims to elucidate the elementary mechanisms of tribologically-induced oxidation by paring polycrystalline high-purity copper plates with sapphire spheres. The experiments are performed under mild tribological loading at room temperature in a strictly controlled atmosphere with reciprocating linear sliding.

Our results show an oxidation process of the sample surface with rates order of magnitudes faster than the native oxidation of copper under the same environmental conditions and without tribological loading. With increasing sliding cycles we found the formation of amorphous oxygen-rich cuprous-oxide (Cu_2O) islands formed below the surface and grown to hemispherical amorphous/nanocrystalline cuprous-oxide clusters [1]. After the islands have grown, they coalescence and form a continuous oxide layer on the surface, determining from then on the tribological properties of the contact. This works intends to understand the influence of the sliding velocity on the formation of these oxide clusters. We systematically vary the sliding speed from 0.1 to 5.0 mm/s and investigate the resulting microstructure. Furthermore, we increase the exposure time of the sample to the controlled environment after the tribological loading since we relate the growth of the clusters to the diffusion of oxygen in and on copper. With help of different exposure times, we investigate the diffusion properties of the oxygen within the plastically deformed microstructure. Scanning electron microscopy techniques are further used in order to reveal the fundamental mechanisms of tribologically-induced oxidation.

ACKNOWLEDGMENTS

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THE ROLE OF TRIBO-CHEMICAL PROCESSES IN THE FRICTION AND WEAR BEHAVIOR OF CONTACTS IN NANOLITHOGRAPHIC SYSTEMS

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KEYWORDS
Friction; Surface topography; Tribofilms and 3rd bodies; Wear

ABSTRACT

Understanding the fundamental aspects of the friction and wear mechanisms that occur in several areas of the chip production process in photolithography systems, is highly relevant to solving the positioning challenges that currently limit the minimum achievable feature size. Variations in friction and surface wear at critical points in the photolithographic process (e.g. the interface between the wafer table and the silicon wafer substrate), can lead to nm-scale distortions in alignment, inhibiting improvements in overlay performance and as a consequence, directly contributing to the fading of Moore's Law.

In order to experimentally investigate the variations in friction and surface wear of this tribological system, model experiments were performed in ambient conditions, using silicon carbide (SiC) and silicon (Si) as the two selected industrially relevant contacts in a dry sliding ball-on-flat configuration. Focus was placed on furthering the understanding of the role played by tribo-chemical processes, namely, the parameters that govern the formation of tribofilms and the subsequent influence of these layers on the system surface friction and wear.

The sliding mode (unidirectional and reciprocated) and SiC surface roughness were varied in order to expose the impact of these particular parameters on tribofilm growth, friction and wear. Both sliding surfaces were characterized in terms of their morphology (optical profilometry and scanning electron microscopy) and chemical composition (energy dispersive x-ray spectroscopy) before and after wear testing.

Post-wear analysis revealed in all cases, the formation of SiO_x inside the wear track on the Si wafer. A clear correlation was also found between SiO_x growth, ploughing surface interactions, and the friction force of the system, as shown in Figure 1. The sliding mode was seen to influence the nature of SiO_x growth, and subsequently the surface friction and wear rate of both the contacts. Extensive SiO_x growth resulted in accelerated wear of the SiC counter surface, thus highlighting the potential influence of tribo-chemical processes in nanolithography.

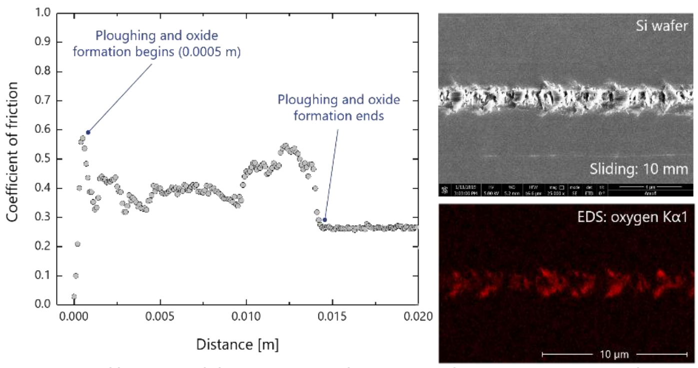

Fig.1 Coefficient of friction as a function of sliding distance for SiC-on-Si contacts. SEM image and corresponding EDS map illustrating ploughing and oxide formation at 10 mm sliding.

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This work has been carried out at ARCNL, a public-private partnership of UvA, VU, NWO and ASML.

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QUANTIFICATION OF THE SYNERGY EFFECTS BETWEEN WEAR AND CORROSION OF 316L STAINLESS STEEL IN DEEP-SEA ENVIRONMENT

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KEYWORDS
Wear; Surface topography; Experiments in tribology, Tribocorrosion

ABSTRACT
Under deep-sea environment, the correlation between tribocorrosion and seawater hydrostatic pressure, i.e., seawater depth, is an important issue for the increasing deep-sea engineering[1]. In this study, corrosion and wear of 316L stainless steel were investigated under simulated deep-sea environment concerning seawater hydrostatic pressure using a pin-on-disc tribometer integrated with a high-pressure autoclave for keeping hydrostatic pressure constant and an electrochemical workstation for potential control. It is found that solution hydrostatic pressure and electrode potential have significant effects on the corrosion and wear behaviour of 316L stainless steel. The polarization curves under static (no wear) conditions revealed that corrosion current density increased with increase in solution hydrostatic pressure. The tribocorrosion tests within different solution hydrostatic pressure were conducted under open circuit potential (OCP) and potentiostatic conditions. The cathodic shift of OCP and the enhancement of anodic current occurred during sliding due to mechanical depassivation within wear track[2]. Meanwhile, wear morphology and wear volume were analysed using scanning electron microscopy (SEM) and non-contact scanning laser profilometry respectively. SEM analysis demonstrated that the wear mechanism, independent of solution hydrostatic pressure, is characterized by plastic deformation, adhesive wear and abrasive wear. Wear volume increased with the increasing applied potential in a form of first-order exponential function, and the significantly larger volume loss was observed under higher solution hydrostatic pressure. Moreover, the quantification of synergistic effects in terms of standard ASTM G119-09[3] showed mechanical wear and synergistic term are major components. Remarkably, the synergistic effects increase with the electrode potential and solution hydrostatic pressure, and the corrosion-induce wear is dominant in the synergism.

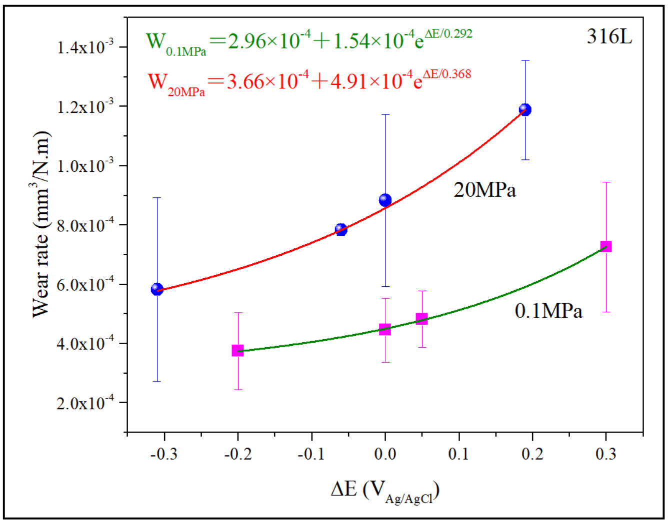

Fig.1 Dependence of wear rates of 316L stainless steel on the value of polarization at different hydrostatic pressures.

ACKNOWLEDGMENTS
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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

THE ROLE OF MODTC TRIBOCHEMISTRY IN ENGINE TRIBOLOGY PERFORMANCE. A RAMAN MICROSCOPY INVESTIGATION.

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KEYWORDS

Friction; Lubricant additives; Everyday life tribology, Engine tribology

ABSTRACT

In order to tackle the new challenges towards the reduction of carbon emissions in transport industry, the present work aims to understand the effect of the friction modifier (FM) molybdenum dithiocarbamate (MoDTC)[1] on the performance of an automobile engine[2].

In particular, a petrol engine has undergone trials in a motored test, measuring the friction torque drop as a function of the engine speed when the FM additive is used in a fully formulated API group III oil. Moreover, the engine has been dismantled after the test, checking the tribochemistry of MoDTC at different key engine components undergoing boundary or mixed lubrication, such as valve train parts, piston assembly and liner, connecting rod and engine auxiliary systems, using Raman microscopy and comparing the analysis results with literature on tribological bench tests [3].

This work demonstrates that the working conditions, the materials selection and the surface topography plays a crucial role in MoDTC tribochemistry to form a low friction tribofilm, contributing to a global engine friction reduction and fuel economy.

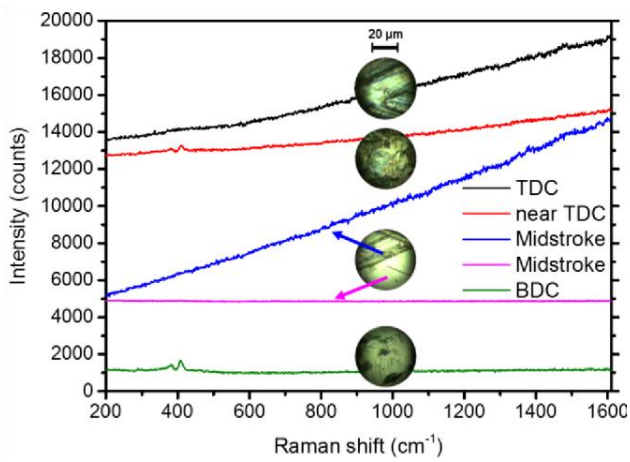

Fig.1 Raman spectra of cylinder liner at different stroke points

ACKNOWLEDGMENTS

The authors want to acknowledge Total Marketing Services and the EPSRC for financial support.

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

THE EFFECT OF ADDITIVE CHEMICAL STRUCTURE ON THE TRIBOFILMS DERIVED FROM VARYING MOLYBDNEUM-SULFUR CHEMISTRIES

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KEYWORDS

Friction; Lubricant additives; Tribofilms and 3rd bodies; MoS_2

1. INTRODUCTION

Inorganic friction modifiers are critical components in lubricant formulations. These additives reduce friction in the boundary regime where extensive surface asperity contact occurs. Lubricant-soluble friction modifiers are able to deposit on contact surfaces *in-situ* to provide localized low-friction performance where it is needed [1].

The most commonly employed friction-reducing species employed in automotive applications is molybdenum disulfide (MoS_2), which is formed from the decomposition of the ubiquitous additive; molybdenum dialkyldithiocarbamate (MoDTC). The mechanism of MoDTC activation and characterization of the resulting tribofilm have been the subject of extensive study. However, MoS_2 can be formed from a much wider range of molybdenum-sulfur chemistries and can be formed both as the result of molybdenum-sulfur cluster decomposition and by multi-molecular reactions [2]. In this work, a structure-activity relationship approach has been taken to understand the nature of the tribofilms formed from three different types of molybdenum-sulfur inorganic friction modifiers, MoDTC, a molybdenum trimer and an organic molybdate species.

2. EXPERIMENTAL

The three additives (MoDTC, molybdenum trimer and organic molybdate) were subjected to tribological testing in reciprocating contact to compare their friction performance in both model oils and fully formulated systems. Friction testing was performed on a Cameron Plint TE77 pin-on-plate tribometer using AISI 52100 bearing steel pins and plates. A range of tribological conditions and lambda ratios were tested. Base oil tests were used as a control. The resulting tribofilms were then chemically characterized with Raman spectroscopy and transmission electron microscopy (TEM) [3]. Mechanical properties and relative durabilities of the films were determined using Atomic Force Microscopy (AFM) in Lateral Force Microscopy (LFM) contact mode by rubbing the resulting MoS_2 tribofilms until a rise in localized friction was observed.

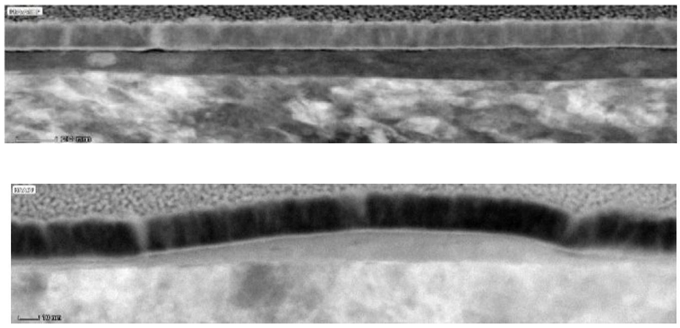

Fig.1 Transmission Electron Micrographs of molybdenum trimer (top) and MoDTC dimer (bottom) tribofilms

3. RESULTS AND DISCUSSION

The additives studied formed MoS_2 under the conditions tested with comparable friction results, the organic molybdate showed a lower friction coefficient and greater degree of crystallinity in fully formulated systems than the other molybdenum species [2]. The molybdenum trimer formed a thicker tribofilm than the dimer under identical contact conditions but had comparable friction performance. A purified MoDTC dimer showed strong friction performance with only an extremely thin MoS_2 layer. These results suggests that the quality of the MoS_2 formed in a tribotest is the determining factor in friction modifier performance rather than the amount or ease with which MoS_2 is formed.

ACKNOWLEDGMENTS

The EPSRC and Infineum UK Ltd. are gratefully acknowledged for their support of this work.

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

TRIBOFILM FORMATION DURING DRY SLIDING OF GRAPHITE- AND M_OS_2-BASED COMPOSITES FABRICATED BY SPARK PLASMA SINTERING

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KEYWORDS
Solid lubrication; Tribofilm and third body; Friction, SPS sintering

ABSTRACT

This work investigates the effect of the microstructure on tribofilm formation during the dry sliding of graphite- and MoS_2-based composites fabricated by Spark Plasma Sintering (SPS) . Mixtures of Astaloy 85Mo steel with the addition of 8 wt.% of MoS_2 or graphite or a mixture with 4 wt.% of graphite and 4 wt.% MoS_2 were obtained by SPS at 950 C, 60 MPa and 5 min as sintering parameters. The identification of crystalline phases was conducted by X-ray diffraction (XRD), and the observation of the morphology of secondary phases, as well as microstructural defects, was conducted using field emission scanning electron microscopy (FESEM). Dry sliding wear tests were conducted at different normal loads (5, 10 and 20) N with sliding speed of 0.1 m. s^{-1} using sintered samples and an AISI 52100 steel ball as counterpart. The top surface of the wear track and the tribolayer cross-section were analyzed using Raman spectroscopy and energy dispersive X- ray spectroscopy (EDS). The effect of the contact pressure on the extrusion of solid lubricant particles was investigated using instrumented indentation (Fig. 1) and scratch tests. Graphite addition to the steel matrix composite provided the formation of a protective tribolayer, which lead to lowest values of friction coefficient (Fig. 2) and wear rate. For the two MoS2-containing composites, both the modification of the layered structure by formation of Fe-Mo-S secondary phases during sintering and the higher amount of oxidative wear products resulted in a significant increase in the friction coefficient at the highest normal loads. For the MoS_2/graphite-containing composite, the synergistic effect of the two solid lubricants, resulted in samples with intermediate friction coefficient and the highest hardness (57%), in comparison to the Astaloy 85Mo steel.

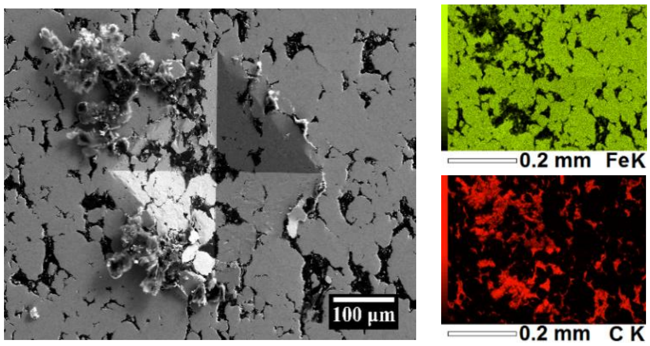

Fig.1 SEM and EDS images of graphite particles extrusion after Vickers indentation with a load of 10 kgf

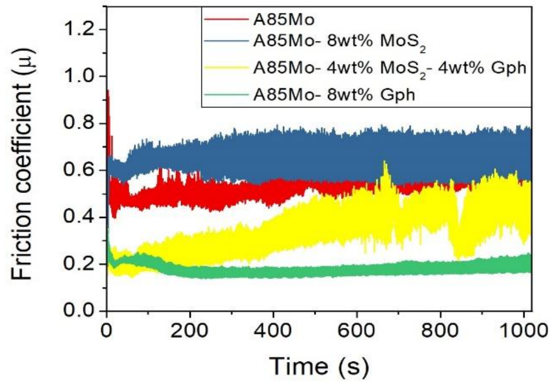

Fig.2. Friction coefficient of the sintered composites under dry sliding test at 20 N of applied load

ACKNOWLEDGMENTS
Authors would like to thank to CAPES and CNPq from Brazil for the financial support of this work.

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

MOS_2 NANO SHEETS FORMATION KINETICS FROM LOW VISCOSITY LUBRICANTS

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KEYWORDS
Friction; Lubricant Additives; Rheology; Boundary Lubrication,

ABSTRACT

The future of engine oils is moving towards lower viscosity oils, enabling a reduction of energy losses in systems such as pumps but also increasing the boundary lubrication occurrence in engine components in the cylinder block. Friction and wear in boundary lubrication are highly determined by chemical properties of the lubricant, where important features are solvency, dispersancy, detergency, antiwear, anticorrosion, frictional properties, and antioxidant capacity. Some of these properties are already part of the base oil mixture, and others are introduced separately as additives in the oil [1].

This study focuses on the friction and wear performance of fully formulated oils containing MoDTC friction modifier at different concentration. This additive is known to produce MoS_2 molecular sheets in the tribocontact providing a low coefficient of friction under boundary lubrication conditions. However, there is a gap of knowledge considering oil friction behaviour and formed tribofilm quality. The study conducted in [2] has set the combined Raman Spectroscopy and AFM methodologies as efficient techniques to quantify tribofilm distribution and thickness. In the current study, this methodology has been used to study the kinetics of MoS_2 formation from MoDTC in a low viscosity engine oil, during the induction time and their effect on friction and wear.

Tribological tests using low viscosity fully formulated oils are run. Rheological properties of the oils are modified by varying the base oil and the polymeric viscosity modifier, keeping the rest of the oil composition constant. Oils are blended with 0.2, 0.5, 0.7 and 1 wt% MoDTC friction modifier and tested in boundary lubrication regime using a pin-on-disk tribometer.

Raman Spectroscopy, AFM and FIB/TEM systems are used to analyze the formed tribofilm chemical and structural quality on the wear track surface.

A correlation between MoDTC concentration in the oil and the duration of the induction time prior to the friction reduction has been observed. This performance has been linked to the physical and chemical properties of MoS_2 tribofilm formed on the wear scar.

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Formation of MoS_2 flakes from molybdenum dithiocarbamate-based molecules in a severe lubricated contact: toward a better understanding

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Keywords: Lubricants, friction, MoDTC, MoS_2

1. Introduction

Nowadays, there is a strong need to reduce gas consumption of passenger cars as well as emissions. The reduction of friction losses in internal combustion engines is a way to achieve this. Moreover, Holmberg. *et al.* [1] have estimated global friction losses in cars to be about 33% with 11.5% for the engine. A way for reducing such losses in severe contacts is to use a fully formulated lubricant containing friction modifier additives such as Molybdenum dialkyl Dithiocarbamate (MoDTC). A tribochemical reaction of MoDTC molecule in steel/steel contact is known to occur under boundary lubrication conditions and allows the generation of MoS_2 flakes responsible for friction reduction. An important research work has been previously devoted to the study of MoDTC friction reduction capabilities [2-3].

Figure 1: MoDTC molecule – x could be either O and S. R are alkyl groups

But the tribo-chemical pathway from the MoDTC molecule to the generation of MoS_2 flakes instead of MoO_xS_y needs to be further investigated. The aim of this study is so to provide a better understanding of the MoS_2 generation mechanism from the MoDTC molecule in steel/steel contact.

In order to study the decomposition of this additive within steel/steel contact, different MoDTC-based molecules have been synthetized controlling O/S ratio (X atoms on figure 1 could be either O or S), oxidation state of molybdenum as well as alkyl chain types (R groups). Conducting investigations with such well-controlled synthetic molecules is very important as it is not the case in classical studies found in the literature where ill-defined commercial MoDTCs are commonly used.

2. Materials and methods:

Tribotests are conducted using steel ball and flat samples (AISI52100). Base oil (PAO4) blended or not with two different MoDTC-based molecules are used as lubricants. Tribotests are performed on a reciprocating tribometer with a ball-on-flat configuration (boundary lubrication). The influence of various contact parameters such as temperature (20°C and 100°C) and Hertzian max pressure (0.64 GPa to 1.4 GPa) is studied. Optical microscopy is used to estimate the wear on both ball and flat samples. Raman and XPS spectroscopies are carried out to characterize the physico-chemical compositions of generated tribofilms.

3. Results and discussion:

All results are discussed for a better understanding of tribochemical decomposition of MoDTC based molecule in steel/steel contacts working under boundary lubrication conditions.

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MODELING NOISE ORIGINATING AT A SLIDING CONTACT

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KEYWORDS
Everyday life tribology*;* Modelling in tribology*;* Experiments in tribology*;* Rubbing noise

ABSTRACT
Noises originating from the action of dynamic forces at sliding or rolling contacts are ubiquitous in our daily lives. Noise from squealing brakes, squeaking doors, creaking floors, rustling leaves, and various forms of scraping, rubbing and scratching are always around us. Many machines and devices that radiate noise also include moving contacts as sources. An extensive review by Akay (1) touches on most of the acoustic phenomena in which friction plays some role. To model the full tribo-acoustic problem, the excitation at the contact, the vibratory response of the system, the conversion of the vibration to radiated sound and its subsequent propagation to the receiver in an acoustic space, must be included. In this paper we model a relatively simple case wherein a pin on disc apparatus operates in a controlled acoustic environment, namely at the end of a square duct with an anechoic termination. The source of excitation is roughness being swept through the contact as the disc rotates against the nominally stationary pin, i.e., rubbing noise. The conversion of the resulting disc vibration into sound invokes the concept of radiation efficiency that accounts for the fact that not all of the oscillating air flow adjacent to the disc is converted into propagating sound. Since the frequency range goes from 500 to 5000 Hz, the transverse duct modes are also included. The input to the model is the power spectrum of the fluctuating contact force. Multipication by the plate mobilty gives the vibratory response as the mean square plate velocity. The levels are then adjusted by the fraction of the duct cross-section occupied by the disc. The duct response is included next. The radiation radiation efficiency is then introduced to provide the sound level above the disc averaged over the cross-section of the duct.

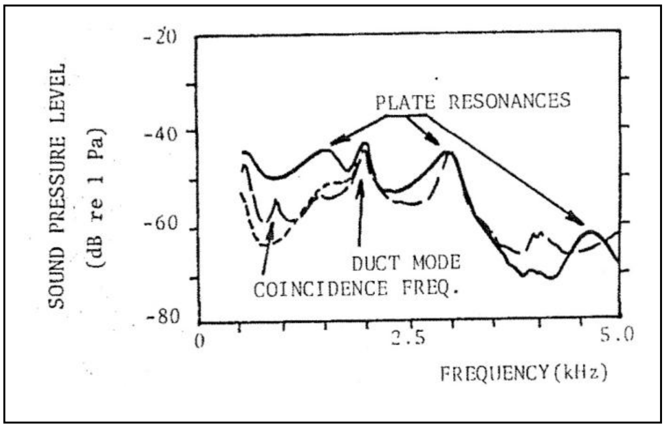

Figure 1. Measured (long dash), Modeled with radiation efficiency =1 (solid), Modeled with radiation efficiency estimated from theory (short dash)

The measurements are compared with the estimate/model as shown in Figure 1. The model that includes radiation efficiency matehes the measurements quite well. The model that assumes a radiation efficiency of unity, overestimates the sound at low frequencies where there is some cancellation due to out of phase rocking motion of the disc. The radiation efficiency accounts for this. The coincidence frequency, at which the plate bending waves travel at the same speed as the sound in air is not included in the model. The sound radiation from plates is known to be enhanced in the neighborhood of the coincidence frequency.

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46th Leeds-Lyon Symposium on Tribology - September 2 - 4, 2019, Lyon, France

ROAD POLISHING: STUDYING THE EFFECTS OF TRAFFIC LOAD, OPERATING VELOCITY AND AGGREGATE TYPES

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KEYWORDS
Wear, Modelling in tribology, Friction, Road

ABSTRACT
Skid resistance, which is related to the friction generated between road surface and tire tread, is necessary for good road safety. The main road surface parameter that controls this friction level is the texture which itself depends on the used particle size distribution, bitumen and aggregate proportioning, shape and angularity of aggregates … But due to the traffic which affects the aggregate microtexture by polishing, this texture changes continuously. The maintaining of that texture depends mostly on the type of aggregates which is used when building the road, the level of normal pressure subjected to the road surface by the vehicle tires and the velocities with which the cars travel on that surface.

On previous experimental studies, it was found that the aggregates became the main factor controlling the evolution of the road skid resistance after the binder is removed from the tips of the aggregates. Based on the above experimental studies, a model was developed to quantify the evolution of skid resistance. This present work is a continuation of the previous ones. It tries to include the effects of load, velocity and aggregate type in the above model from analysis of experimental test results. An updated model of evolution of skid resistance including this latter effect is proposed.

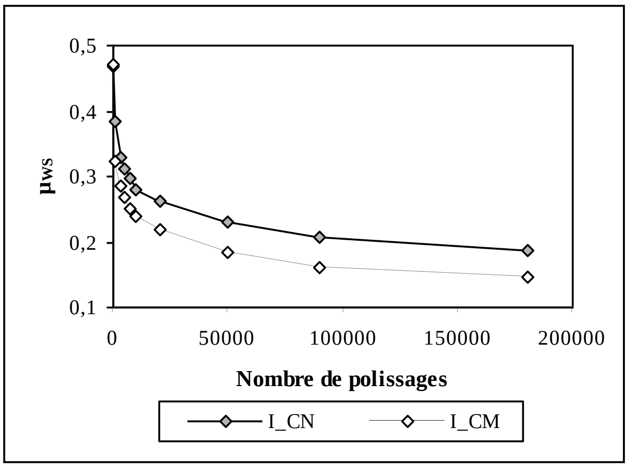

Fig.1 Evolution of the skid resistance versus the number of polishing cycles and load

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NUMERICAL MODELING OF THE MICROMECHANICAL ANISOTROPY EFFECT ON FRICTION WHEN DRY CUTTING OF GREEN COMPOSITES

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KEYWORDS
Friction; Experiments in tribology; Modeling in tribology, Machining

ABSTRACT
Green composites are nowadays getting a particular interest in the automotive and aerospace industries because of the strengthful environmental constraints [1]. In the composite industry, green composites are manufactured with natural fibers (such as flax, hemp, jute … ect) embedded in natural polymers (such as polylactic acid (PLA), polyamide 11 (PA11) … ect) in order to have a 100% bio-based composites. The use of these eco-friendly materials in different industry fields is an interesting way to improve a circular economy and sustainable development [2].

Machining operations for green composites present many tribological issues due to the complex anisotropic structure of natural fibers that induces a high variability of the mechanical properties [3]. Therefore, the experimental validation of the machinability of these novel materials remains expensive and laborious to achieve. Developing a numerical predictive tool for the machinability of green composites could be an effective solution to reduce the complexity of the experimental validations in the composite industry.

In this paper, a finite element analysis (FEA) is considered to model the machining behavior of flax fibers reinforced PLA composites with the orthogonal cutting process. The FEA is investigated at microscale in order to model each composite phase separately (the elementary fibers, the polymer matrix, and the interfaces). Unlike synthetic fibers, natural fibers are modeled in this paper with a ductile criterion for damage initiation. The interfaces are modeled using cohesive elements. FEA is made for different fiber orientations to carry out the anisotropic behavior. The FEA results are validated with orthogonal cutting experiments at the similar FEA cutting conditions. The FEA/experiments correlation is based on the comparison of both the cutting friction and the microscopic cutting behavior of natural fibers regarding their orientation within the composite.

Results show that the proposed FEA model is able to reproduce efficiently the cutting friction behavior of natural fibers composites in function of their microscopic anisotropy. The ductile criterion used in this model allows the plastic deformation of elementary flax fibers during machining which corresponds to the real cutting behavior of natural fiber composites. Changing the fiber orientation in the micromechanical model leads to a better understanding of the tribological mechanisms that occur on the elementary fibers, the polymer matrix, and the interfaces which is strongly important to control and improve the machinability of these eco-friendly materials.

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

MODELING OF ADHESION AND ADHESIVE WEAR: A COMPARISON BETWEEN ATOMISTIC AND CONTINUUM METHODS

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KEYWORDS
Modelling in tribology; Contact and adhesion, Wear; Molecular Dynamics

INTRODUCTION

This work presents a comparative study between molecular dynamics (MD) and finite element method (FEM) models of the unidirectional contact between a two-dimensional plane-strain square (indenter) and a flat slab, in order to evaluate adhesive contact and adhesive wear. The FEM models were based on the previous work by Bortoleto et al. [1], who analyzed different pairs of materials and their adhesion intensity by calculating surface attractive forces in terms of the Lennard-Jones interatomic potential and Hamaker constants. The MD models reproduced the same geometry used in the previous FEM models in order to allow the correlation between the atomistic MD numerical modeling results and the cases analyzed by the continuum mechanics using FEM. The results reveal that there is a qualitative correlation between the amounts of material transferred between the surfaces as calculated in the two numerical approaches. This indicates that the FEM adhesion models [1] could reproduce phenomena that previously required atomistic approaches.

MATERIAL AND METHODS

A finite element analysis was conducted to investigate the contact problem of a linear elastic square punch indenting an elastic-plastic deformable slab. Different arrangement of surface pairs were evaluated, by combining cooper, aluminum and iron surfaces. An *ad hoc* user FORTRAN subroutine designed to calculate the adhesion forces was coupled to finite element solver Abaqus. Adhesion forces were introduced in the system as forces acting on the surfaces as a function of the separation distance between the surfaces.

Regarding MD models, interactions between atoms in all simulations were described by the embedded atom method (EAM) potentials for cooper, aluminum and iron surfaces.

For both MD and FEM analyses, approximation and separation steps were modeled. During the separation step, material transfer between surfaces can occurs due to adhesion with respect to damage initiation and propagation at the flat slab. The parameters considered in the simulations included normal load, chemical affinity, and system size.

RESULTS AND DISCUSSIONS

Wear related to adhesion phenomena in dry contacts was estimated based on the amount of material transfer from the slab to the indenter, evaluating this transfer for each of 24 different combinations of surface pairs and contact conditions. An adhesive wear map, based on an equation that correlates the material parameters and material loss due to adhesion, was proposed. The results indicate that the chemical affinity between bodies in contact is more related to adhesion than the applied load. The amounts of material transferred between the surfaces as calculated by FEM models is correlated with the results of MD models (Fig. 1), which indicates that the proposed FEM adhesion models were able to reproduce atomistic phenomena.

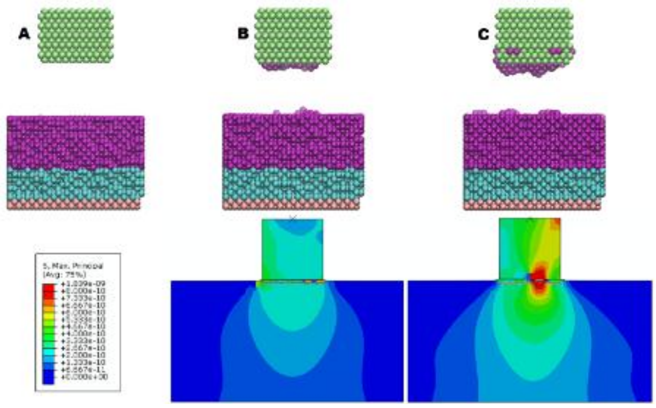

Fig.1 Comparison between MD (top) and FEM (bottom) analyzes showing the contact sequence (copper surfaces): initial touch (A) and penetration of 1 (B) and 2 (C) atomic layers.

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46th LEEDS-LYON SYMPOSIUM on TRIBOLOGY

Lyon, 2-4 September 2019

Invited talk

Molecular simulations for additives and coatings.

By Hitoshi Washizu

Graduate School of Simulation Studies, University of Hyogo, Kobe, Japan

Molecular simulations are useful tool to investigate the dynamics of tribological surfaces. In this presentation, we demonstrate our extended methods to treat the dynamics of additives in base oils, and surface coatings.

In order to simulate the dynamics of polymer additives, we combine Langevin dynamics for segment motions of polymers, with lattice Boltzmann method for flow of base oils. We succeeded to reproduce the effect of viscosity index improver molecules in both bulk and under confinement. The chemical nature of functional groups on the additive molecules are modeled from quantum simulations.

The other topic is surface coating. In molecular simulation, heat generation and transfer in the sliding interface is very restricted. We introduce novel simulation technique based on smoothed particle hydrodynamics. The surface interactions and frictional oscillation parameters are taken from molecular dynamics simulations. In this simulation, heat generation, plastic deformation, heat transfer in micron scale is reproduced.

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EFFECT OF AGED OILS ON RING-LINER WEAR

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KEYWORDS
Lubricant additives; Wear; Mixed Lubrication, Cylinder Liner

ABSTRACT

With the trends to increase drain oil interval to reduce cost of ownership of Heavy-Duty vehicles and to use low ash oils, the efficiency of lubricant additives, especially the anti-wear ones, are of great interest. However, most of tribological tests are still done with fresh oils or in a few cases with artificially aged oils.

In this work, piston ring and cylinder liner were rig tested for friction and wear on a short reciprocating tester with two oils: a fully formulated SAE 10W-40 API CI-4 / ACEA E7 and a sample of the same oil after 500h of engine test. Liner wear was evaluated by different parameters based on the Bearing Curve. Higher cylinder wear and slight lower friction values were found with aged oil. Samples of a liner with accumulated 500 engine hours were also tested with the aged oil and showed intermediate results.

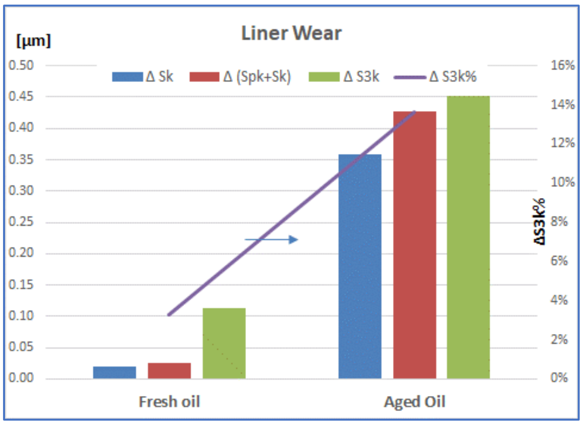

Figure 1- Liner wear.

After test, wear track of cylinder liners was analyzed by EDS (Energy Dispersive X-Ray Spectrometry) and compared with analyses of the parts before test. Much more Zinc and Phosphorus were found on the liners tested with fresh oil.

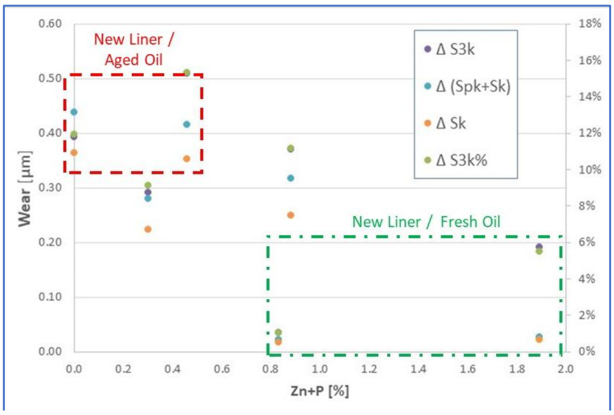

Figure 2- Liner wear and % of Zn+P found in the wear track.

CONCLUSIONS:

- Compared with the fresh oil, the aged oil showed slight lower friction but significant higher liner wear.
- More Zinc and Phosphorus were found on the liner wear track of the liners tested with the fresh oil.
- The fresh oil formed more ZZDP derived tribofilms that mitigated liner wear but increase friction.
- The used liners, tested with the aged oil presented intermediate values of friction, wear and ZDDP tribofilms.

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HIGH RESOLUTION CHARACTERIZATION OF ZDDP TRIBOFILM ON CYLINDRICAL ROLLER BEARING BY X-RAY PHOTOELECTRON SPECTROSCOPY AND ATOM PROBE TOMOGRAPHY

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KEYWORDS
Lubricant additives; Tribofilms and 3rd bodies; Boundary lubrication; Atom Probe Tomography

ABSTRACT
For the purpose of decreasing wear and friction, zinc dialkyldithiophosphate (ZDDP) has been used in engine oil for several decades. In this study, ISO VG 100 mineral oil mixed with ZDDP was used in sliding tests on cylindrical roller bearings. Tribofilm formation could be observed after 2 hours sliding tests with normal load of 80 kN, working temperature of 80°C, and rotational speed of 20 rpm. X-ray photoelectron spectroscopy (XPS) and atom probe tomography (APT) were used for chemical analysis of the tribofilm. The results show that the ZDDP tribofilm consists of the common ZDDP elements along with iron oxides. Considerable amount of zinc and a small amount of sulfur were observed. In particular, an oxide interlayer with sulfur enrichment was found between the tribofilm and the steel substrate, which was characterized explicitly at the atomic scale by APT. The depth profile of the chemical composition was obtained and a tribofilm of approximately 40 nm thickness was identified by XPS. Finally, the finding of sulfur enrichment supports the predictions according to the Hard and Soft Acids and Bases (HSAB) principle.

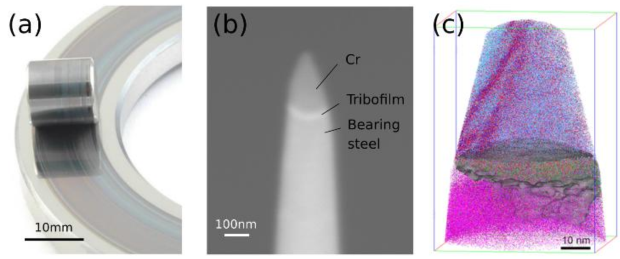

Fig.1 Overview of the atom probe sample preparation. (a) the wear track on the surface of a bearing ring, and (b) the shaped tip sample of the tribofilm for APT analysis; (c) the 3-D reconstruction of APT analysis.

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TRIBOLOGICAL PROPERTIES OF MALEIC DITHIOPHOSPHATE DERIVATIVES

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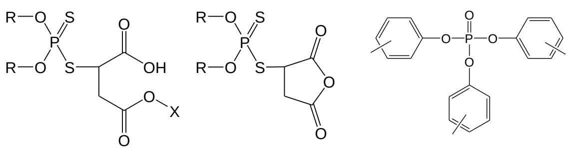
KEYWORDS
Lubricant additives; Wear; Friction, EP/AW additives

INTRODUCTION
Zinc dialkyl dithiophosphate (ZnDTP) has been widely used in hydraulic fluid as antiwear additive, but because of its poor stability at high temperature and in the presence of water, many additive technologies have been studied as replacements for ZnDTP.

One solution is to use a combination of phosphorus type antiwear additives and Sulfur type extreme pressure additives. In this study, with the aim of developing hydraulic fluids with improved antiwear and extreme pressure performance, tribological properties of a combination of maleic dithiophosphate derivatives (MDTPs) as a new sulfur-phosphorus type additives and tricresyl phosphate (TCP) were investigated. MDTPs contain polar groups, which should show good adsorption to metal surfaces.

EXPERIMENT
Chemical structures of additives in this investigation are illustrated in Fig. 1. Four kinds of MDTPs were used, each having polar groups with a different structure. API Gp.III VG32 is used as base oil. Formulations of test oils are presented in Table 1.



(a)MDTPs (R:2ethylhexyl) (b)MDTP-AM (c)TCP

Fig.1 Chemical structures of additives

Table 1 Test oil formulations, mass%

Test Oil	TCP	MDTPs [-X]		MDTP-AM
A	0.5	H	0.015	-
B	0.5	CH3	0.016	-
C	0.5	C2H5	0.016	-
D	0.5	C3H7O2	0.017	-
E	0.5	-	-	0.015
F	0.5	-	-	-

Lubricating properties were measured using Block-on-ring tests according to ASTM D 2714.

RESULTS AND DISCUSSION
Figure 2 shows the wear scar width for each test oil used in this study. The wear scar width with TCP/MDTP-AM (OIL-E) is the widest among the test oils, and was about the same as that with TCP alone (OIL-F). OIL-A, -B, -C and -D all outperformed OIL-F, with OIL-A showing the best antiwear property. From the above, it was found that antiwear performance is greatly improved when MDTPs are used in combination with TCP. Further, with the exception of OIL-C, the antiwear properties improved with the increasing polarity of the MDTPs. We will look into why OIL-C was the exception to this trend in a future study.

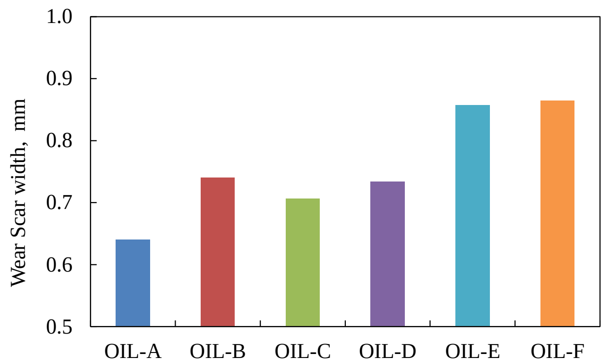


Fig.2 Wear scar width on block-on-ring test

The tribofilms formed on the block surfaces were analyzed by XPS to investigate the relationship between the tribofilms and antiwear properties. According to the XPS depth direction analyses, it is inferred that the sulfur-containing MDTPs readily adsorb and react with the metal surfaces, because the S/P ratios for the tribofilms formed TCP/MDTPs are higher at deeper areas in the film. These results suggest that when MDTPs having more than one carboxyl group are used in combination with TCP, it greatly aids in the formation of a tribofilm despite being added in a amount less than 1/20 that of TCP.

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NEW INSIGHTS IN ADSORPTION PROCESSES OF LUBRICANT ADDITIVES

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KEYWORDS
Lubricant additives; Tribofilms and 3rd bodies; NanoTribology; Adsorption

ABSTRACT

Since the initial studies by *Spikes* in the 80s, adsorption mechanisms of lubricant oil additives gained significant attention, as can be seen by a total of approximately 20 publications in 2018 (see e.g. [1,2]). The presented theories are mostly based on ex- and post-mortem studies or simulations. Here, we present in-situ adsorption studies, using a quartz crystal microbalance with dissipation QCM-D (e.g. [3,4]).

The QCM-D is a nanogram-sensitive technique to study adsorbed amounts (from frequency information) and viscoelastic properties (from dissipation) of the adsorbed molecules. Fig. 1 shows an exemplary frequency and dissipation shift during adsorption of a friction modifier from mineral base oil. The frequency decreases after the media change from base oil to base oil + additive, which indicates a mass increase (adsorption). The dissipation increases after the medium change, so the additive coating shows an increased viscoelasticity compared to the pure base oil. Interestingly, by changing the medium back to pure base oil the frequency decreases and the dissipation slightly increases again. To understand this phenomenon an additional method is needed. The QCM-D gives no information exceeding quantitative adsorption and viscoelasticity. To describe the coating more precisely and also in a qualitative way we used an imaging method to make the adsorption processes, as seen via QCM, visible. The combination of both methods gives interesting new insights in the behavior of lubricant oil additives on surfaces.

ACKNOWLEDGMENTS

The authors acknowledge the assistance of Daniel Bahl and Sven Janson.

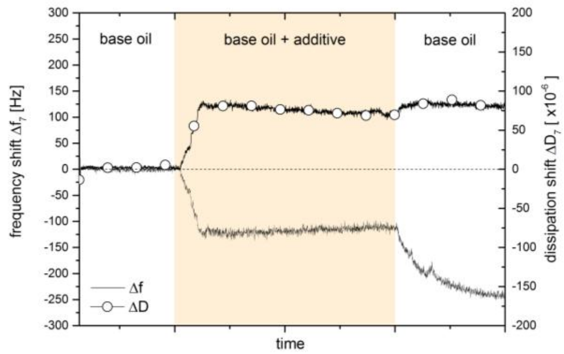

Fig.1 Exemplary frequency and dissipation shift from QCM-D tests: adsorption of friction modifier from mineral base oil

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INHIBITION OF CONFINEMENT-INDUCED SOLIDIFICATION OF MINERAL OIL-BASED LUBRICANTS

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KEYWORDS
Friction; Lubricant additives; NanoTribology; Surface force

ABSTRACT
Reducing energy consumption is a perpetual challenge for human society. Friction is a major source of energy loss to be reduced; it has been reported to consume 20% of total energy in the world [1]. Oil-based lubricants have significantly contributed to reduce friction in human society. In transportation sector, which accounts for almost one third of total energy, these oils lubricate the engines and transmissions of transportation vehicles. In industrial sector, to which another one third of total energy is attributed, oil-based lubricants are also widely used in many types of industrial machineries such as turbines, hydraulics and compressors. The main components of these lubricants are mineral oils derived from petroleum refining. Friction-reducing function of these oils are not only based on the hydrodynamic surface-separating force governed by their viscosity, but also exhibited when this hydrodynamic force is no longer capable to carry load. The latter behavior, so-called boundary lubrication, highly depends on the chemistry of lubricant oils. For example, some surfactants are widely known to reduce friction. However, the mechanisms of boundary lubrication have been not fully understood.

In this study, we investigated the effects of the surfactant chemicals commonly used as friction modifier (FM) and dispersant additives on the mechanical properties of the interfacially confined mineral oils by using a surface force apparatus. Resonance shear measurements (RSM) [2] revealed that spatial confinement induced solidification of the mineral oil at ~10 nm surface separation. Addition of a glycerol mono-oleate FM into the oil strongly inhibited this solidification. The polyisobutenyl succinimide dispersants were also found to deliver such inhibitory effects on confinement-induced solidification. Polar group chemistry of the dispersants was critical to this inhibitory effects of the dispersants. The hard-wall thickness was not significantly different between inhibitory and non-inhibitory dispersants. As with RSM, macroscopic friction measurements showed that these solidification inhibitors reduced metal-to-metal friction. These results suggest that inhibition of confinement-induced solidification plays a dominant role in boundary lubrication performances of surfactant additives.

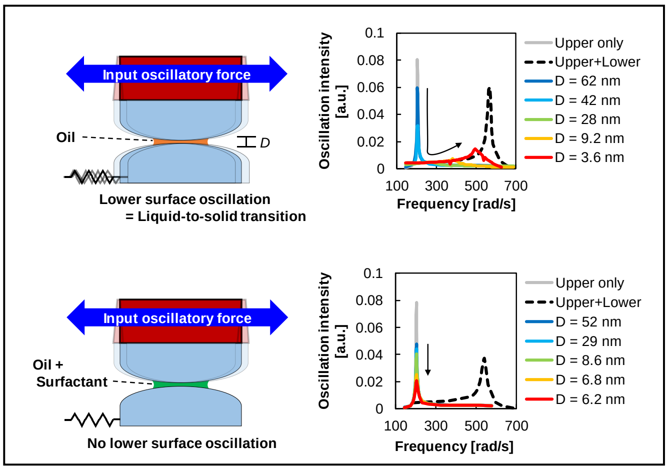

Fig.1 Schematic representation (left) and data (right) of RSM of confined lubricants. While mineral oils solidified under nano-confinement (upper), surfactant-containing oils did not (lower).

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Effect of Organic Friction Modifiers on the Tribological Performance of Engine Oils

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KEYWORDS

Lubricant additives; Friction; Fluid lubrication, OFMs

ABSTRACT

A commercial engine lubricant is composed of base oil(s) and additives for enhanced engine performance. The viscosity of the base oil mainly determines the friction in the EHL regime. However, under boundary and mixed regime the tribological behavior mostly depends on the friction modifiers (FMs) and Anti wear (AW) additives and therefore has a decisive role to play in reducing friction and wear of moving mechanical components[1]. One of the important class of FMs that are key additives for engine oil performance optimization is organic friction modifiers (OFMs)[2]. OFMs are amphiphilic surfactants where the polar head is anchored on the metal surface thereby forming a low shear strength plane that facilitates low friction [3]. As there will be a marked increase in the contribution of piston to engine friction in the future, OFMs mostly based on straight saturated alkyl chain with small polar head groups may not meet the performance demands. Therefore, new OFMs that can operate effectively under harsher conditions that are more prevalent in IC engines are needed for the future. To develop novel systems, a deeper understanding of the functional mechanism of model OFMs is needed.

In this study, the influence of OFM types, chain length and levels of unsaturation of model OFMs (*Table 1*) on the tribological performance was investigated using a Mini Traction Machine under a wide range of sliding/rolling conditions. Model base oils with different polarity were selected for investigation.

As the surface-active molecules has an affinity for steel, understanding the nature of adsorption is vital to develop friction modifiers for next generation engine lubricants. Quartz Crystal Microbalance with Dissipation monitoring (QCM-D) is a convenient tool to study the physical and chemical interactions that occur on the surface. Here QCM-D was employed to study in-*situ* the kinetics of adsorption and structural changes on a stainless steel (SS2343) coated quartz crystal. Sauerbrey equation and Voigt model were utilized to study the mass of adsorption and kinetics of adsorption was obtained using Langmuir Isotherm model.

The QCM-D results were related to the effectiveness of OFMs in reducing friction at macroscale. The difference in tribological performance as a function of the type of oil and additives is also presented.

***Table 1: Different types of OFMs employed in the study*.**

OFM Chemistry	Research objective
An amide, amine and acid	To investigate the influence of OFM types on tribological performance
Acids with different chain lengths (C_{18}, C_{20} and C_{22})	To study the influence of chain length on frictional response
A saturated and unsaturated acid with 18 carbon atoms	To examine the influence of levels of unsaturation on the observed friction

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FM-AFM OBSERVATION OF THE ADSORPTION FILM STRUCTURE ON STEEL SURFACE IN OILINESS ADDITIVE SOLUTION

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KEYWORDS
Lubricant additives; NanoTribology; Surface topography, FM-AFM

ABSTRACT

Oiliness additives added into lubricants form adsorption film with nanometers thickness. It is well known that such adsorption film dominates the friction and wear properties. However, high-resolution analysis techniques are required to observe such nanometer thickness film. Also in-situ measurement is strongly desired because the adsorption film is formed in solution and the interfacial structure changes dynamically with the sliding of two substrates [1]. Due to such difficulties in analysing adsorption film precisely, its friction mechanism is still to be fully understood. Hence, revealing the details of adsorption film structure will lead to the clarification of the friction mechanism and the development of the higher performance lubricant.

FM-AFM (Frequency Modulation AFM) enables to observe interfacial structure with higher resolution than conventional AM-AFM (Amplitude Modulation AFM), and is expected as a microscopic technique to measure the detailed adsorption film structure in the thickness direction [2]. However, most of all FM-AFM studies so far are focused on smooth surfaces such as mica, and the adsorption film on actual steel surfaces has not been reported. In this study, the adsorption film structure of oiliness additives on steel surfaces was investigated by liquid cell FM-AFM (SPM-8000, SHIMADZU, Japan) in order to understand its friction mechanism.

The cantilever is oscillated at its resonance frequency by utilizing self-excited vibration on the control system of FM-AFM. When the head of the cantilever approaches a substrate, interaction force acts on the probe and shifts the self-excited frequency of the cantilever oscillation. The interaction force between the sample and the top of the cantilever can be measured by detecting this frequency shift. The image of X-Y plane can be acquired by scanning the cantilever so that the frequency shift is constant. Repulsive force distribution can be acquired from the magnitude of the frequency shift, and the distribution of molecules is visually grasped in the Z-X plane image.

We performed FM-AFM measurement on a steel surface in a solution of hexadecane with stearic acid. At the surface 7 hours after soaked in the solution (Fig. 1), two layers of repulsive force areas were observed in the Z-X plane image, and the morphology of X-Y plane was rough. After 29 hours (Fig. 2), expansion of the repulsive force area was observed in the Z-X plane image, and the morphology of X-Y plane became smoother.

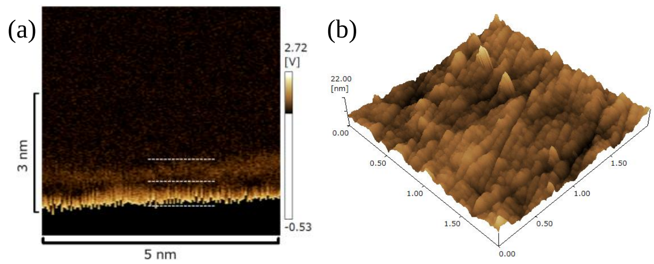

Fig. 1 The result of FM-AFM measurement
7 hours later (a)Z-X image (b)X-Y image

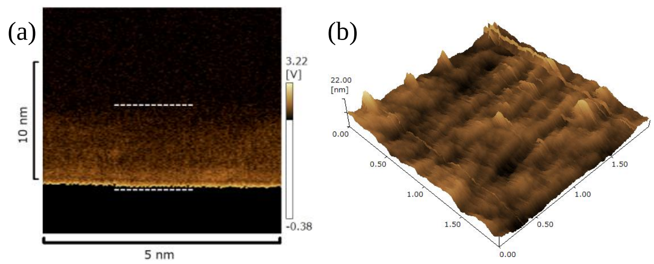

Fig. 2 The result of FM-AFM measurement
29 hours later (a)Z-X image (b)X-Y image

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CONTRIBUTION OF HYDROGEN BONDING TO LUBRICATION PERFORMANCE OF POLYPHENYLENE ETHER

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KEYWORDS
Lubricant additives; Mixed lubrication; Experiments in tribology; Hydrogen bonding

ABSTRACT

Friction modifier (FM) molecules help mitigate friction and wear via their absorption on the surface of the friction pair[1-2]. This absorption is typically physical, however, fails partially at elevated temperatures or extreme conditions and thus provides only limited effect[3-4]. We reported an enhanced boundary lubrication performances of the conventional lubricant polyphenylene ether (PPE) after simple surface treatment, both as lubricant only or as lubricant additives. With the one-step surface hydroxylation of friction pair, the system shows lower friction coefficient then without. We believed the binding between FM and surface comprises physical absorption and hydrogen bonding, which forms stronger absorption and better support between surfaces and thus leads to lower friction coefficient[5]. The relation of film thickness to entrainment speed is studied and discussed as well. The properties of surface characterization and wear will be studied in the future. The findings provide interfacial insights underlying the lubrication performances and shed light on the new design of FM and other lubricant additives.

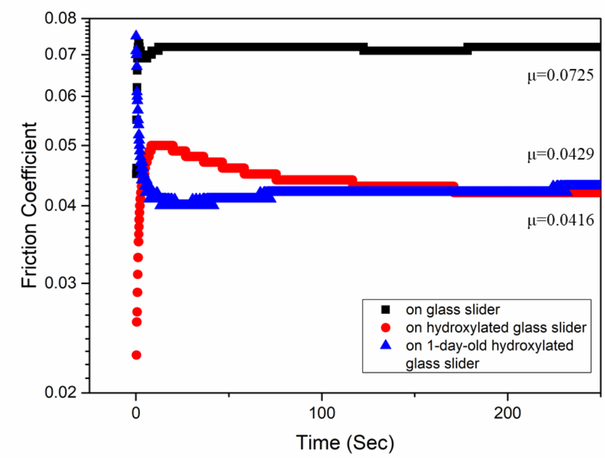

Fig.1 Friction coefficient as a function of time under lubrication between the PTFE ball and glass slider when PPE is used as a lubricant. Different colors stand for different conditions(black square for the plain glass slider, red dot for the fresh hydroxylated glass slider, blue triangle for the hydroxylated glass slider prepared one day before testing).

ACKNOWLEDGMENTS

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MODELING TEMPERATURE RISE IN MULTI-TRACK RECIPROCATING FRICTIONAL SLIDING

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KEYWORDS

Modeling in tribology; Friction; Fretting; Temperature rise

ABSTRACT

Temperature rises due to distributed heat flux spot moving over a surface have been long studied for a single pass, and for reciprocation over the same track where temperatures reached during subsequent passes are augmented as they occur atop temperature rises persisting from prior passes. In tribological testing there are instances where it is instead desired to slide over fresh surface, which in reciprocation can be achieved by a sideways increment in position at the end of each stroke, yielding a collection of multiple parallel neighboring tracks. In such a 'multi-track' case it is anticipated that temperature rises during a given pass will again be augmented by those prior passes over neighboring tracks, though not to the same extent as when prior passes are over the same track.

This model considers a circular heat spot of radius a of uniform flux $\dot{q}$ translating over a half-space of thermal conductivity K and diffusivity □ at speed v along the x-direction for length L during each stroke, and being incremented sideways by distance fa in the y-direction at stroke's end to create the subsequent neighboring parallel track during the stroke back, with the z-direction into the subsurface. □ is the period for a full back&forth reciprocation cycle, so at midstroke (x=L/2) position □ /2 represents the elapsed time since passage of the heat flux on the neighboring track. To broaden applicability of output the model was non-dimensionalized, normalizing lengths to a, times to a^2/□, temperatures to $\dot{q}a/K$, and speed represented by Peclet number P_e=va/(2□).

In Fig.1 an example temperature rise history is shown for the case of f=1, □*=1 and P_e=40 at an arbitrary point of interest z^*=0.3 in the subsurface at mid-stroke (x^*=L^*/2) and y^*=6.5 midway between the 7th and 8th pass, where the maximum temperature rise occurs during that 8th pass due to its proximity as well as temperature rises still persisting from the prior equally proximal 7th pass. By repeated runs ΔT^*_{max} may be mapped at any location (y^*, z^*) in the subsurface cross-section normal to the stroke. In the case of □*=∞ (temperature rise during any pass independent of prior passes) initially studied, it was found that isotherms at any high P_e≥40 would collapse and superimpose if subsurface position z* and isotherm ΔT^*_{max} value are both multiplied by $\sqrt{P_e}$. As shown in Fig.2 where maximum temperature rises $\Delta T^*_{max}\sqrt{P_e}$ are mapped out in the crosssection between the centers of the 7th and 8th passes in such an f=1 case, as values of □* are made finite, isotherms of any given value shift and move to greater depths while values of temperature rise reached on the surface increase as heating during prior neighboring passes still persists to indeed augment temperature rises during subsequent passes. Of additional note is that cases with the same product P_e□* (equivalently L^*) seem to produce common isotherms displaying equivalent augmentations.

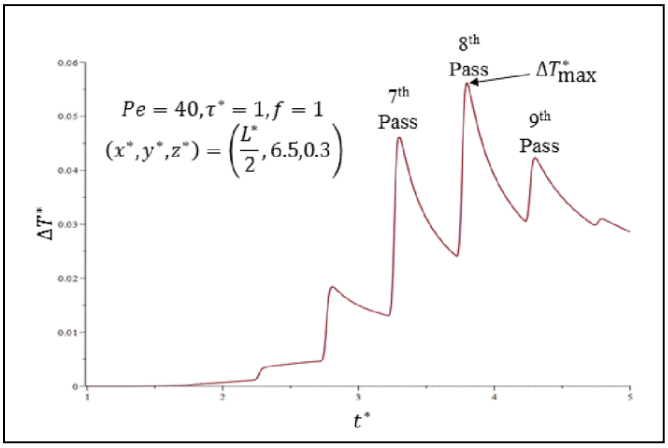

Figure 1 – temperature rise history at a point in multi-track reciprocation

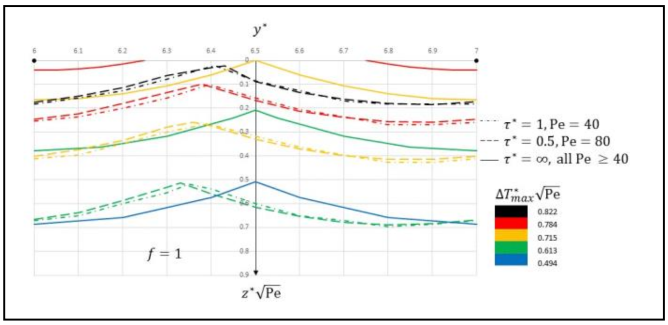

Figure 2 – isotherms of maximum temperature rise mapped through the crosssection between two neighboring successive tracks

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GEOMETRICAL CONSIDERATIONS FOR DEBRIS ENTRAPMENT IN CLOSED CONTACTS

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KEYWORDS:

Tribofilms and 3rd bodies; Wear; Experiments in tribology, Annular contact

ABSTRACT

Unlubricated contact of metallic surfaces is widely found in everyday applications. In these contacts a part of the wear debris is trapped between the wearing surfaces, creating a wear debris bed. Many researchers have reported that such a bed provides a degree of protection against further wear with wear decreasing with increased debris entrapment and vice versa (1-5). This raises the question of what governs debris entrapment. Zmitrowicz (6) explains entrapment through the disparity of length-scales between the contact (dimensions of order of mm) and debris particles (dimensions order of μm). Given this, it is intuitively expected that entrapment is correlated with the ratio of contact size to average particle size (7). In annular contacts the 'length' in the direction of sliding is infinite. Therefore, it can be hypothesized that the contact width to average particle diameter is likely to govern debris entrapment. Noting the widely accepted notion that 'more entrapment = less wear' it was further hypothesized that wider annuli would wear less, due to improved entrapment, all other parameters being held constant.

To test this hypothesis, 60mm diameter annuli of EN1A steel with width 1-4mm were placed in contact and subjected to oscillating rotation with equal displacement amplitude, frequency, contact pressure and total distance slid. This systematically tested the influence of annulus width on wear. The results showed that the wear mass per unit area of contact was constant to within +/- 20% and showed no trend with annular width.

To explain this observation, the form of the radial velocity profile in the debris flow was estimated by considering mass conservation and the average time from particle generation to ejection from the contact was calculated. This average entrapment time was found to have no direct dependence on contact width. It is concluded that debris entrapment is not dependent on the geometry of the annular contact and correspondingly that mass loss per unit area is independent of geometry, consistent with our observations.

This explains the negative experimental result, but also opens a potential opportunity. If debris ejection does not depend on the contact width to particle size ratio, annular contacts are 'wear-similar' in the sense that the wear per unit area is approximately equal as long as local contact conditions (contact pressure, slip amplitude, and speed) are equal. An annular contact could thus be simulated in a laboratory by a contact of different dimensions, simply by appropriately scaling other parameters.

ACKNOWLEDGMENTS

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MICROMECHANICAL EXPERIMENTS TO EXTRACT MECHANICAL PROPERTIES OF A TRIBOFILM FORMED IN A Ti6Al4V/DLC CONTACT BY FRETTING

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KEYWORDS

Fretting; Tribofilms and 3rd bodies; Coating, microcopillar compression

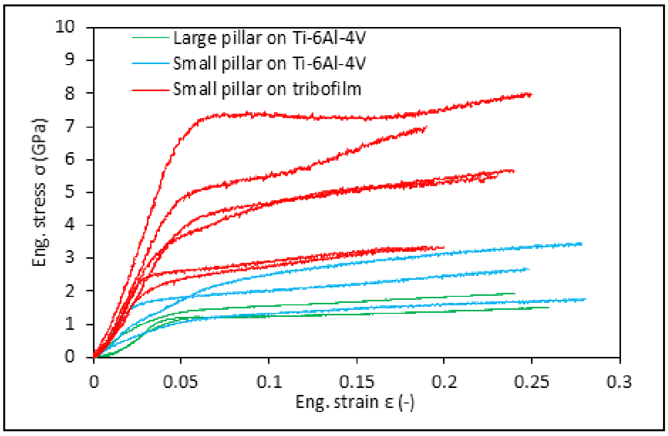
ABSTRACT

Fretting wear of Ti6Al4V versus DLC coating has been investigated [1,2]. It was shown that a tribofilm is formed during fretting. It is mainly composed of oxidized debris of Ti6Al4V, involving a decrease of wear rate and friction.

This study aims at understanding the mechanical properties of the tribofilm responsible of its "lubricating" effect. These mechanical properties have been measured by nanoindentation and by micropillars compression tests. Nanoindentation tests have been performed on the tribofilm, the DLC coating and the titanium alloy. Micropillars have been FIB-machined on the tribofilm and on the titanium substrate. These pillars have been compressed with a diamond flat punch, using an *in situ* Alemnis indenter, installed in a SEM, in order to extract their mechanical behavior (fig. 1).

The results revealed that the tribofilm Young's modulus, hardness, and Yield stress are higher than the ones from the titanium alloy. Consequently, these high properties could be responsible of the good tribological properties of the tribofilm. Surprisingly, the hardness, calculated from the yield stress obtained by micropillar compression, is higher than the one measured by nanoindentation. It was shown there is no substrate influence on hardness measured using y micropillar compression, which is the case by nanoindentation.

Fig.1 Stress–stain (σ–ε) curves measured micro-pillar



compression.

ACKNOWLEDGMENTS

This work was supported by the LABEX MANUTECH-SISE (ANR-10-LABX-0075) of Université de Lyon, within the program "Investissements d'Avenir" (ANR-11-IDEX-0007) operated by the French National Research Agency (ANR). The authors would also like to thank the China Scholarship Council for its financial support.

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EFFECTS OF FRETTING WEAR ON THE EVOLUTION OF HYSTERESIS LOOPS AND CONTACT INTERFACES

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KEYWORDS

Friction; Wear; Experiments in Tribology; Contact Stiffness

ABSTRACT

Frictional contacts are a major source of uncertainty for the correct prediction of the dynamic response of jointed structures. This is due to the poor understanding of the underlying physics of friction. This work experimentally investigates the effects of fretting wear on frictional contacts to eventually provide more reliable dynamic friction interface models. The high frequency friction rig [1] built in the Dynamics Group of Imperial College London is used to measure the evolution of friction coefficient and tangential contact stiffness over time. The friction rig measures friction hysteresis loops by generating a flat-on-flat sliding contact between pairs of specimens with a nominal area of contact of $1mm^2$. A series of five fretting tests was conducted using different specimen pairs at room temperature and run over different time spans. The excitation frequency was 100 Hz and the normal load was maintained constant at 60N for all tests, which resulted in a nominal pressure of 60MPa. Specimens were all made of stainless steel and the contact interface was flat with a roughness value of about 0.1µm. The sliding amplitude was set to 20µm, which ensured hysteresis loops in full sliding regime. After every test, specimens were cleaned in an ultrasonic bath and, after cleaning, images of the worn interfaces were captured using an optical interferometer.

Values of friction coefficient and contact stiffness were extracted from the measured hysteresis loops. Fig. 1 shows the evolution of friction coefficient, □, and tangential contact stiffness, k_t, with wear for tests conducted over different time spans. Results are plotted versus the cumulative energy dissipated, which was obtained by summing the area inside the hysteresis loops recorded over the whole experiment. Fig. 1a shows that the friction coefficient initially increases rapidly from a very low value of 0.1 to a value of 1.1 and it reaches steady state after several thousand cycles. The tangential contact stiffness in Fig. 1b nearly doubles from an initial value of 20N/µm to a steady state of about 40N/µm. The friction coefficient reaches the steady state by dissipating 50J, at least 20 times less compared to the tangential contact stiffness. This suggests that in the case of the friction coefficient the runningin may be driven by the rapid removal of initial surface layers of the material, as already pointed out in past studies [2-3]. This removal leads to a metal-to-metal and/or metal-to-wear particles contact that increase the adhesive and ploughing components of the friction coefficient. In the case of the tangential contact stiffness, results show that the steady state is probably attained when a steady contact conformity is reached due to a full interaction between the contacting interfaces. This hypothesis is supported by the evolution of the contact areas in Fig. 1b where the worn area of contact increases for longer test runs. This in turn is assumed to lead to more asperities and/or wear scars in contact, resulting in a higher number of elastic deformations and hence a higher tangential contact stiffness.

These results provide useful information to obtain more reliable contact models to be used in dynamic simulations.

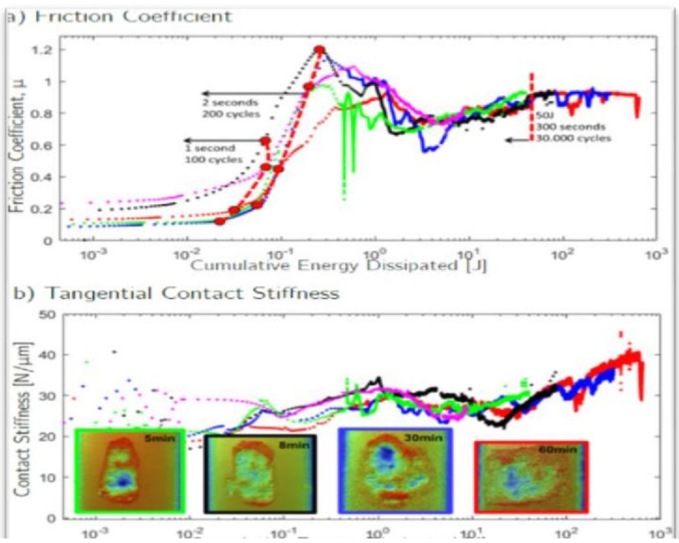

Fig.1 Evolution of contact parameters with wear

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UNDERSTANDING OF THE GLAZE LAYER FORMATION: APPLICATION TO A HS25/ALUMINA CONTACT SUBJECTED TO FRETTING WEAR AT HIGH TEMPERATURE

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KEYWORDS
Wear ; Fretting; Tribofilms and 3rd bodies, High temperature

ABSTRACT

The purpose of this study is to investigate the formation mechanisms of glaze layer during high temperature fretting wear. The studied contact is a cobalt-based alloy against an alumina sample subjected to fretting. The operating temperature varies from 100°C up to 600°C. Wear volume analysis shows that a protective third body is spontaneously created at the interface for high temperatures (T>400°C). The excellent tribological properties of the so-called "glaze layer" leads to an unworn regime.

Microstructure observations at the nanoscale were performed and revealed that the high temperature third body is composed of layers with different grain sizes, chemical compositions and mechanical properties. However, these layers do not appear at the same time at the interface and do not behave equally during fretting. Fig. 1 presents the tribolayer composed of the Effective Glaze Layer (EGL), the Oxidized Debris Layer (ODL) and the Chromium-Rich Layer (CRL). In the light of these results, a high-temperature fretting wear mechanism will be proposed and discussed.

Moreover, previous studies [1,2] showed that the wear behaviour of this tribosystem is well described by an original wear law based on abrasion, oxidation and sintering processes [1,2]. This previous work is extended to predict the glaze layer formation for various tribological parameters. Finally, it is proposed to formalize the glaze layer formation through some "glaze layer maps", as presented in Fig. 1.

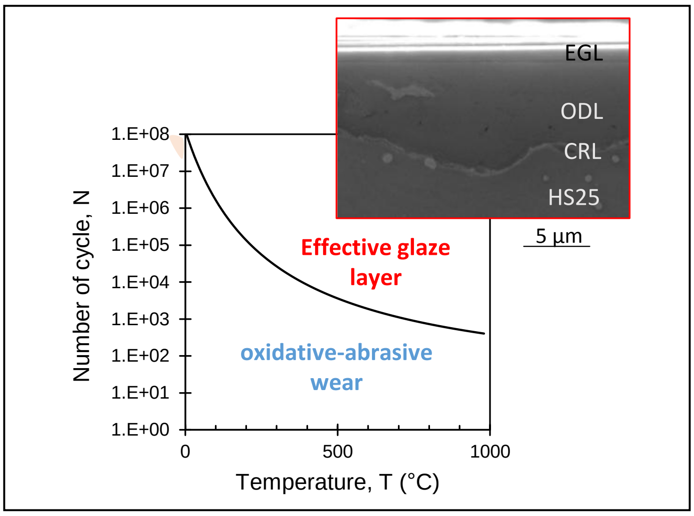

Fig.1 Prediction of the glaze layer formation and SEM observation of the high-temperature tribolayer

ACKNOWLEDGMENTS
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46th LEEDS-LYON SYMPOSIUM on TRIBOLOGY

Lyon, 2-4 September 2019

Invited talk

Lubricious coatings for precision positioning of medical needles

By Sissi de Beer

Materials Science and Technology of Polymers, Twente University, The Netherlands

Many traditional medical procedures are being replaced by needle-based minimal invasive techniques, due to higher survival rates and lower disease burdens. However, to reach the target with a needle can be a difficult task, because the needle needs to be maneuvered around delicate tissue, such as nerves, blood vessels and healthy organs. This procedure is complicated by shear stresses that occur between the needle and tissue as well as the skin, which deform and move the tissue during insertion. To reduce these shear stresses needle-lubricants are necessary. Polymer brushes are well known for their excellent lubricious properties. However, before brushes can be applied on needles, several challenges need to be tackled. In this presentation, I will discuss these challenges and show possible solutions that we have been developing in our research group.

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TRIBOLOGICAL INVESTIGATION ON A GREASED CONTACT SUBJECTED TO CONTACT DYNAMIC INSTABILITY

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KEYWORDS
Friction; Everyday life tribology; Experiments in tribology; stick-slip.

ABSTRACT
Considering mechanical systems with two surfaces in contact and in relative motion, during the sliding of one body over another, friction induced instabilities and stick-slip intermittent motions can occur [1, 2, 3]. In this case, the sliding is not continuous, but instead proceeds with a series of "sticks" and "slips" [4, 5]. These forms of vibration are often undesirable and can cause excessive wear of components, surface damage, fatigue failure, and noise [2, 3, 5]. The problem becomes even more complicated when lubricated contact interfaces are involved, as in this case of study. Nowadays, in literature few works deal with stick-slip in lubricated systems [6, 7]. In the present work, a systematic approach to the stick-slip problem of a greased contact is proposed, by identifying the tribological triplet and analysing the parameters that most influence the appearance of the phenomenon, using together surfaces analysis, with experimental and numerical dynamic simulations.

Considering the specific application of a mechanical spring-brake, used in electric tubular actuators, the lubricated contact of the parts in relative motion is here analysed. The possible instability appearance (i.e. stick-slip phenomena) of such contact is the result of the coupling between the system dynamics and the frictional response of the parts in greased contact. The components under examination can be schematized by a torsional spring rotating and sliding on the inner surface of a cylinder. The topological analyses showed an axial movement of the spring, with consequent misalignment of the nearby mechanical parts, when stick-slip occurs. This singular behaviour of the first bodies can cause the dynamic system conditions that accommodate the appearance of the stick-slip. Following the identification of the phenomenon and the components involved, the frictional response of the greased contact is investigated. The local frictional response has been characterized by experimental tests carried out on a specific tribometer, reproducing the as close as possible the operating parameters of the system. The local contact conditions bringing to stick-slip are then investigated. The local frictional response is coupled with the system dynamics by lumped numerical simulations, in order to better evaluate the unstable dynamic response of the system (i.e. the stick-slip phenomena) and identify the parameters that most influence its appearance.

In conclusion, as underlined thought this work, lubricated systems are supposed to reduce the frictional losses, but they can also generate undesirable vibrations. Understanding the conditions for which the system is more predisposed to the stick-slip phenomenon may allow for preventing the appearance of such instabilities in spring-brake design.

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TRIBOLOGICAL BEHAVIOR OF FIBER REINFORCED PA66 UNDER HIGH CONTACT PRESSURE AND GREASE LUBRICATED CONDITIONS

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KEYWORDS
Wear; Friction; –fiber reinforced polymer material; grease lubrication

ABSTRACT

1.Introduction

Polyamide66 (hereinafter PA66) is widely used for sliding parts. Glass fibers (GF) or Carbon fibers (CF) are usually added to PA66 to increase its strength. There are various conventional researches on the tribology of fiber reinforced PA66 in contact with metallic material [1]. However, these research works are mostly carried out in dry conditions. In addition, there are few reports on the effect of molecular mass of resin or hardness of metallic counterbody on the tribological properties under sliding conditions in grease. In this work, we investigated the tribological mechanisms of fiber reinforced PA66 in contact with metallic material under grease lubrication.

2.Experimentation

Tribological properties were evaluated in sliding test under grease lubricated conditions, with a rotating resin ring in contact with 4 steel cylinders. Fig.1 shows a schematic view of the testing device. Normal force is applied to obtain high contact pressure. Table 1 shows test conditions. Effects of counterpart metal hardness was also studied. Different values of hardness of steel were obtained by different conditions of heat treatment.

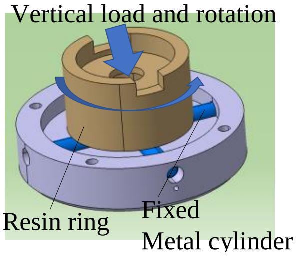

Fig.1 Schematic view of testing device

Table1 Test conditions

Item		Value
Resin ring	Outer diameter	25.6 mm
	Inner diameter	20 mm
	Height	12 mm
Metal cylinder	Material	S45C (Fe+0.45% C)
	Diameter	3.5 mm
	Hardness	HV311-HV660
Grease		Urea grease
Normal load		220-350 N
Contact pressure		156-198 MPa
Rotation speed		1 m/s
Temperature		RT
Testing time		Total: 4 hr in which 10sec driving and 20sec stopping are repeated

3.Results and discussion

The experiments showed the presence of wear and creep deformation. At first, breakage and dropping of GF occurred and micro cracks related to the GF were generated, and finally peeling of resin occurred. The creep deformation was higher just after the peeling, however the wear increased by increasing sliding time. In addition, by increasing molecular mass of resin, it took longer time for the vertical displacement to start to increase linearly compared to the normal molecular mass sample, and the increasing speed of displacement was lower. The breakage energy (which is related to toughness of resin) was increased by increasing molecular mass. Therefore, fatigue properties related to repeated stress were supposed to be increased and high wear resistance properties were obtained.

Wear of metallic cylinders was also investigated. A decrease in wear of both resin and metal is observed when the molecular mass of resin is increased. The effect of metal hardness on the wear of PA66 is presented in Fig.2. Metal hardness in the inflection point of deformation coincided with the hardness of fiber itself measured by nano-indentation and converted to Vickers hardness. Thus, it was supposed that when the hardness of fiber is higher than the hardness of metal, wear of fibers in surface occurred and resin was worn in abrasive wear mode.

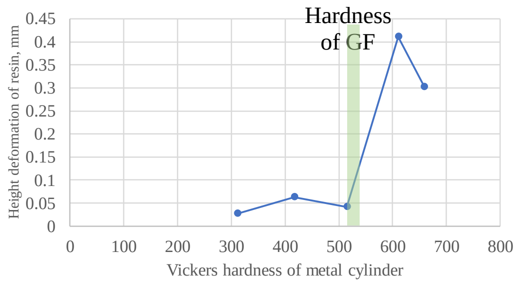

Fig.2 Relation between Vickers hardness of metallic cylinder and height deformation of resin ring reinforced by GF.

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AUTOMOTIVE TRANSMISSION EFFICIENCIES V/S NVH CHARACTERISTICS- AN EXPERIMENTAL STUDY

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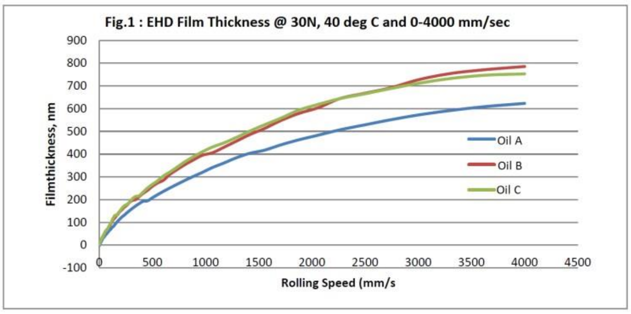
KEYWORDS

Fluid Lubrication, Lubricant Additives, Experiments in Tribology, Noise-Vibration-Harshness study.

ABSTRACT

This paper presents an experimental study on the influence of lubricant formulations to strike a balance between transmission efficiencies and their Noise Vibration and Harshness (NVH) characteristics. There is increasing trend to reduce lubricant friction and viscous drag to achieve high transmission efficiencies of automotive gear boxes. Discerning vehicle customers besides asking for good fuel economy also look for refined NVH performance. This would mean the absence of transmission rattle and gear whine noise emanating from the vehicular gear transmissions.



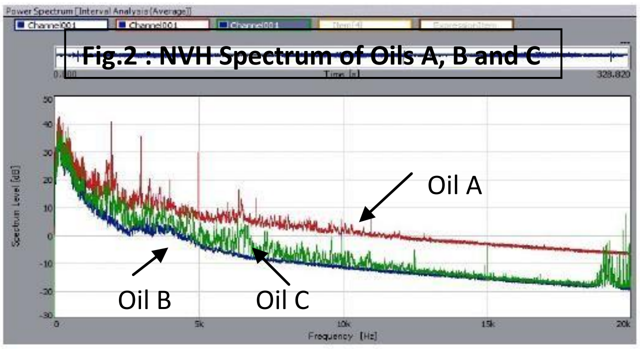


Fig.2 : NVH Spectrum of Oils A, B and C

It has been reported by Mohammadpour et all [1] that conditions which correspond to reduced friction and increase in efficiencies promote increased residual vibratory energy leading to noisy transmissions and poor NVH performance. This would reflect, if NVH performance was assessed as part of standard protocol of the driving cycle which focusses on fuel efficiencies and reduced emissions. Baumann et al [2] indicated that gear rattle noise reduction can be achieved by avoiding meshing impacts, using low traction gear lubricants. Theodossiades et al [3] reports that lubricant behaves like a non-linear spring damper, which significantly affects the response of idle gears during the meshing cycle altering the system NVH performance.

Transmission oils with different viscometrics and FMs were selected for this study. The transmission efficiency was studied using bench tests for film thickness and traction coefficients. The oils were then evaluated for their NVH performance on a

vehicular gear transmission in a chassis dynamometer. Viscosity of the oils @40^0 C and comparative test results of EHD film thickness, traction coefficient in MTM and NVH at a given test conditions are shown in Table 1. Comparative traces of EHD Film thickness and NVH performance of the different oils are given in Fig. 1 and Fig. 2 respectively.

Sound level measurements inside the cabin were measured using a FFT(Fast Fourier Transform) sound spectrum level analyser on the driver side and the front passenger side. The key attributes studied were the gear whine while ramping to high speeds and the gear rattle when running at low speeds. FFT Spectrums for the range of 20Hz to 1 KHz were compared for different oils. Based on these studies, oils offering optimum transmission efficiencies and improved NVH characteristics were selected. Based on the above results, it may be inferred that Oil B has given best NVH performance.

Table 1 comparative properties of different oils

Name of oil	KV @ 40^0 C (Cst)	EHD film thickness @ 30N,40^{0}C, 4m/s (nm)	Traction coeff.@ 40^{0}C, 10% SRR, 3 m/s, 0.95GPa	NVH sound level @ 1kHz (dB)
Oil A	91.5	623	0.035	25
Oil B	116.5	785	0.045	15
Oil C	116.9	753	0.042	18

Fig. 1: EHD Film thickness of oils @30, 40^{0}C

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Investigate the behavior of zwitterionic polymer brushes under different environmental conditions.

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1. Introduction

There has been a great deal of focus in understating the polymerization techniques and behavior of neutral brushes for biomedical applications However, there is limited research with regards to understanding the tribological behavior of zwitterionic brushes.The responsive behaviour of polymer brushes is largely due to the confirmation occurring in different environments. Zwitterionic brushes have shown effective reduction in friction under hydrated conditions (water) as a result of swelling of the brushes. The swelling occurs when the water molecules bind to the polymer via intermolecular electrostatic induced hydration.[1]

Other factors which affect the friction response include pH, solvent, ions and temperature.[2] The effect of differential ions has been reported to be the result of ionic pairing of opposite changes between zwitterionic groups which can cause the brushes to stretch.[3]

Conformational behaviour of brushes on metal substrates in different environmental conditions has not been explored. Therefore the aim of this project is to investigate the frictional behavior of zwitterionic brushes in relation to different salt concentrations to further understand the mechanism of hydration lubrication.

2. Methodology

Stainless Steel (SS316L) substrates were modified with charged zwitterionic polymer 2-Methacryloyloxethyl Phosphorylcholine Polymer MPC) brush through surface initiated photoinduced polymerisation. To investigate the wettability of the brushes in the different environments contact angle measurements were conducted. The Anton Parr Nano Tribometer was used to understand the frictional behavior of surfaces mediated with brush layers and understand the effect of different ions (sodium chloride) on these surfaces.

3. Results and Discussion

The coefficient of friction had a spike in friction for 35 seconds it then remained steady under 0.9 wt % sodium chloride, with coefficient of friction similar to samples tested in deionised water (Figure 1). Therefore, a lower concentration of salts has little effect on the behavior. However, as the wt % of sodium chloride increased the coefficient of friction decreased (Figure 2). This decrease is a result of the ions in the solution screening and reducing the strength of the electrostatic attraction between the chains.[3] The free floating ions thus cause the brushes to maintain a brush like structure reducing entanglement. Consequently, the brushes maintains a low coefficient of friction over time.

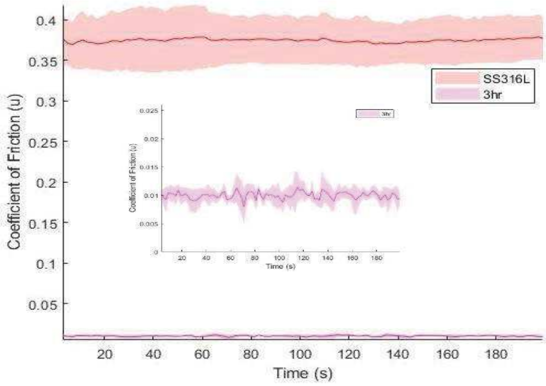

Figure 1 *Coefficient of friction of ungrafted stainless steel and stainless Steel grafted MPC polymer against PDMS probe, under 10mN load in di-water.*

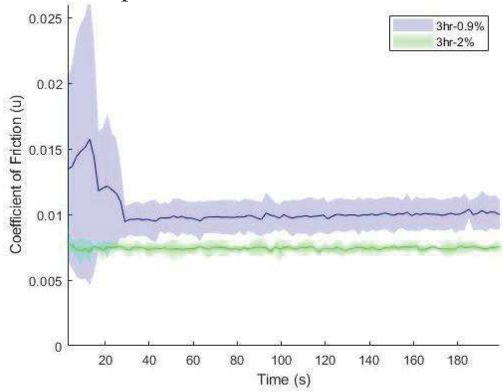

Figure 2 *Coefficient of friction of Stainless Steel grafted MPC polymer against PDMS probe, under 10mN load in 0.9% NaCl and 2% NaCl.*

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

IONIC LIQUIDS AS LUBRICANTS FOR STEEL-STEEL CONTACTS IN SPACE DEVICES

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KEYWORDS
Fluid lubrication; friction; wear; ionic liquids

ABSTRACT

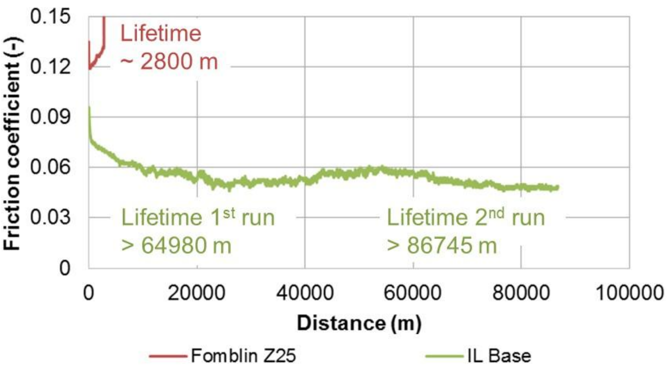
Modern television, navigation, weather forecasts and many other aspects of our everyday lives would not be possible without satellites. Space devices contain a number of tribosystems, among others precision roller bearings, actuators, and gears. 'Extraterrestrial tribology' therefore has a great influence on daily life.

For lubrication in space, typical solid lubricants are MoS_2 coatings and common liquid lubricants are based on perfluorinated polyethers (PFPE), e.g., Fomblin Z25, and multiply alkylated cyclopentanes (MAC), e.g., Pennzane 2001A. Ionic liquids, i.e., room temperature molten salts that are liquid at 25°C, are seen as candidates for vacuum and space lubricants as they offer some unique properties [1, 2]: low volatility due to their ionic nature, fluidity over a wide temperature range, and beneficial tribological properties.

The ionic liquid 1-butyl-1-methyl-pyrrolidinium bis(tri-fluoromethylsulfonyl)imide (IL Base) was benchmarked against PFPE Fomblin Z25 comprising the most crucial requirements: thermal outgassing due to evaporation or decomposition in thermal vacuum, corrosion protection on the ground, friction and wear performance in vacuum comprising endurance tests. The ionic liquid outperformed the reference Fomblin Z25 in vacuum stability and tribological performance as well as lifetime, the latter by a factor larger than 30 (see Fig. 1). The runs with IL Base were stopped manually as no failure of lubrication could be observed.

Ionic liquids can be envisioned to become the third pillar of space and vacuum lubrication besides PFPE and MAC. Their unique properties – i.e., low if any vapour pressure, excellent thermal and oxidative stability, good viscosity-temperature properties, load carrying behaviour, and the ability to develop customized formulations due to selection of cation and anion – make them candidates for lubricants for space.

Fig.1 Friction and distances covered by Fomblin Z25 and IL Base in lifetime runs



ACKNOWLEDGMENTS

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

FM-AFM OBSERVATION ON EFFECT OF WATER ON ADSORPTION LAYER OF HYDROPHOBIC AND HYDROPHILIC IONIC LIQUIDS

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KEYWORDS
Nano Tribology; Physics of friction; Tribofilms and 3rd bodies, Ionic liquids

ABSTRACT

Ionic liquids are salts that exist as liquid at room temperature. They have been used as new lubricants because of their attractive properties, such as low vapor pressure, high thermal stability, and flame resistance [1]. Moreover, these physical properties can be controlled by changing ion pairs. To know lubricating mechanism, it is important to clarify adsorption structures of lubricants. Especially, ionic liquids form specific adsorption layer derived from surface smoothness and ion interaction [2, 3]. However, there is possibility that the adsorption structure of the ionic liquids are disturbed by the presence of water because ionic liquids, and this phenomenon cause degradation of tribological performances of ionic liquids [4, 5]. This investigation evaluated that the adsorption structures of ionic liquids using Frequency modulation atomic force microscopy (FM-AFM, SPM-8000, Shimadzu, JP), which have higher force resolution than conventional AFM. In addition, the effect of water as impurity on adsorption structures of ionic liquids.

This investigation used 1‐Butyl‐3‐methylimidazolium dicyanamide ([EMIM][DCN]) with a purity of > 98% and water content of <10000 ppm (Merck). This ionic liquids show hydrophilic. Before use, [BMIM][DCN] was evacuated at a pressure of 1.0×10^{-4} Pa for 48 hours. Mica was used as the solid substrate and was washed with ethanol before analysis. A cantilever was made of silicon (NCHR, NANOSENSORS, Germany). The spring constant is 42 N/m. Before the measurements, the cantilever was washed with ethanol. Force curve measurements were performed at an amplitude of 40 mV (approximately 4 Å), measurement speed of 5 Hz, temperature of 25°C, and relative humidity of 50%.

Figure 1 shows the Z‐X mapping image of the force curve of the [BMIM][DCN]. The high-brightness region indicates high repulsive force. This results indicated the ionic liquids form mult-adsorption layer. This layer will work as protection film against normal load. In the presentation, the adsorption layer of hydrophobic ionic liquids and effect of water on adsorption layer will be shown.

ACKNOWLEDGMENTS

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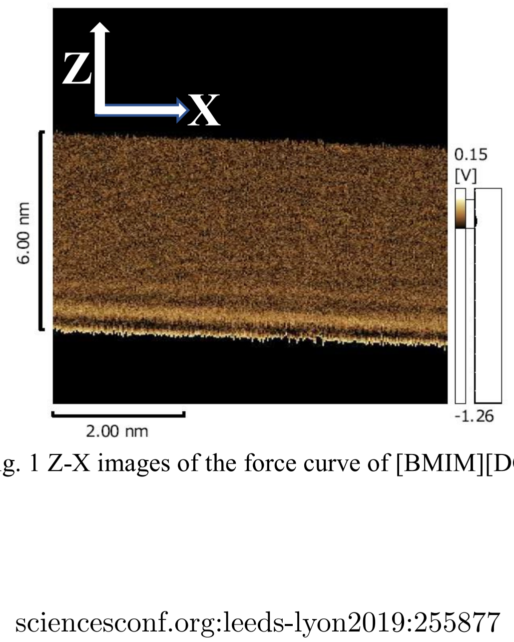

Fig. 1 Z-X images of the force curve of [BMIM][DCN]

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Effect of ILs' chemistry on their lubrication mechanism under various sliding distances

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KEYWORDS

Keyword list 1; Friction; keyword list 2: Wear, free keyword: Ionic Liquids lubricant, tribofilm.

ABSTRACT

Using Ionic Liquids (ILs) as potential lubricant is limited in two applications; aerospace and in the lubrication of Electro Mechanical Machines Systems (MEMS) due their high cost [1-4]. In order to simulate the lubrication of MEMS; a micro scale study is conducted to investigate the effect of ILs' chemistry on their lubrication mechanism at various sliding distances. Five ILs are employed to cover the effect of cation chain length, anion chain length, cation type and anion type. Ball on plate configuration is utilized using Nanotribometer (NTR). The quantification of wear volume and surface morphology are characterized using white light interferometry. Surface chemistry is characterized using XPS. The results showed that ILs' chemistry is crucial in the determination of their lubrication mechanism. The increase of anion/cation chain length enhances the tribological behaviour of the lubricated surfaces. The influence of anion/cation type strongly is varied with the variation of sliding distance. In addition, for all ILs, the increase of sliding distance from 3.6 m to 14.4 m increases friction coefficient and initiates wear. Further increasing in sliding to 36 results either an increasing or decreasing in the friction and wear coefficients depending on the utilized IL.

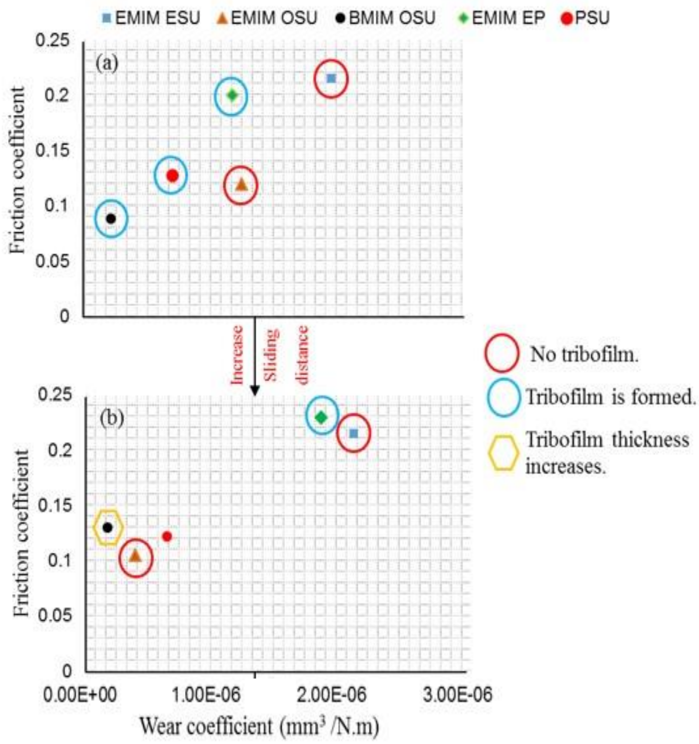

Fig.1 : The lubrication mechanism of ILs at various sliding distances.

ACKNOWLEDGMENTS

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Glycerol/ionic liquids mixture as potential candidate for superlubricity on W-DLC surface under boundary lubrication conditions

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KEYWORDS
Lubricant additives; Mixed Lubrication; Coating, superlubricity (ultralow friction)

ABSTRACT
In this report we present ultralow friction obtained with green glycerol/ionic liquid mixtures on tungsten doped diamond-like-carbon (WDLC) coatings produced with physical vapour deposition (steel ball with 5 mm diameter were used as counter body) under severe mixed and boundary lubrication regime ($\lambda<1$). We investigated different ionic liquids as additives in glycerol to study the effect of contact pressure and temperature on coefficient of friction (COF) and wear. We observed that increase in contact pressure from 0.2 to 1 GPa significantly reduces COF from 0.1 to 0.02 for all mixtures with additives. The mechanism of low friction under high contact pressures with glycerol is still unknown however some authors (e.g. Martin *et al.*) associate such phenomena to friction induced dissociation of glycerol to form a network of water-like species on the surface which provides easy shear under high pressures. In this report we discussed tentative lubrication mechanism which fits nicely with our results. The effect of the temperature on COF was found to be significant for all mixtures. The obtained results for WDLC with 1 GPa contact pressure were compared with steel surface. The surface of the disks (steel and WDLC) and the steel balls were examined with 3D Bruker interferometer, SEM+EDS and AFM. The WDLC coating had much better wear resistance and lower COF than the steel surface at 1 GPa, indicating that combination of glycerol/ionic liquids on WDLC coatings constitute very prosperous solutions for providing anti-wear and low friction properties for many applications. In order to determine the corrosive effect of the ionic liquids on the disks (steel and WDLC) corrosion tests at 100 ºC were performed. Results indicate that steel surface was corroded due to aggressive reactive nature of the ionic liquids however no deterioration was observed for WDLC surface, possible reason why steel surface showed higher COF and wear rate. Thus, this investigation enabled us to determine the important influencing parameters for WDLC and glycerol/ionic liquid mixtures which are of crucial importance for designing new, efficient and environmentally-friendly, lubricants for the coated and other advanced functional surfaces.

Conclusion

- Full solubility of the ionic liquids with 1wt% concentration was achieved in glycerol base oil.
- Ionic liquid additives are not active at low loads (< 1 GPa) thus there is no significant difference in COF as compared to pure glycerol.
- Overall COF reduces with ionic liquid additives progressively at higher loads as compared to pure glycerol. Ultralow COF of 0.02 on WDLC surface was achieved. Temperature effect on COF was significant.
- Wear rate k on WDLC coated disks is negligible for all mixtures at different loads and temperatures. However wear rate is high for steel surface especially at higher temperature 100ºC.
- Ionic liquid additives caused corrosion on the steel surface at higher temperature 100 ºC however WDLC surface remains unharmed. Further chemical analysis with FTIR and XPS is on the way. Such studies will help us to co-relate the chemical structure of ionic liquids (cations and anions) with their tribological properties as well. Such study can also help us understanding tribofilm formation on WDLC surface.
- Wear rate on the counter body (steel) is observed to be associated to the different loads on WDLC coatings. Steel/WDLC tribopair performed better than steel/steel.

ACKNOWLEDGMENTS
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MODELING SOLID CONTACT BETWEEN SMOOTH AND ROUGH SURFACES WITH NON-GAUSSIAN DISTRIBUTIONS

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MOTIVATION

High accuracy of prediction is required for solid contact calculation in mixed lubrication to predict friction loss or wear in sliding parts. In general, the solid contact is calculated by the Greenwood-Williamson model [1] or the Greenwood-Tripp model [2]. But it is not possible to take into account the distribution bias (ex. skewness and kurtosis) that exists on many sliding surfaces in these models, so there is a possibility of causing a deviation from an actual phenomenon. In this study, in order to calculate the solid contact of the rough surface assuming the actual sliding surface, we constructed a model capable of predicting the asperity height distribution by the value of skewness and kurtosis. By using this model, it is possible to predict its distribution shape separately without measuring the height distribution of protrusions.

ASPERITY HEIGHT DISTRIBUTION

Assuming that the asperity height distribution is similarly transformed when the roughness distribution is converted from the Gaussian distribution to the non-Gaussian distribution, the asperity height distribution in the no-Gaussian rough surface is derived analytically (Fig.1). By using the Johnson distribution model [3] as a non-Gaussian distribution, it becomes possible to handle various the asperity height distributions as mathematical expressions. Calculating this model distribution by measured roughness parameters, despite the fact that the skewness and kurtosis are far away from the Gaussian distribution, the distribution tendency is also in good agreement with the asperity height distribution of measured surfaces.

CONTACT CALCULATION

We applied this asperity distribution model to the Greenwood - Williamson model, and a predicted contact area and contact force. Although the increasing tendency of these with respect to the film thickness ratio greatly varies depending on the skewness and the kurtosis, the predicted values by this model are in good agreement with the results of the large scale direct calculation (Fig.2). We also calculated the mean real contact pressure (the ratio of the contact pressure and the real contact area) for each skewness and kurtosis, and confirmed that its absolute value and change tendency with respect to the film thickness ratio is greatly different. This fact seems to suggest that the tendency of friction or wear characteristics varies depending on kurtosis and skewness.

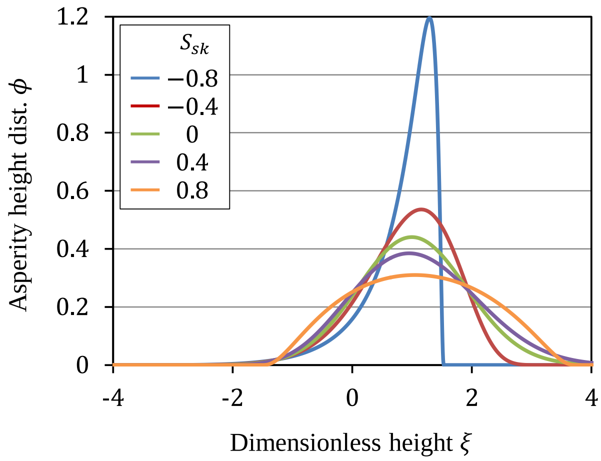

Fig.1 Asperity height distributions for different skewness

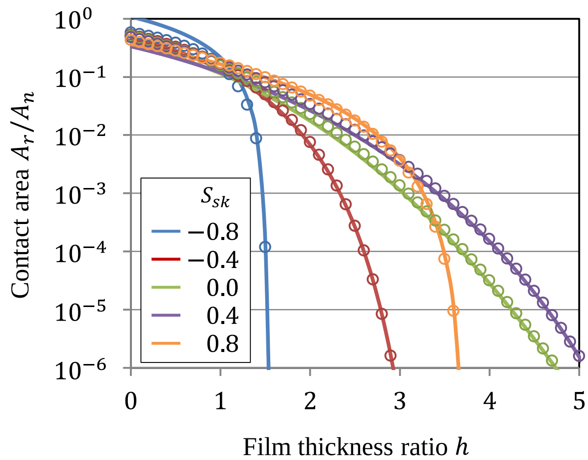

Fig.2 Contact areas under plastic deformation for different skewness(lines: present model, points: theoretical solutions)

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INFLUENCE OF THE TEMPERATURE ON THE WEAR OF AUTOMOTIVE TRANSMISSION BELTS

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KEYWORDS

Wear; friction; experiments in tribology, elastomers

ABSTRACT

Cars are one of the main forms of transportation that we use on daily basis. Poly-V belts are flexible members used for power transmission between rotational elements of automotive engine drives. Wear is inevitable because friction between the belt and the pulley is needed for the transmission of momentum. Furthermore, slip between the belt – pulley is induced by the resistant torque [1]. The combination between the initial tension and the slip generates frictional heating in the interface between the belt – pulley. Frictional heating can produce significant damage to the external surface of the transmission belts (Fig. 1). In this framework, the elastomeric coatings of transmission belts must have a considerable wear resistance at high temperatures while maintaining their power transmission capacity and anti – noise properties.

The aim of this study is to evaluate the wear behavior of different elastomeric coatings in order to select future materials solutions that shall enhance wear resistance and increase the lifetime of transmission belts.

First, the wear features of the surface of the belts abraded under realistic conditions are identified using Scanning Electron Microscopy (SEM). Then, abrasion tests on different elastomeric compounds are carried out using an innovative rolling-sliding tribometer with controlled environmental temperature. This device is able to reproduce the real operating conditions of an engine drive with a good similarity, in terms of kinematics and contact temperature, at a laboratory scale. Normal load and slide-roll ratio (SRR) are used as operating parameters, whereas conditions such as contact temperature and coefficient of friction (COF) are monitored during the wear test. Lastly, the linear wear loss is measured using the wear track profile scan.

Preliminary results indicate that different elastomeric coatings exhibit distinctive wear features and consequently different COF and wear rates.

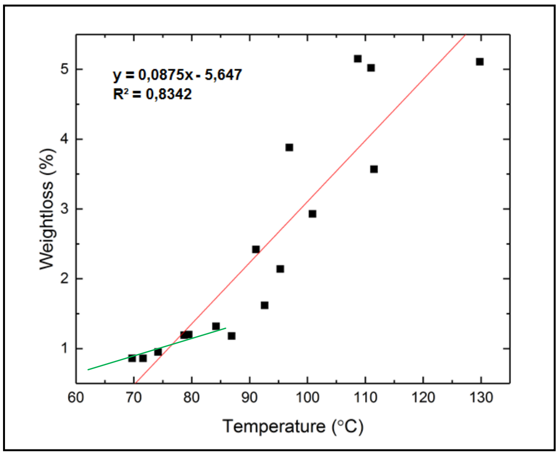

Fig.1 Effect of the pyrometer-measured contact temperature on the weight loss for an elastomeric coating (tests on a belt-pulley laboratory simulator)

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EFFECT OF RUBBER TREAD HEIGHT AND SHAPE ON FRICTION

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KEYWORDS
Friction; Experiments in tribology; Everyday life tribology, Rubber friction

ABSTRACT

The frictional performance of treaded rubber has implications to many everyday applications (sports shoes, tyres etc.). The effect of tread on rubber friction on dry rough surfaces is not clearly defined in the literature. The analytical theories do not include parameters to account for changes in a rubber block’s height or shape. However, studies conducted to determine the coefficient of friction (μ) between rubber and rough surfaces find significant differences to occur with different tread patterns [1,2].

Sliding experiments were performed on three different shapes (square (S1), rectangle laid perpendicular to sliding direction (S2) and rectangle laid parallel (S3)) of rubber all with the same nominal contact area and flat ends. The rubber samples were clamped at different heights (5 and 10 mm) allowing the investigation of tread shape and height and their respective influence on the frictional performance of rubber.

No significant differences in static μ were found between any of the shapes tested. Additionally, no difference in dynamic μ was recorded at the two different tread heights. However, significant difference in dynamic μ is found between all three tread shapes. This is contrary to the classical laws of friction.

Based on the findings of [3] it is theorised that these frictional variances found between tread shape occur as a result of the differing amounts of frictional heating that occur. As shown in Figure 1, when plotting the length of the sample that is parallel to the direction of sliding, against the dynamic μ, a negative correlation is found. More tests are needed to further investigate the exact reason for these frictional differences.

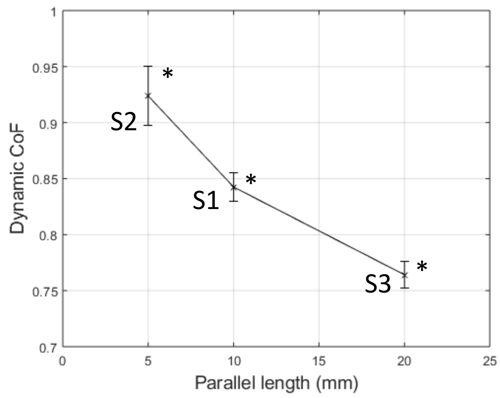

Fig.1 Relationship of rubber sample length and dynamic μ of three different shapes of rubber

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Friction and Wear of Additive Manufactured Polymers in Dry Contact Application

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KEYWORDS

3d-Printed polymers, Friction, Wear, surface topography

1. INTRODUCTION

The working principles and functionality of an additive manufacturing (AM) system which define material properties plays a pivotal role in surface texture definition, accuracy and refinement. As supposed to most polymer processing techniques such as injection molding, extrusion etc., 3d printing affords the flexibility in polymer manufacturing and provides geometrically stable polymer based materials (PBM) for varied engineering applications. Polyjet additive 3d printing technique as amongst many AM techniques uses a multi piezo-inject printing technology combined with UV-curable materials to accurately and economically produce detailed layer-bylayer PBM with varied chemical, mechanical and physical properties[1].

Their relatively reduced mechanical and structural properties compared with most metallic and ceramic composites, have provided them with an added advantage in tribo pair applications such as lip seals, rollers, ball bearings and artificial joints due to their excellent tribological performance under such conditions [2]. However, depending on the type of AM technique employed in the manufacturing process, material properties such as surface roughness, hardness, and elastic modulus etc., which serves to provide the bulk of the material properties are altered in the process. In theory, a high crosslinked density PBM is crucial in preventing material loss and fragmentation during surface contact in tribological application [3]. However, the effect of print orientation and degree of surface roughness introduces new sets of challenges when characterizing both friction and wear regimes of these PBM, hence providing a good justification to further study the tribological behavior and mechanisms in dry reciprocating sliding contacts.

2. Experimental Method

2.1 Sample Preparation

The ball and plate PBM samples were both prepared to examine the tribological properties of three PBM. A 6.5mm AISI52100 steel ball bearing was used in a multi-functional UMT TriboLab equipment as the counterface body in a reciprocating dry sliding experiment. Two out of the three PBM (3D printed ABS and VeroGrey) studied were produced using the Polyjet®1000 AM machine with dimensions 20mmX15mmX2mm. Moulded ABS polymer of similar dimensions was used as a reference PBM in this experiment.

In this test, the anisotropy of surface finishing giving rise to varied surface roughness properties along (parallel) and across (perpendicular) the print direction. A normal applied load of 1, 5 and 10N and a Stroke length 2mm and a sliding speed of 8mm/s are studied in a 60minute test

3. RESULTS AND DISCUSSION

Results from this study reveal a strong correlation between surface anisotropy effect as a function of time and applied load (Fig.2).Under lower load conditions, the coefficient of friction (COF) along and across the print direction showed varying and distinct friction and wear properties. The COF perpendicular to the print orientation generally showed increased friction values compared with the friction parallel to the print orientation. This is as a result of the increased real contact area resulting in strong adhesion between the surface asperities and the counter surface. Israelachvili *et al*. (2000) noted that, the adhesion-controlled input to the overall friction force is proportional to the real contact surface.

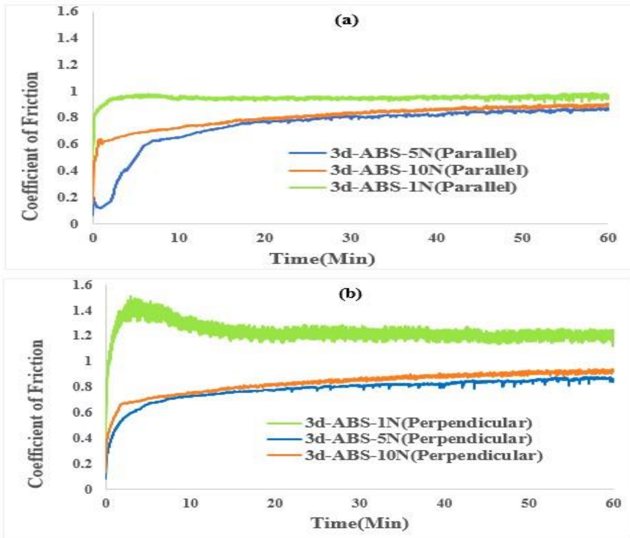

Fig.1 Coefficient of friction results of 3d-ABS under 1-N, 5-Nand 10N of (a) parallel and (b) perpendicular print orientations.

Full report on the tribological test are discussed in the full page paper.

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

PARTICULARITIES OF TRAM WHEELS WEAR IN FOUR SEASONS CLIMATE: FOCUS ON MECHANISM IDENTIFICATION & SURFACE TOPOGRAPHY

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KEYWORDS

Wear, Surface Topography, Rolling Contact Fatigue, Tram Wheel Tire

ABSTRACT

Starting from the 80s of the XX century, one can see the renaissance of trams as the main means of urban transport in large cities of Europe and North America. The current return to this public transport solution is caused by many social and economic factors, including: designing routes independent of a car traffic (fast moving avoiding traffic jams), an ergonomic and comfortable construction (e.g. low-floor vehicles), beneficial an economic and pollution aspect.

Increasing development of tram networks and increasing number of used urban rail vehicles generates the need to search for solutions that maximize their durability and reliability. Taking into consideration the tribological point of view particularly relationship between motion and friction, the wheel/rail contact of tram is particularly important. Therefore, the purpose of this part of study was the identification of wheels tires wear mechanism as a starting point to increase their wear resistance in the future (in continental climate - Dfb according to Köppen classification). The analysed objects were wheels tires dismantled from three types of trams: Siemens Combino, Moderus Beta and Solaris Tramino. All mentioned trams are operating in Poznan Public Transport Company (Poland, 18 lines of 147 km). Analysed tires were from the first bogie – the driven bogie of the tram (hypothetically highest wear due to highest load).

The wheel-rail contact durability is related to the synergistic effect of various mechanisms of wear due to friction, rolling and fatigue. For typical rail transport the length of straight sections of rails is definitely higher than arcs and the acceleration/breaking frequency is relatively low. In this case a fatigue crack initiation and propagation typically dominates (RFC – rolling fatigue crack). RFC of wheel and rail surfaces can be twofold and evolve as: spalling or shelling. The effect of both mechanisms is the flaky surface failures, but their course and activating factors are different. Tram traffic is characterised by frequent starting and braking of vehicles as well as the need to overcome narrow curves and crossovers. As a consequence tram wheels are exposed to slip which can cause their local heating to a temperature even above 300 °C for a longer period time. A less frequent but more dangerous form of RFC – shelling can occur on tires surfaces (Fig. 1).

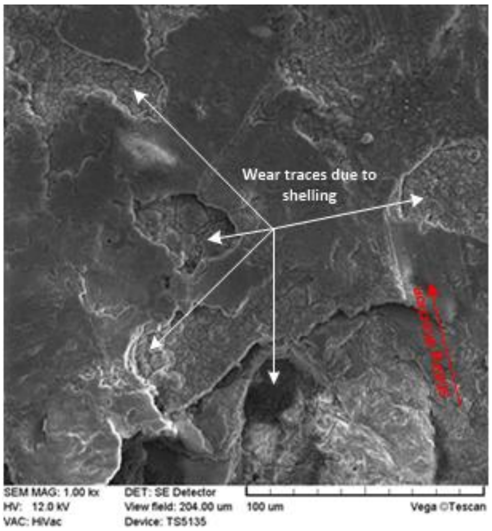

Fig. 1. Selected SEM pictures of worn surface of tram wheels tire at four season's continental Dfb climate.

It is some paradox that the wear's studies of wheels and tram rails in a slight way relate to the geometric aspect of their surfaces. Therefore, the analysis of the surface topography of tram wheels tires in the context of identified wear processes was additionally carried out. On this basis, specific roughness parameters were selected that may be helpful in servicing tram wheels tires and early detection of developing wear process.

Posters

Big top (outside)
Poster session on Monday sept. 2 at 18:30

Poster group n° 1

Dry friction,
fundamentals and applications

46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

TRIBOLOGICAL MODEL SYSTEM TESTING IN LIFE SCIENCE APPLICATIONS AND MEDICAL ENGINEERING

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KEYWORDS

Biotribology; Experiments in tribology; Everyday life tribology; MCR Tribometer

ABSTRACT

Various tribosystems can be found in scenarios related to the human body (see Fig. 1). On the one hand, there are tribosystems consisting of biological counterfaces such as the tongue-palate tribopair [1], articular joints, or the eyelid sliding against the cornea, and on the other hand, there a medically engineered products which come into contact with biological tissues such as implants or catheters. Knowing about the tribological behavior of such systems can be beneficial for questions like:

- How to correlate tribological data and sensory perception of food, cosmetics, etc.
- How to characterize the effects of pharmaceutical products such as eye drops, artificial synovial fluid, etc., on the frictional behavior at biological counterfaces
- How to improve medical devices and implants in terms of product optimization and safety [2]

The real-world tribosystems often show a complex structure but can be abstracted and simplified for testing at model scale. The tests can be carried out with real biological tissues, articular cartilage for instance, or with synthetic substitutes such as artificial skin, Polydimethylsiloxane (PDMS), as well as with medically engineered materials. Most biotribological scenarios are characterized by low speeds and relatively low contact pressures. The authors here present a methodology for model system testing at low loads and low speeds to approach the above mentioned questions. Results from tribological measurements are presented in the form of extended Stribeck curves [1] and breakaway torque measurements. The contribution also covers how to choose between biological and artificial specimen and how to fix them in the Tribometer with special adapters.

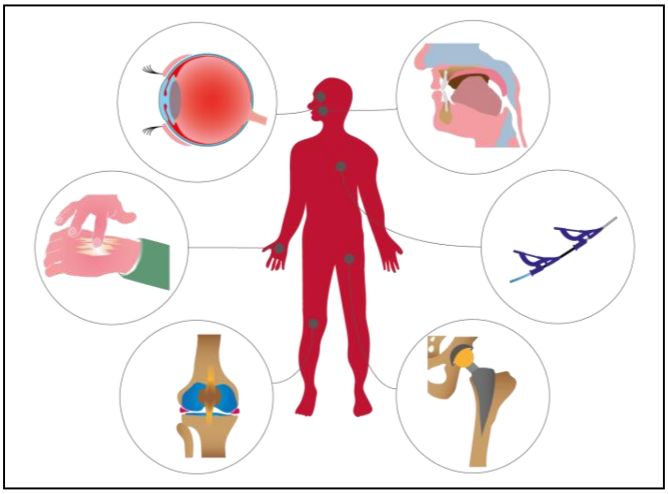

Fig.1 The human body from a tribological point of view: Tribology can be a key to understand sensory perception (e.g. food and cosmetics) but also to optimize medical products (ophthalmic and orthopedic applications, catheters).

ACKNOWLEDGMENTS

The authors appreciate the generous support and enriching discussions with Dr. Gabriele Vecchi, Ibsa Farmaceutici Italia.

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MELAMINE CYANURATE ADDITITVE FOR LOW FRICTION POLYMER COATING

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KEYWORDS

Solid Lubrication; Hydrodynamic Lubrication; Coating; Bearing Overlay

ABSTRACT

Within new generations of bearing materials, recent trends have been focussed on adopting polymer overlays to balance the demands from arising engine developments.[1] In particular, with the advent of start-stop engines the bearing surface suffers from an increasing number of start stop cycles in which the oil films are depleted, increasing the amount of time spent in mixed and boundary lubrication. This factor, combined with trends for thinner oil films and lower viscosity oils are leading to the frictional properties of bearings becoming of increasing importance. Most conventional polymer overlays for bearing materials use well known solid lubricants such as PTFE, MoS_2 and graphite.

Recently MAHLE has developed a polymer coating utilizing melamine cyanurate as a novel and superior solid lubricant additive to improve the overlay properties. Melamine cyanurate, a crystalline complex of melamine and cyanuric acid is able to demonstrate unique lubricating properties through a complex network of hydrogen bonds. Melamine cyanurate has several interesting properties, being well known as a flame retardant, the material possesses a high thermal stability whilst maintaining impressive solid lubricant properties generating a low coefficient of friction due to a multi-layered structure. Melamine cyanurate has been incorporated in the coating formulation promoting benefits in frictional properties including a reduction in the speed at which hydrodynamic lubrication is achieved, leading to enhanced bearing lifetime. Improving the frictional properties of polymer coatings is important for helping customers to continue to improve internal combustion engine efficiencies whilst maintaining a robust solution.

This work reviews the effect of the addition of melamine cyanurate as a solid lubricant additive for polymer coating overlays for engine bearings to provide a cost effective, high performance solution. A series of in-house bearing rig tests evaluated the frictional performance, wear and seizure characteristics and fatigue capabilities of the polymer coated bearing. The results have shown superior frictional performance to conventional polymer coatings alongside increases in the seizure resistance. The material has shown particular benefits during early life of the bearing, with notably improved speeds at which hydrodynamic lubrication is achieved during the first few cycles of testing. An internal engine test was also conducted utilising the new coating for both main and connecting rod bearings to strengthen the applicability of the concept.

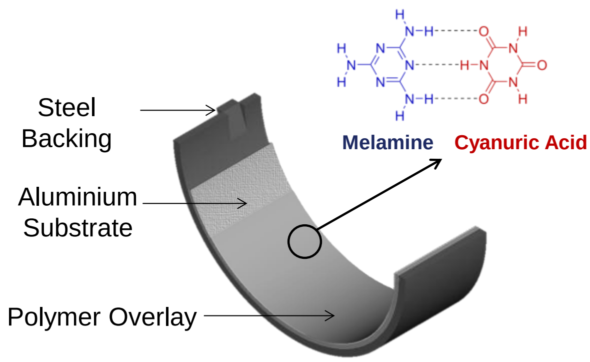

Fig.1 Bimetal polymer coated bearing with polymer overlay containing melamine cyanurate additive.

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TACTICLE SLIDING BEHAVIOR OF PLLA NANOSHEETS PRODUCED BY R2R SYSTEM

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KEYWORDS
Friction; Wear; Nano Tribology; Nanosheets

ABSTRACT

In this study, sliding friction was measured between a fingertip on a silicon substrate and a nanosheet [1]. A nanosheet was prepared by a roll-to-roll (R2R) production method [2] in which a film was supported by a plurality of rollers and conveyed, and a microgravure printing method. Using the fabricated 50 nm nanosheet, friction measurement was carried out using a probe type surface profile measuring apparatus. The friction between the nanosheet and the fingertip on the silicon substrate was experimentally measured. By using force transducers, tactile friction forces and loads are measured. Based on the experimental results, the relationship between the frictional force and the applied load has a positive correlation as shown in Fig. 1(a). In addition, coeffcient of friction (COF) was increased within 4 N, and then COF was guradually decreased as shown in Fig. 1(b). Assuming a perfect contact condition, the expected contact area will increase as the load increases. In addition, based on wear observation, the sliding performance of the skin causes minor damage to the surface of the nanosheet sample with mild wear track along with sliding direction. Overall, researches on frictional force, COF, load, contact area, sliding behavior between skin and nanosheet have been conducted, and these findings may contribute to biomedical research in skin application.

ACKNOWLEDGMENTS

This work was supported by MEXT (Japanese Ministry of Education, Culture, Sports, Science and Technology)-Supported Program for the strategic Research Foundation at Private Universities.

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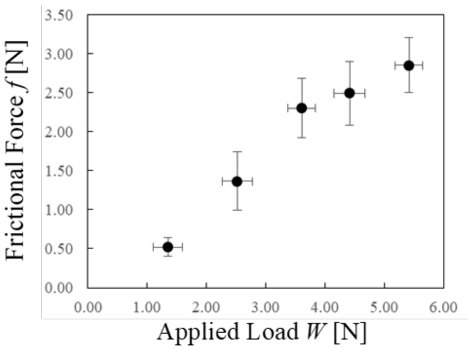
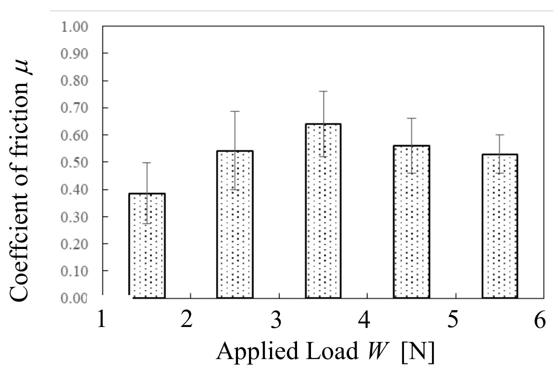


(a) Average friction force versus applied load



(b) Average COF versus applied load

Fig. 1 Average friction force versus applied load and average COF versus applied load

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TRIBO-CORROSION ON CoCrMo ALLOYS: UNDERSTAND THE ROLE OF APPLIED POTENTIAL AND TRIBO-FILM FORMATION

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KEYWORDS
Biotribology; Everyday life tribology; Tribofilms; Hip implants

INTRODUCTION

The nature of the tribofilm formed on the surface of CoCrMo alloy has been shown to affect the tribology and corrosion processes at sliding interfaces [1]. Protein adsorption has important roles in the implant surface performances such as corrosion, tribology and biocompatibility [2]. CoCrMo alloys are suitable used for the application of hip implants [3]. Bovine serum contains albumin which can affect the corrosion reaction of CoCrMo surfaces [4], increasing passive and transpassive dissolutions rates. The presence of protein also influence the wear properties of CoCrMo alloys [5]. Local pH presumed to be changed by the applied potential and rubbing, which influences the electrostatic forces within surface and proteins [6]. Thus the electrochemical environments are presumed to impact adsorption process. The applied potential affects the level of metal ion release which determines the denatured protein and chemistry of the film [7]. The protein adsorption rate is also higher at cathodic condition compared to what observed at more passive potentials [8]. The galvanic coupling of the implant area has a chance to experience low potentials near to the reversible potential of implant metal [9]. Therefore, it would be essential to assess the tribofilm on CoCrMo alloys in the serum containing lubricant under tribological and applied potential conditions. The hypothesis is that the protein adsorption will be changed by the applied potentials and rubbing conditions, then affect to the lubrication performance.

This study aims to investigate how the tribofilm formation on CoCrMo affected by lubricant constituents (non-protein and protein) at the several treated potentials (0.4V and -0.8V vs Ag/AgCl). The formation also will be linked to the tribocorrosion behaviour compared to the OCP condition.

MATERIAL AND METHODS

A reciprocating pin-on-plate tribometer was used to replicate tribocorrosion conditions as similar to those conducted in-vivo. The contact configuration comprised of a sphere on flat geometry, with an alumina ball (Ø = 12 mm) directly in contact with a flat low-carbon CoCrMo plate (Ø = 22 x 6 mm). The plate surfaces were polished to Ra ~ 10 nm. The applied load is 15 N. The three different types of lubricant used were:

- Phosphate Buffered Saline (PBS)
- 25% Foetal Bovine Serum (FBS) diluted in PBS
- Dulbecco's Modified Eagle Medium (DMEM)
- 25% Foetal Bovine Serum (FBS) diluted in DMEM

The results analysed from the 2-hour wear test at OCP vs Ag/AgCl and potentiostatic tests at 0.4V and -0.8V vs Ag/AgCl in terms of tribocorrosion behaviour and surface chemistry.

RESULTS AND DISCUSSION

Fig. 1 shows the average of tribology results of all sample conditions. The results will compare the tribology behaviour of friction coefficient, total volume loss at all conditions. The surface chemistry is compared based on the XPS peaks result to interpret the tribofilm formation. Then, all data will be linked of the potential (electrochemistry) and lubricants effect to the tribofilm formation. It is interesting to breakdown the tribofilm formation to understand the metal-protein-passive film complexation. Lastly, the tribofilm formation is assessed to the tribological behaviour.

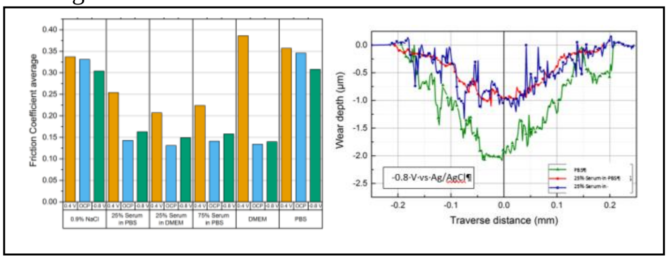

Fig.1 Tribology results of all sample conditions

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EXPERIMENTAL ANALYSIS OF THE FRICTION ANGLE BETWEEN CARBON SINGLE FIBRES AND TOWS AND ANALYTICAL MODEL

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KEYWORDS
Friction; Experiments in tribology; Contact and adhesion; Carbon fibres

ABSTRACT
With the increase of the use of carbon fibres as reinforcement of composites, many studies are conducted to better understand these fibrous materials. During the manufacturing of these composite materials and at different steps (handling, weaving, shaping process…) tows move and rub together and with the others parts. These interactions play an important role because they can affect the final reinforcement quality and can generate fibre and tow breakages. These studies have to allow to optimize the development and the manufacturing of such carbon reinforced materials. The aim is to reduce the occurrence of defects, to improve the productivity and to allow the design of more complex parts. These studies also allow to perform developed models in order to help the designers.

During the different steps of the manufacturing of these materials, the motion of the tows are complex and many kinematic and dynamic parameters influence the interactions.

Many experimental studies have ever been conducted to analyse the friction behaviour between tows or between single fibres [1-3]. These experiments aim to analyse the interaction phenomena that occur and to quantify the friction forces. The influence of several friction parameters have been evaluated (sliding velocity, normal force, kinematic, sizing of the tows, number of fibres per tow).

The present study concerns the influence of the contact angle. Two experimental methods have been developed to realize friction test at tow scale and at fibre scale with the same kinematic. The tribometers used allow to measure the friction forces and an apparent coefficient of friction can be computed.

Experimental results show a decrease of the friction coefficient with the increase of the contact angle from 0° contact angle (i.e. the samples are parallel) to 90° contact angle (i.e. the samples are perpendicular) following a nonlinear evolution. The trend is similar at tow (cf. Fig.1) and at fibre scale (the contact angle is then limited to 10°). This behaviour, already known [4, 5], is similar for the two types of carbon fibre tested (IM7 and T1100), and for different sizes of tows (a tow constituted of 3000 fibres is called 3K).

An analytical model has been established to link tow scale and fibre scale behaviours.

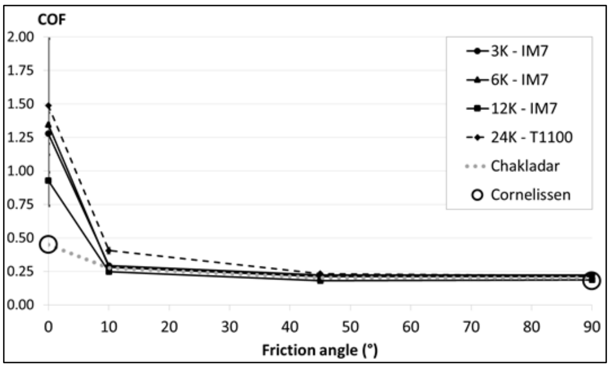

Fig.1 Evolution of the COF relative to the friction angle with the error bars at tow scale with additional data extracted from [4, 5].

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VISCOELASTIC ADHESION OF POLYDIMETHYLSILOXANE DURING CROSS-LINKING REACTION

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KEYWORDS
Contact and adhesion; Rheology; Experiments in tribology, cross-linking

ABSTRACT
Polydimethylsiloxane (PDMS) is the most widely used silicon-based organic polymer and is particularly known for its unusual rheological properties. In certain applications, like e.g. dry adhesives or dry transfer of 2D materials, adhesive properties of PDMS play crucial role. For solid PDMS, it was shown that the work of adhesion are influenced by such factors as base to cross-linker ratio, number of contacts (i.e. adhesive wear) and pull-off velocity [1].

In this work transformation of PDMS material from a non-cross-linked condition to a fully cross-linked solid state is investigated from the point of view of contact mechanics according to the classical Johnson-Kendall-Roberts (JKR) scheme [2]. The PDMS material sample was produced by mixing two components, namely PDMS base and cross-linking agent in a predetermined ratio, and a further continuous measurement of adhesion was performed during a chemical cross-linking reaction. It is demonstrated how adhesion between a glass ball and a PDMS sample depends on the PDMS cross-link density.

The sample was in the liquid state for the first ~14 hours. In this state, the adhesive interaction can be described as the result of the formation of a capillary bridge with an insignificant influence of the viscosity of the liquid up to the gel point. Then the sample turned into a soft gel-like structure, which corresponds to the formation of a percolated molecular network, see Fig. 1. During this transition period, contact mechanics are characterized by the formation of "strings" and irreversible deformation, which are not observed either in the initial liquid state or in the completely cross-linked state. Furthermore, the gel PDMS material continues to solidify, that is associated with changing of dynamical parameters of contact interaction as well as decreasing of adhesive “wear” of the PDMS surface.

Fig. 1 Photo of strings formed between the glass ball and the PDMS with a gel-like structure

We also conducted separate experiments to determine the viscosity in the binding process as a function of time, which show an increase in viscosity by 3 orders of magnitude (from ~103 to ~106 cSt) for 8 hours [3].

ACKNOWLEDGMENTS
This work was supported by Russian Science Foundation project grant 18-19-00645 “Adhesion of polymerbased soft materials: from liquid to solid”.

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TUNABLE FRICTION THROUGH ISOPROPANOL VAPOR-PHASE LUBRICATION: HOW DOES IT WORK?

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KEYWORDS
Everyday life tribology; Experiments in tribology, Vapor-phase lubrication

ABSTRACT

In vapor-phase lubrication, a lubricant is supplied in the vapor phase and subsequently condenses onto the sliding surfaces where it reduces friction and wear. Because the composition of the vapor can easily be controlled externally, this method has the potential to enable stable and tunable friction at a variety of interfaces.[1,2]

We study SiC on Si wafer interfaces that undergo non-reciprocated sliding movement; i.e. sliding motion in which the contact is continuously supplied with unworn Si counter surface. We show that through isopropanol vapor phase lubrication, friction and wear can be reduced substantially for these sliding conditions, with respect to the friction and wear observed in ambient tests. By what mechanism does the vapor phase lubrication enable this reduction in friction and wear and is there a difference between vapor phase lubrication and liquid phase lubrication? This will be the subject of this presentation.

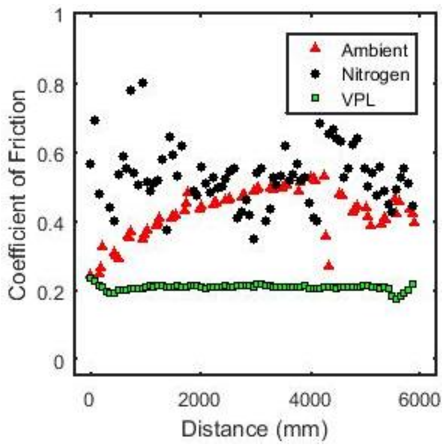

Fig.1 Coefficient of friction measured at the interface between a rough SiC sphere and a smooth silicon substrate while the interface is immersed in nitrogen, ambient air, or isopropanol saturated nitrogen.

ACKNOWLEDGMENTS

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Low friction behaviors of Ag-doped γ-Fe_2O_3@SiO_2 nanocomposite coatings under high temperature

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KEYWORDS
Friction; Coating; Solid lubrication, High temperature tribology

ABSTRACT

In this study, applying the sol-gel method for coatings of Ag-doped γ-Fe_2O_3@SiO_2 entrusted on steel was investigated. Experimental evidences illustrated that core-shell microstructure in the Ag-doped γ-Fe_2O_3@SiO_2coatings and Ag nanoparticles were distributed in coatings. Tribological properties were investigated by tribometer at temperatures of RT, 100 °C, 300 °C, 500 °C and 600 °C. It has been found that the coatings exhibit low and stable friction (from 0.25~0.06) from RT to 600°C. However, coefficient of friction (CoF) for frictional pairs decreases with the increase of temperature. XRD, Raman spectra and SEM measurements demonstrated the anti-friction behaviors of the frictional pairs are owed to the soft noble metal Ag below 600°C which is involved in the transformation between α-Fe_2O_3 and γ-Fe_2O_3 at 600°C during sliding. The γ-Fe_2O_3 is lucrative to form low shear interface with achieving high temperature low friction. The core-shell microstructure of coatings inhibits γ- Fe_2O_3 changing into α- Fe_2O_3.

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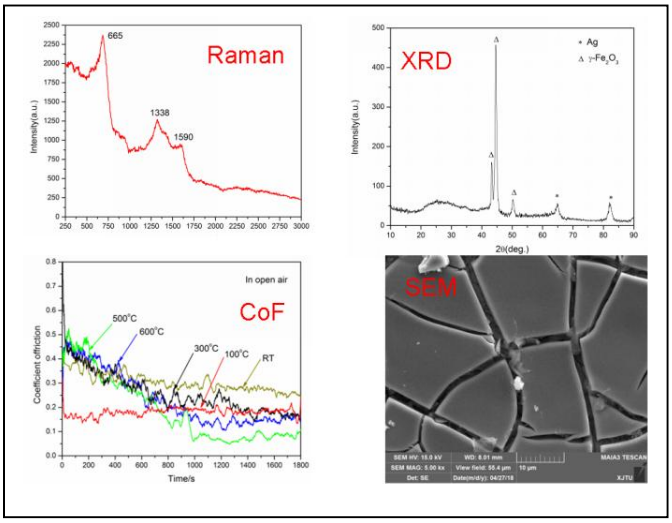

Fig.1 Microstructure, CoF and SEM Ag-doped γ-Fe_2O_3@SiO_2 nanocomposites

ACKNOWLEDGMENTS

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Mechanical and tribological properties of carbon fabrics/epoxy composites containing aligned CNTs@Fe_3O_4 in through-thickness direction

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KEYWORDS

Lubricant additives; Solid lubrication; Nano tribology, Carbon fabrics/epoxy composites

ABSTRACT

The polymer composites reinforced with aligned nano-particles have attracted much research interests due to its excellent mechanical and tribological properties by make full use of anisotropy of nano-particle[1-4]. The CNTs@Fe_3O_4 hybrids have been prepared by modified co-precipitation method and aligned in carbon fabrics/epoxy composites at thickness direction using a weak magnetic field to simultaneously improve the mechanical and tribological properties. The research results have shown that modified co-precipitation method can synthesize Fe_3O_4 nano-particles in smaller size (less than 10 nm in diameter) compared conventional co-precipitation method (20-30 nm in diameter)[5] and the achieved the better dispersity in solution, promoting more Fe_3O_4 nano-particles attached to the surfaces of CNTs. The interlaminar shear strength and hardness of composites containing aligned CNTs@Fe_3O_4 achieved significantly improvement because of the presence of CNTs along thickness direction of composites, compared to those containing randomly distributed CNTs@Fe_3O_4. And the lubricating property and wear resistance of composites containing aligned CNTs@Fe_3O_4 achieved significantly improvement, particularly under high applied load, compared to the composites containing randomly distributed CNTs@Fe_3O_4, which mainly use of the friction anisotropy of CNTs.

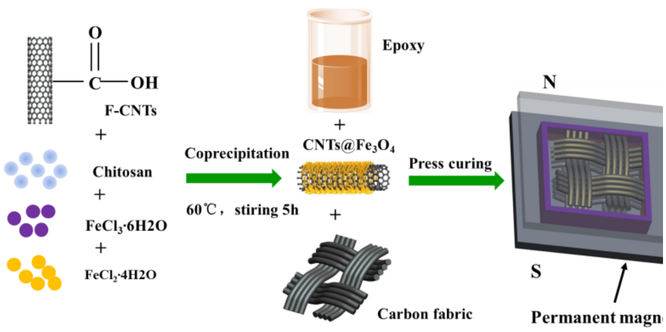

Fig.1. Schematic diagram of the fabrication process of carbon fabrics/epoxy containing aligned CNTs@Fe_3O_4.

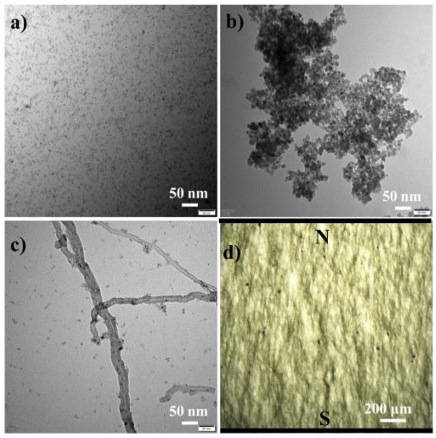

Fig.2. TEM images of a) Fe_3O_4 particles by modified co-precipitation method, b) Fe3O4 particles by conventional method, c) CNTs@Fe_3O_4 hybrids and d) optical image of CNTs@Fe_3O_4 in liquid epoxy applying magnetic field.

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CHARACTERISATION *IN VITRO* OF THE FRICTIONAL BEHAVIOR OF DIFFERENT CONTACT LENSES BY INNOVATIVE METHOD

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KEYWORDS
Biotribology; Physics of friction; Everyday life tribology, Contact lenses

Understanding the biotribology involved between the contact lenses and eye is a key factor to prevent irritation, from the contact lenses rubbing against the eye, and eye infection.

The aim of the present research work is to investigate the tribological behaviour of different contact lenses under different contact conditions. Since there is no commercially available equipment to study the frictional behaviour of contact lens materials, a special test machine was developed in order to be used as a tribometer.

The developed tribometer operates as a pendulum with vibration horizontal movement. In order to simulate the conditions of the human eye, the geometry used is plane-sphere. The contact lens is placed over a hemisphere of silicone and a glass lamella was used as counter material. A weight of controlled mass causes a normal force *N* on the contact of the lens.

Three different commercial lens, made of different materials where tested, Table 1.

Table 1 Type and material of the different contact lenses.

Type	Silicone Hydrogel	Hypergel	Hydrogel
Material	Somofilcon A	Nesofilcon A	Nelfilcon A

Tests were done under lubricated conditions, being the contact lubricated with a buffered saline solution. The friction assessment method is based on the evaluation of the free damping vibration movement, of mass-spring system, induced by a mechanical impulse. The contact with the lenses acts as a supplementary dissipation of energy and the friction is determined by inverse analysis. The numerical integration of the second-order differential equation will allow the calculation of the friction. Fig. 1, shows the comparison between the theoretical and the experimental data demonstrated an almost perfect overlapping of the results.

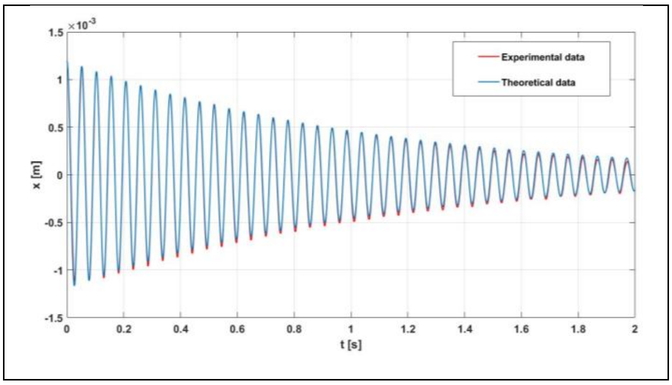

Fig.1 Typical curve for a lubricated contact between the contact lens and the lamella – comparison of theoretical and experimental data

The applied normal load was varied between 9 and 62 mN. The friction model, adjusted from the experimental results, includes a Coulomb part more a viscous component. Figure 2 shows the results obtained with silicone hydrogel lens, assuming a constant speed of 100 mm/s.

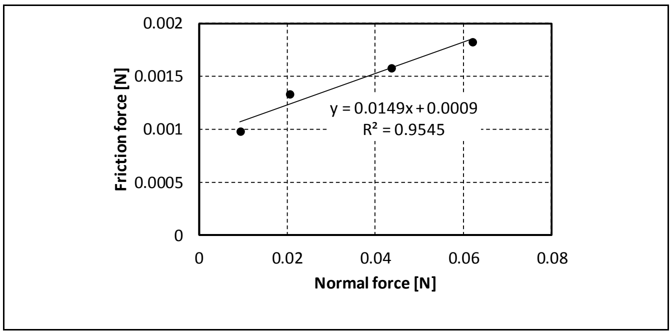

Fig.2 Friction force of a silicone hydrogel lens, for different normal loads, assuming a constant speed of 100 mm/s.

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ELECTRICAL MATERIAL CHARACTERISATION FOR APPLICATIONS IN TRIBOELECTRIC NANOGENERATORS

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KEYWORDS
Experiments in Tribology; Physics of Friction; Solid Lubrication, Contact Electrification

ABSTRACT
The triboelectric effect (or contact electrification) has long been understood as the process of electrical charge transfer resulting from the mechanical contact of material surfaces [1]. The underlying mechanisms that contribute have been the subject of much research [2,3] and applications have been developed in order to harness and control this charge transfer for a variety of purposes [4]. This research will focus on the development of quantitative methodologies for characterising the triboelectric properties of materials on both the macroscale and nanoscale [5,6].

The macroscale methodology in question involves the development and construction of a novel test apparatus, capable of replicating and analysing the electrical output and tribological properties of a scaled-up triboelectric nanogenerators (TENGs). This allows for tribological parameters to be correlated with triboelectric properties such as contact potential difference, induced current and charge polarity for different material pairings, both insulting and conductive.

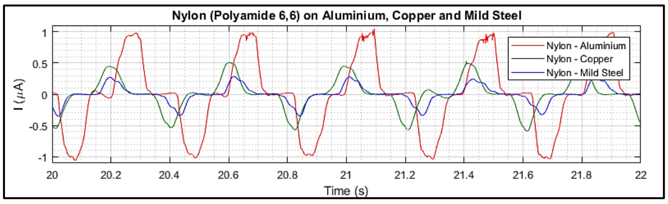

Fig.1 Current induced by relative charge movement within a 50x50mm reciprocating (50mm stroke at 2.5Hz) sliding contact with different material pairings as part of the proposed macroscale methodology.

The nanoscale methodology combines the Lateral Force Microscopy (LFM) and Kelvin Probe Force Microscopy (KPFM) variations of Atomic Force Microscopy (AFM). This allows for the deposition of static charges onto material surfaces through triboelectrification in LFM, which can then be analysed using KFPM to find their polarity and distribution. This methodology allows for the correlation of friction mapping and topographical data with surface potential data from the contacted and surrounding non-contacted areas.

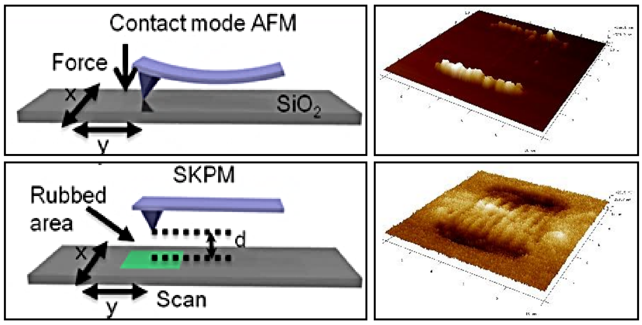

Fig.2 Visual representation of the proposed Lateral Force Microscopy (Top Left) and Kelvin Probe Force Microscopy (Bottom Left) with maps of topography (Top Right) and surface potential (Bottom Right) as performed on a SiO_2 substrate.

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SLIP IN GRANULAR FAULT GOUGES

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KEYWORDS

Friction, Rheology, Modelling in tribology, Granular fault gouge

ABSTRACT

Discrete Element Method (DEM) is one of the most relevant approaches to simulate granular materials, in particular in rocks mechanics and soil study. A wide variety of research on slip mechanism within granular fault gouge use circular or spherical particles, due to the simplicity of generation and contacts detection. However, over-simplifications of particle shape does not represent the reality, where most of the grains have a complex and angular shape.

In order to study the slip mechanism in a granular fault gouge (soil mechanics as part of Enhanced Geothermal Systems), we propose a 2D model under normal stress and imposed tangential displacement. Two rough surfaces representing the rock walls of the fault contain a granular media obtained by the wear associated to previous slips. We use the DEM method with realistic non-circular grain shapes, imposing shear velocity on the upper rock wall to simulate slip triggering. The model is implemented with discrete simulation (multibody dynamic) for the granular part within the code MELODY [1]. The simulation uses realistic angular grains based on grain shapes obtained from the literature and generated with the code Packing2D [2].

We first confirmed with our model that the shape of particles have an influence on friction, based on comparisons with previous results [3] and [4]. Another objective is to study the influence of the granular size distribution within the gouge. We test several types of distribution, as fractal distributions, distributions with granular gradient, Gaussian distribution, etc., with various size of particles. We also test the mechanical contribution of small particles in the media and their influence on the slip. Meaningful results on shear band localizations and slip behaviors into the granular gouge are also presented.

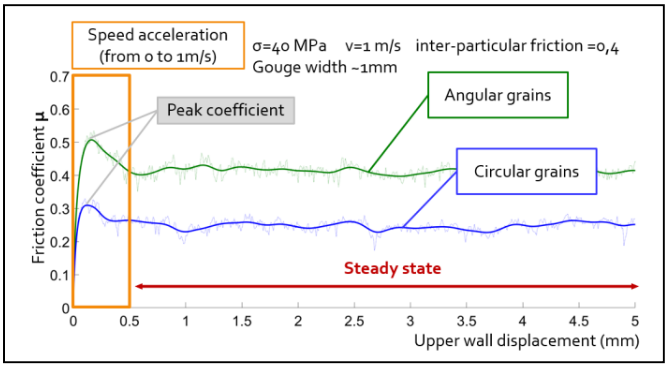

Fig.1 Friction coefficient in function of upper wall displacement, for angular and circular grains.

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MOLECULAR DYNAMICS SIMULATION OF ORGANIC MOLECULAR POLYMERIZATION IN SOLID LUBRICATION USING REACTIVE FORCE FIELD

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KEYWORDS
Tribofilms and 3rd bodies; Modelling in tribology; Solid lubrication, polymerization

ABSTRACT

The Friction Fade-Out (FFO) is a phenomenon that the friction coefficient dropped to 10^{-4} level when the Zirconia (ZrO_2) are rubbed against the diamond-like carbon (DLC) surface in the hydrogen and ethanol gas environment [1]. It is known that the catalytic action of ZrO_2 is involved although there are many chemical processes not understood in detail.

As a hypothesis, it is suggested that gas-lubrication effect is possible as following. The mechanism is that the gaseous substance support the load generated by catalytic decomposition of tribofilm generated between the surfaces. It is formed on the ZrO_2 surface by increasing the load at running in process. In addition, it is known from experimental results that the tribofilm contains an alcohol-derived component in the atmosphere, although, the constitution of it is not known. In this study, we aimed to reveal the constitution of tribofilm and the FFO mechanism using molecular dynamics simulation including chemical reactions. A model for sliding ZrO_2 or YSZ (Y doped ZrO_2) against DLC with ethanol is shown in Fig.1.

In order to analyze the FFO, it is necessary to investigate the gas lubrication due to the formation of gaseous molecules. In addition, the ReaxFF capable of handling chemical reactions, which is based on classical molecular dynamics, is adopted as a calculation method [2, 3].

Fig. 2 shows the degree of polymerization of hydrocarbons in each model. In the 18 models adopted this time, results are greatly different. Three points are suggested from Fig.2. YSZ show larger polymerization than ZrO2. H_2 molecules help polymerization in YSZ system. H Radicals are obstructive for polymerization.

Molecules with 8 carbon atoms ($C_8H_{19}O_4$) are generated by polymerizing. The following 3 kinds of chemical reactions were mainly observed in the generation of it. 1. Bonding between radical carbons. 2. Bonding between oxygen and radical carbon. 3. Desorption of hydrogen atoms. Compared with the experimental results, it is shown that a tribofilm is produced by a long time polymerization mechanism.

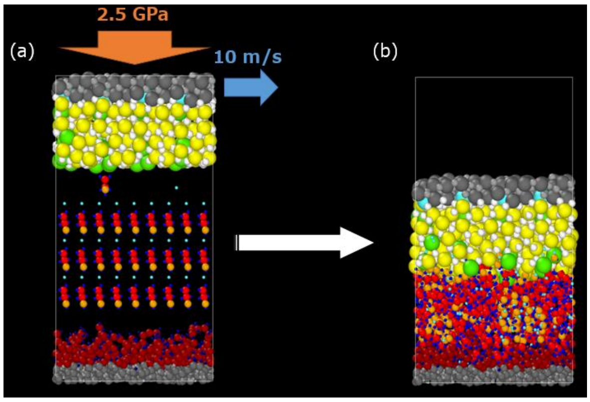

Fig.1 Sliding between YSZ and DLC with ethanols and H radicals.
(a) Initial distribution. (b) After sliding for 100 ps.

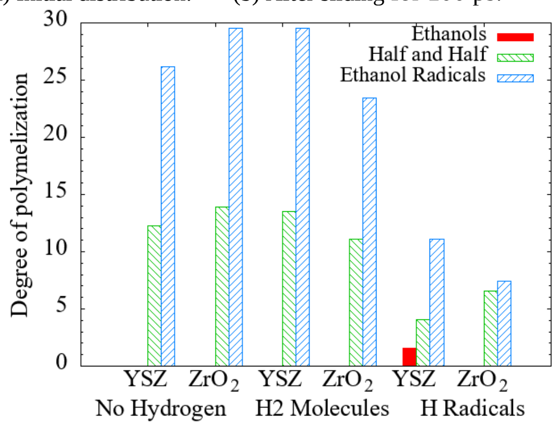

Fig.2 Degree of polymelization of products.

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THE EFFECTS OF ADDITIVE AMOUNT OF ACRYLIC COMPOSITE MATERIALS ON DRILLING PROPERTIES TOWARDS DEVELOPMENT OF BONE BIOMODELS

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KEYWORDS
Biotribology; Friction; Experiments in tribology, Drilling

ABSTRACT

Bone drilling is a basic surgical technique in dentistry or orthopedics. Sawbones® rigid polyurethane foam is often used for the evaluation of medical devices such as bone screw or pin, based on the standard specification [1]. However, drilling properties presented by thrust force and torque are found to have a large difference compared to those of natural bone [2–4]. In order to effectively advance the development of medical devices, an alternative test material is required. This work illustrates drilling properties of acrylic composite materials including ceramic additives such as alumina cement in order to improve hardness and stiffness, as a candidate alternative to natural bone.

Acrylic composite materials with alumina cement (AC) with different composition ratio at 10, 20, 30 and 40% were prepared for drilling tests. Mandible bones and Sawbones® test materials made for both cortical (EP-S) and cancellous bone (PU20, PU50) were tested as controls.

Drilling tests were performed under constant loading system. Machining conditions were 1,000 rpm of spindle speed, 20 N of thrust force, and 5 mm of drilling depth, considering orthopedic surgeries. Drilling properties such as friction torque, drilling time of reaching maximum depth, and were recorded along penetration using a drilling tribometer, developed by LTDS.

Figure 1 shows the relationship between maximum values of smoothed friction torque and drilling time, averaged from three times of drilling. The results indicate that drilling needs longer time along the increase of the amount of alumina cement. Therefore, there is a possibility that the inclusion of alumina cement might change any mechanical properties that are related to drilling properties of the composite materials, and the effects varies on the composition ratio.

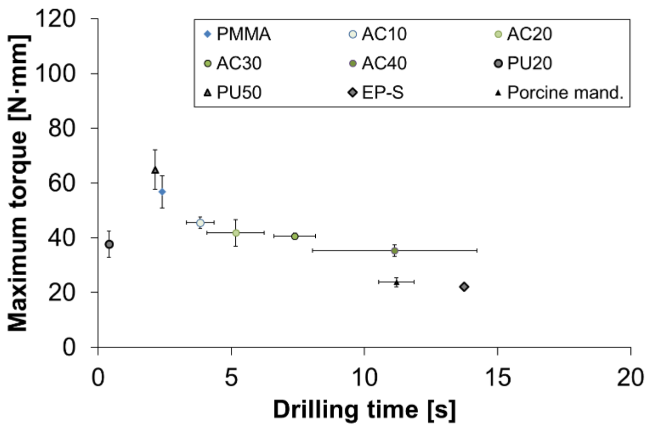

Fig.1 Relationship between maximum torque and drilling time

ACKNOWLEDGMENTS

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A SLIDER INCLUDING AN ARRAY OF PIEZOELECTRIC SENSORS TO MEASURE LOCAL MICRO-IMPACT FORCES

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KEYWORDS
Experiments in tribology; Physics of friction; Surface topography; Micro-impact forces

ABSTRACT
A better understanding of the dynamic forces acting between rough frictional surfaces at the micro-asperity scale, (as opposed to macroscopic normal and tangential loads) is required to address a large variety of tribological issues, including the energy efficiency of a contact interface [1], the localized deterioration of interfaces and the roughness and squealing noises [2, 3, 4].

In this context, the main goal of this paper is to describe and characterize a new instrumented slider allowing to access micro-contact normal forces and their local distributions.

The slider was designed as a parallelepipedic pad (60x60 mm² apparent surface), which integrates nine piezoelectric sensors (Fig. 1).

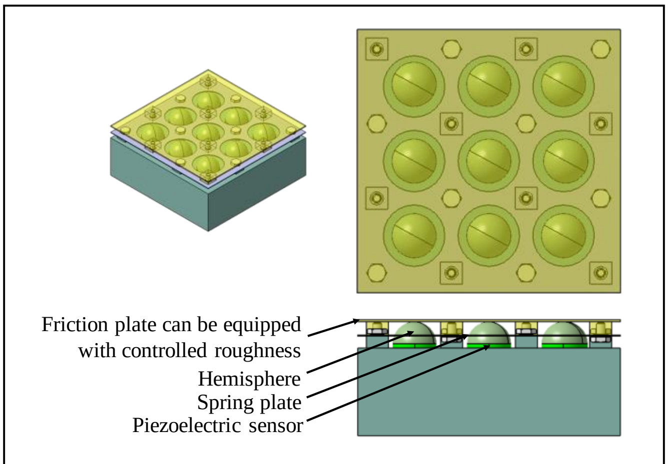

Fig.1 Schematic view of the slider

To characterize the dynamic performances of the instrumented slider, we developed a finite element model (FEM) of it. We checked key dimensioning quantities, including the eigenfrequencies (which determine the measurement bandwidth) and the associated eigenshapes. This model was also used to compute the influence function between the location/magnitude of a point force and the response of each of the nine sensors. Then we built such a slider and compared the actual performances to the FEM-based predictions. We will first summarize our dimensioning conclusions.

To demonstrate the relevance of this slider on tribological situations, we used it in steady sliding against a randomly rough surface. In this measurement the slider's surface was further equipped with one millimetric bead at the vertical of each sensor. We will present our first results for the space-time dynamics of the micro-impacts between antagonist asperities and the associated forces.

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SANDWICH TRIBOLOGY

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KEYWORDS

Modelling in tribology; everyday life tribology; friction; drop

ABSTRACT

The phenomenon of a sandwich filling slumping to the bottom of its packaging, known as a skillet, is termed "the drop". After conducting a literature survey, it was evident that the optimal arrangement of sandwich fillings had not been researched extensively. It was noted that theories involved the determination of an arrangement that would minimise the amount of filling slippage during eating and not when standing stationary within packaging [1].

The literature survey revealed that the question most commonly asked within this topic area was: What is the most effective sandwich filling arrangement to avoid slippage during eating? It was concluded in [1] that "greens" interspersed between the layers of the sandwich improved the amount of friction between each interface and thus reduce the amount of slippage. The results of this study contradict this theory somewhat along with the hypothesis that the interface formed between tomato and cucumber possessed the smallest friction coefficient and was mainly responsible for the slippage of fillings within the sandwich.

The aim of this study was to investigate the amount of "drop" in two of the most commonly sold sandwiches across campus. The outputs of the research were a suggested optimal sandwich filling arrangement for each sandwich that succeeded in minimising the amount of "drop".

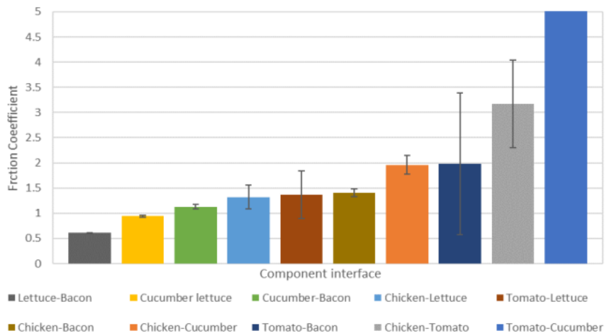

Figure 2 Coefficients of friction for each filling interface

Sliding experiments were conducted to determine the friction coefficient (μ) of some of the most popular filling components (see Figure 1). The components in question were chosen after evaluating data supplied by the university that suggested that the two most popular sandwiches sold across campus were chicken salad and BLT.

In order to obtain the interfacial friction coefficient, the critical angle at which one of the fillings began to slide was recorded. Optimal and worst arrangements for the two cases are presented. Subsequently, finite element analysis (FEA) models for both arrangements are modelled. Results show the percentage of delay in drop time and the displacement of the fillings is considered over a constant period of time for both optimal and worst arrangements of sandwiches. Figure 2 shows the displacement of the fillings of the optimal arrangement of chicken salad. The models are evaluated with the experiments and can be employed for other configurations.

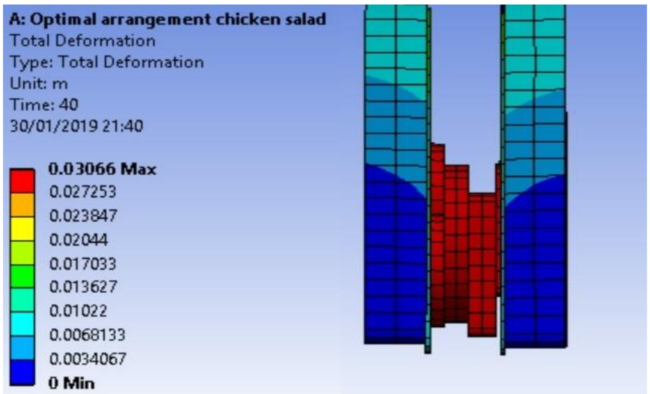

Figure 1. Optimal arrangement for chicken salad

ACKNOWLEDGMENTS

This research was funded by the Engineering and Physical Sciences Research Council (EPSRC) through the integrated Tribology Centre for Doctoral Training (iT-CDT)

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Poster group n° 2

Fluid lubrication, lubricants

46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

NON-CONTACT HANDLING EQUIPMENT UTILIZING ULTRASONIC SQUEEZE FILM LEVITATION

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KEYWORDS
Fluid lubrication; Hydrodynamic Lubrication; Experiments in tribology; Ultrasonic squeeze film Lubrication

ABSTRACT
It is known that when a flat surface vibrates vertically at ultrasonic frequencies, both vertical and horizontal forces act on an object placed on the vibrating surface, enabling the vibrating surface to support an object vertically and horizontally without any contact [1]. In this study, we have investigated holding characteristics of the non-contact chuck utilizing this phenomenon to handle a small IC chip. Experiments were carried out on measuring the thickness of squeeze film and horizontal handling characteristics of the chuck when the small IC chip was floated in a noncontact manner.

ULTRASONIC SQUEEZE FILM LEVITATION
Figure 1 shows the schematic principle of the squeeze film levitation. When one of two opposing planes vibrates in ultrasonic frequency, an air film which has larger time-averaged pressure than atmospheric pressure is generated between two opposing planes. As a result, one of them is held vertically without any contact.

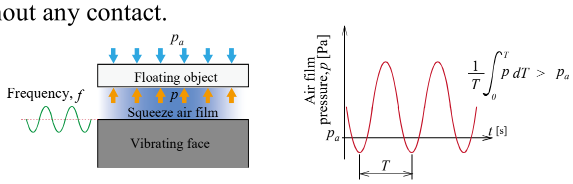


Fig. 1 Schematic of the squeeze film principle

EXPERIMENTAL METHOD AND RESULTS
Figure 2 shows the schematic views of the experimental apparatus. Because the pressure due to the squeeze effect increases with the increase in the vibration amplitude, the amplitude of the Langevin transducer was amplified by using a horn and its resonance as shown in Fig. 3. In the experiments, the Radio Frequency Identifier (RFID) chip was used as the floating object. The outer shape of the RFID chip was a square with a side of 3.2mm and the tip of the chuck had also the square shape with the same dimensions as the floating object. To implement the idea of the contactless chuck, the levitation force created by the squeeze film must be balanced with another force. Therefore, a 1.0mm hole was machined in the tip of the chuck and a suction pressure, p_v of various magnitude created by using a vacuum ejector.

In the experiments, effects of V_{amp} and p_v on the average floating height of the RDIF tag (=average thickness of squeeze film) was measured by using displacement sensor (Fig.4). In addition, the horizontal vibration of the RDIF chip after giving an initial displacement of about 0.5 mm to the chip was recorded with a highspeed camera and the relationship between time and horizontal displacement was obtained by an image processing software (Fig.5). Regarding these experimental results, it is thought that the squeeze air film shear force and the surrounding air flow are affecting on the characteristics of the squeeze chuck. Therefore, we are currently investigating the mechanism of the horizontal holding characteristics from the viewpoint of both experiments and numerical calculations using CFD analysis.

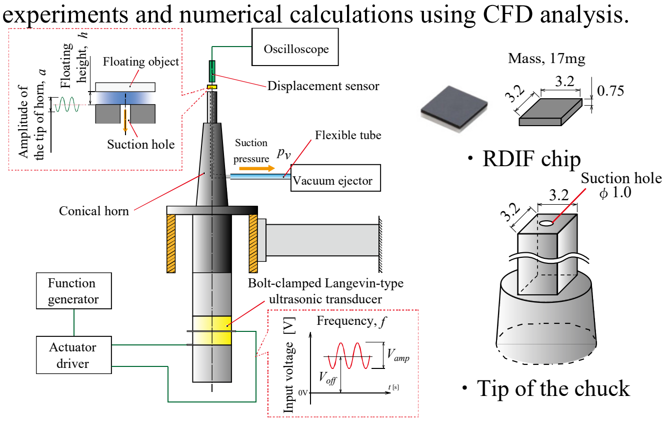
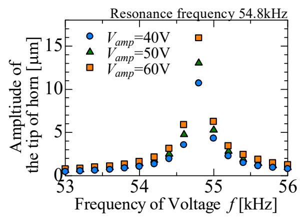


Fig. 2 Schematic views of the experimental apparatus



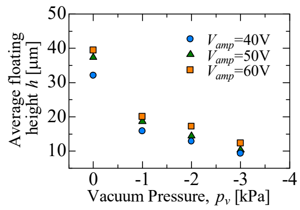


Fig.3 Relationship between f and a Fig.4 Relationship between p_v and h

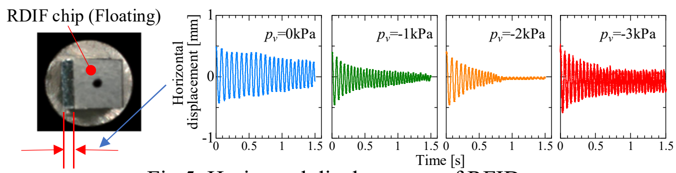


Fig.5 Horizontal displacement of RFID tag

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NUMERICAL SIMULATION OF GREASE PENETRATION TEST

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KEYWORDS

Rheology; Fluid Lubrication; Modelling in Tribology, CFD

INTRODUCTION

To comprehend the grease behaviour in ball bearings, not only experimental method but CFD analysis has also been carried out[1]. However, grease has unique rheological properties such as shear thinning, and viscoelasticity. And it is still unclear which of these should be taken into consideration. In addition, the simulation of grease flow in ball bearings is highly complicated, for the grease experiences churning and channeling phases. In this study grease penetration test is simulated to examine how well the grease behavior can be expressed focusing on shear-thinning, out of the properties mentioned above, for the test is much simpler, where a cone is dropped into grease and the depth is measured.

METHODS

Grease has several unique rheological properties, one of which being shear thinning, where the apparent viscosity μ changes depending on the shear rate $\dot{\gamma}$. To express this, Carreau-Yasuda model[2] is adopted, one of the non-Newtonian fluid model as in Eq. (1)

$$\mu = \mu_{inf} + \left(\mu_0 - \mu_{inf}\right)(1 + (\lambda\dot{\gamma})^a)^{(n-1)/a} \quad (1)$$

Here μ_0, μ_{inf}, λ, and a stand for zero-shear viscosity, infinite-shear viscosity, relaxation time constant respectively. These parameters are obtained by fitting the rheometer test results with the viscosity model.

To simulate the cone's motion interacting with grease, fluid-body interaction analysis is adopted. The cone is dropped into grease and the penetration depth for five seconds was measured for several kinds of greases including urea and lithium greases.

RESULTS

Penetration is compared between numerical simulation and experiment in Figure.1. The correlation coefficient is 0.538, showing a positive trend. From the viewpoint of the error, however, penetrations are greater in numerical simulation than in experiment. One major reason appears to be that the

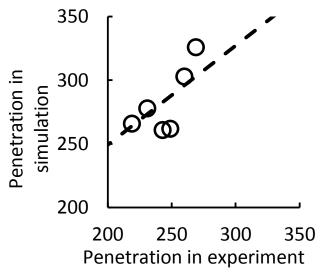

Fig.1 Penetrations in numerical simulation and experiment

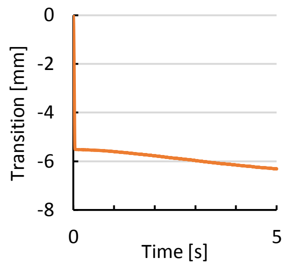

Fig.2 Cone's transition for one grease

cone does not come to a halt and continues to drop gradually even after the initial fall(Fig.2). This is expected to be solved by incorporating elasticity to represent the solid-like feature of grease.

CONCLUSION

Through this study, it was found that the grease simulation with shear-thinning can reproduce the trend of penetration test. However, in order to obtain quantitatively more exact results, it might be necessary to take elasticity into account in addition to shear-thinning.

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HOT LUBRICATION OF IN SITU FORMED SODIUM BOROSILICATE TOWARD THE GENERATION OF MULTIFUNCTIONAL TRIBOLAYER AT THE STEEL INTERFACES

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KEYWORDS

Friction; Wear; Tribofilm and 3rd bodies, Borosilicate glass

ABSTRACT

The present investigation aims to deliver the tribological performance via understanding multifunctional tribofilm of in situ formed sodium borosilicate at heated rubbing surfaces. In this study, the test lubricants was applied by coating method. The addition of 10 wt.% sodium borate to sodium silicate solution (Si-B-1) shows the best friction reduction (0.17) compared with plain sodium silicate (0.5) at 800°C. Since sodium silicate has high transition temperature (1088°C) [1], it is believed that an addition of sodium borate is beneficial to decrease the melting point by thermally driven reaction. Thus, the melting viscous glass of in situ formed sodium borosilicate is capable to deliver outstanding lubrication at the interfaces. Hierarchical tribofilm on both counterparts were examined and the results show the formation of multifunctional tribo-structure under shearing-stress conditions. The uppermost layer on the disc plays an important role in reducing friction and anti-wear due to its amorphous in nature [2]. On the other hand, the intermediate second layer shows its anti-oxidation properties. The tertiary glassy layer plays an important role in maintaining the durability of the whole tribo-system by infiltrating through restructured oxide layer and chemically bonding to the substrate. Self-adaptation of iron oxide layer with the presence of columnar oxide particles under the infiltration of hot melting glass through the friction test was observed. On the ball counterpart, the chemical complex tribolayer on the top is responsible for anti-oxidation and a confinement of the second layer. Meanwhile, there is a formation of nano-grained oxide layer underneath with the anti-wear and shear-surpassing capability [3]. The obtained results advance the understanding of near-surface structural evolution under complex working conditions.

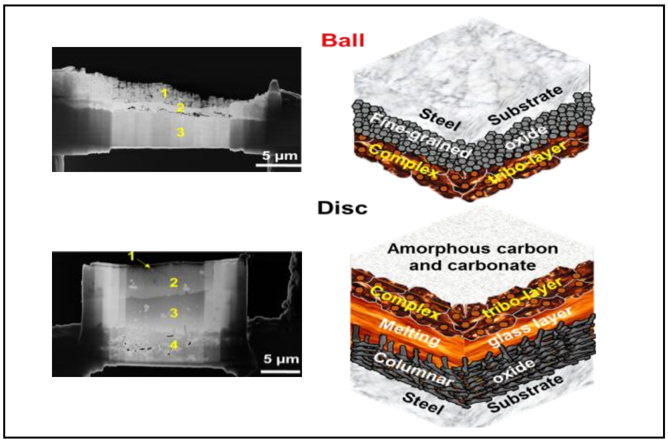

Fig.1. Multifunctional tribofilm structure on both counterparts.

ACKNOWLEDGMENTS

The study is funded by Australian Research Council (ARC) Discovery Project (DP) 150103718.

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FRICTION BEHAVIOR OF NATURAL FIBER COMPOSITES IN FINISHING PROCESS UNDER DIFFERENT LUBRICATION CONDITIONS

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KEYWORDS
Friction; Experiments in tribology; Fluid lubrication, Surface topography

ABSTRACT
Manufacturing processes of natural fiber reinforced plastic (NFRP) composites still need some finishing operations like machining or polishing to achieve the edge surfaces of composite parts. However, the tool/material contact during finishing process generates a tough tribological stresses that can deteriorate the NFRP surfaces. Moreover, the use of water lubrication in the case of NFRP finishing can induce structural damages to the composite because of the hydrophilic nature of cellulosic fibers that is due to the non-crystalline parts and the void content of fibers [1] which affect the mechanical properties of natural fibers [2]. On the other hand, the literature misses the oleophilic/oleophobic behavior of natural fibers and its influence on the mechanical performances. The oil lubrication in tribo-manufacturing of NFRP composites is still not understood.

The lubrication issue of NFRP finishing is investigated in this paper for the mechanical polishing process on flax fibers reinforced polypropylene composites using a rotary tribometer. Dry polishing, water lubricated polishing and oil lubricated polishing are considered in this study. The in-situ friction forces are acquired to rate the friction behavior and the polished surfaces are analyzed by scanning electron microscope (SEM) and the atomic force microscope (AFM) to determine the surfaces state and the induced micro-mechanical damages. The integrity of the polished surfaces is evaluated by the optical interferometer.

Results show an important influence of the lubricant nature on the surface forming of both flax fibers and the polypropylene matrix. The lubricant type affects also the micro-mechanical behavior of flax fibers at the polished surfaces. The lubricated friction behavior of NFRP worksurfaces under the different considered process conditions have a significant influence on the polished surfaces roughness.

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A MODIFIED BALL-ON-DISC TRIBOMETER FOR ASSESSING THE FILM THICKNESS OF STARVED POINT CONTACTS

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KEYWORDS
Fluid lubrication; EHL; Experiments in tribology; Starvation

ABSTRACT

Starvation is one of the main conditions affecting the load carrying capacity of lubricated contacts when they operate under the lack of a sufficient oil supply. As a result of it, the temperature of the fluid rises, its rheological properties are expected to vary and the mating surfaces wear down at a faster pace.

Through time, different criteria for measuring starvation have been suggested [1] [2]. Most of the numerical and computational approaches followed to model starvation are based on the assumption that the thickness of the lubricant film flowing into the contact is known [3]. From an experimental standpoint, this question is not trivial. Indeed, one may feed the contact with a certain known volume of lubricant, but there is no actual indication of its distribution at the contact inlet region, whether it will spread evenly or asymmetrically across the area and, in case of the first premise being true, the exact equivalent film thickness accessing into the contact.

To solve this issue, a modified ball-on-disc tribometer is proposed following the concept previously presented by Svoboda et al. [4]. The new assembly introduces a rolling element in the form of a roller in addition to the initial spherical contact studied. Starvation is controlled through the operating conditions defined for the roller. Moreover, the roller generates a sufficiently large elliptical contact that depletes at its outlet a homogeneous lubricant film track [5] whose dimensions can be precisely measured via optical interferometry.

Herein, the conditions and criteria followed for the effective design and implementation of the modified test rig will be discussed.

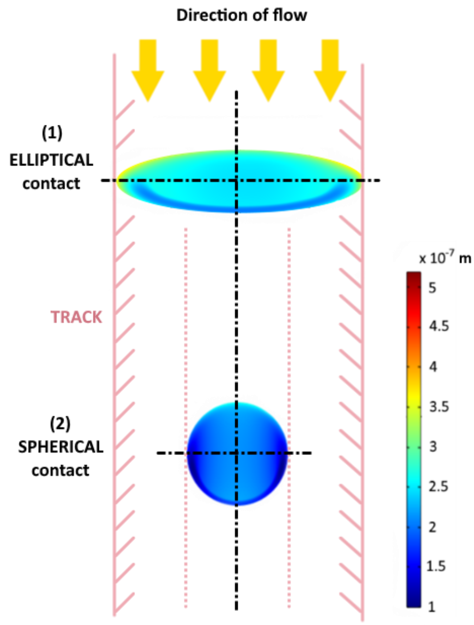

Fig.1 Interaction between the two contacts.

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1D DESIGN MODEL OF AN OPEN FORM PRESSURE BALANCED HYDROSTATIC BEARING

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KEYWORDS
Fluid Lubrication, Modelling in tribology, EHL, Pressure balancing

ABSTRACT
Traditional hydrostatic bearings are rigid machine components and do not allow for large counter surface variations.

Open form pressure balancing makes use of internally pressurized chambers to design an elastic bearing with high deformation capabilities without heavily decreasing its load bearing potential. The one dimensional model presented can be used as a concept design tool to design a bearing geometry with a desired stiffness profile.

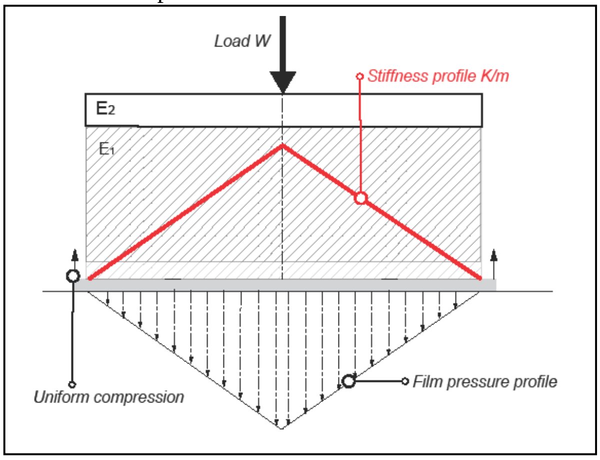

Fig.1 In order to obtain the pressure profile for a parallel bearing at uniform compression, the stiffness of the bearing needs to have the same shape.

The model assumes a desired pressure profile for a specific bearing configuration, like the pressure profile presented in figure 1 for a parallel infinite length bearing. For uniform compression this means The stiffness profile should have the same shape as the pressure profile. The stiffness profile of the compliant bearing can thus be designed. The effects of track deformations can thus be directly defined by a pressure resulting from The bearing stiffness and the track displacement.

The computational model inversely calculates the film height from the pressure profile. This film height can change significantly by the track effects as seen in figure 2.

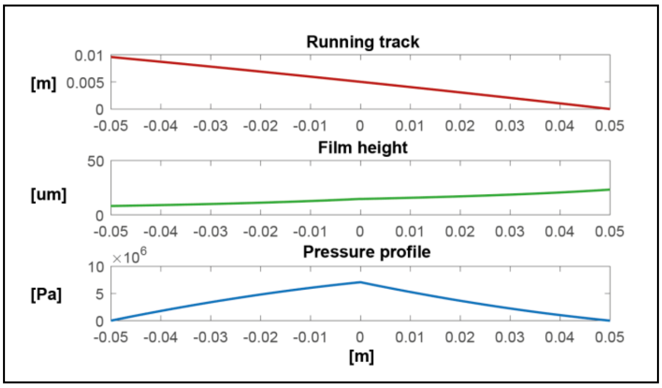

Fig.1 Film height and pressure profile for a parallel bearing with track deformations in the order of magnitude of 10% of the bearing lengths. The pressure profile changes from the triangular shape due to the effects of track curvature.

By modelling the bearing using simple compression elements, the stiffness of the bearing can be designed to match the desired stiffness profile. The effects of pressure balancing can be modelled as an additional pressure profile counteracting the film pressure profile. This method allows to design both the stiffness and pressure profile of the pressure balanced bearing. Using the method to initially determine the load capacity and deformation capabilities of an open form pressure balanced bearing. The method is not limited to just open form bearing, since it can determine initial bearing performance given its stiffness profile.

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SIMULATION OF SLIP IN ROLLER ELEMENT BEARING WITH LUBRICANT RHEOLOGICAL MODELS

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KEYWORDS
EHL; Friction; Rheology; Multibody Simulation

ABSTRACT
A multibody dynamics simulation model of a cylindrical roller bearing has been developed for the prediction of slip behavior under dynamic radial and axial loading [1]. The contact modelling based on iterative penetration calculation and an advanced slicing technique has been adopted [1]. The roller-roller and roller-race friction have been modeled based on rheological data in EHL friction to consider both viscosity and composition of the lubricant [2]. Subsequently, a parameter study has been performed to see both the effect of operating conditions and rheological oil parameters on slip tendency of rollers in the bearing. The parameter study will cover all the lubrication condition ranging from full EHL to mixed lubrication.

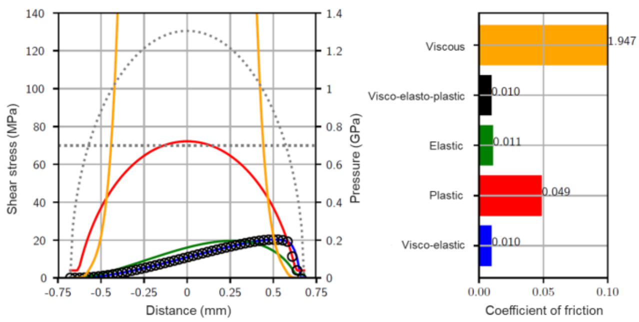

Figure 1: Comparison of shear stress distribution for various traction models with lower SRR

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FILM THICKNESS MEASUREMENTS IN EHL-CONTACTS USING CAPACITANCE MEASUREMENTS

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KEYWORDS
Fluid lubrication, EHL; Experiments in tribology; Film Thickness

ABSTRACT

The lubricant film in non-conformal machine elements, e.g., gears, and rolling element bearings, separates the metalic surfaces. Thus, wear and friction is reduced, enabling operation. The film thickness is of great interest both to understand the operating behaviour, as well as the film formation mechanism. A measurement of film thickness within real machine elements remains challenging. Methods employed are ultrasonic sensors, resistance based methods, and capacitance based methods [1].

In this work We present measurements of film thickness in real rolling element bearings by using the capacitance based method [1,2]. Due to parasitic capacitances caused by the areas around the contact the measured capacitance is not purely caused by the contact area. A well established method to address this problem is by using a relationship of the capacitances of the Hertz'ian contact area C_{Hertz} and the measured capacitance C_{meas}. The thus gained ratio k_c allows the determination of the Hertz'ian capacitance.

$$k_c = \frac{C_{\text{meas}}}{C_{\text{Hertz}}}$$

From this capacitance, the film thickness can be estimated.

$$h_{\text{meas}} = \epsilon_0 \cdot \epsilon_r \cdot \frac{A_{\text{Hertz}}}{C_{\text{meas}}}$$

While this method yields film thickness results, the factor k_c necessary needs to be known. Typical values are in the range of 3…3.5. However, this factor itself depends on the film thickness. To study the behaviour of this factor and thus enable correct film thickness determination and to validate the measurements, a PCS film thickness setup was modified so that an optical film thickness measurement through interferometry can be combined with film thickness by capacitance. Similar work was presented by Jablonka et al [3].

Furthermore, a numerical simulation was set up to determine the capacitances occurring in and around the contact area. Thus the factor k_c can be determined numerically.

The results of the numerical simulation can be validated by comparison to measurements with the EHL rig.

The results show that the factor k_c varies significantly with the amount of lubricant surrounding the contact. The measurements of the film thickness in the model system shows a good agreement with a numerically chosen factor k_c. When investigating the film thickness in a rolling element bearing a decision of the choice of a correct factor must include the lubricating condition. While this is not known, maps of film thickness factor relation from the numerical simulation may be used to determine the correct factor for the film thickness.

ACKNOWLEDGMENTS

The authors thank the VW GmbH for making available their EHL test rig.

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TRIBOLOGICAL BEHAVIOUR OF THE W-S-C COATINGS IN THE BOUNDARY LUBRICATION CONDITIONS

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KEYWORDS

Friction; Fluid lubrication; coatings, T-M-D

INTRODUCTION

Among the additives used in the boundary lubrication (BL) regime are the additives based on the Transition Metal Dichalcogenides (TMD). TMD based additives are used, either as nano-particles [1] or as complex chemical structures such as well-known MoDTC [2]. Also, TMD based coatings gained the attention because of their excellent self-lubricating properties [3], most of them being in the conditions in which traditional (liquid) lubrication is not a possible solution.

Surprisingly, there were very few attempts to combine the TMD based coatings with the base oil in the BL regime; TMDs release from the coating should provide sufficient supply of low friction material while in the same time problems such as toxicity and dispersion of the nano-particles are avoided.

To further exploit the concept, we have prepared two TMD based coatings and investigated them in the BL regime with thorough follow-up surface chemical characterization.

EXPERIMENTAL

Materials

Two W-S-C coatings (H=4.9 GPa and H=7.6 GPa) have been deposited by plasma vapor deposition. Total thickness of the coatings was measured to be 1 – 1.1 μm. Both coatings were deposited on the polished ASP2023 steel coupons while for the counter-body the AISI 521000 ($R = 6mm$) steel ball was chosen.

Two lubricants have been used, PAO 4 and PAO 4 mixed with the 1 wt. % of the organic friction modifier (OFM).

Experimental

Tribo-tests have been performed on the TE-77 (Phoenix Tribology, U.K.) reciprocating tribometer. Normal load was set to 60N while the reciprocating frequency was gradually reduced every 20 minutes to explore coatings behavior in different stages of the BL regime. Starting frequency was 5 Hz and the final one 0.5 Hz. Total test duration was set at 220 minutes.

RESULTS

Results from the tribological tests (Figure 1) show that the coating of the highest hardness (C) has the best tribological properties compared to the coating A lubricated either with PAO or the combination of the PAO and the OFM. Moreover, wear of the WSC-C coating was lowest while WSC-A coating were completely worn-off. Nevertheless, both of the coatings produced low friction coefficient ($\mu \approx 0.1$) showing that even with the depleted coating TMDs recirculate with the oil trough the contact and improve the tribological properties. Furthermore, it is shown that OFM's do not affect the friction coefficient much, but they do decrease overall wear-rate of the coating.

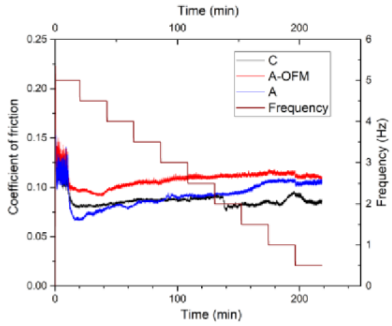

Figure 1 Friction curves of the investigated coatings

ACKONWLEGDMENTS

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QUANTIFIED ORDER OF IONIC LIQUIDS: IMPACT OF CONFINEMENT AND MOLECULE SHAPE

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KEYWORDS
Rheology; Lubricant additives; Modelling in tribology, Structure factors

ABSTRACT

Continuous effort is being made for the reduction of energy consumption and the accompanying emissions related to transport sector. Friction plays a significant role in the energy losses. In order to come up with novel concepts leading to significantly lower losses, it is necessary to zoom in the molecular scale and uncover the correlations of matter with the physical properties of interest. By understanding the fundamental mechanisms we expect to be in a position to design customised materials which can lead to friction reduction by at least an order of magnitude.

Ordering of lubricant molecules can be observed in thin liquid films, confined by walls. Under these conditions the bulk properties of the liquids do not apply anymore and phase transition can be observed [1]. Ordering parameters such as structure factors are a useful tool for quantifying such system changes. One interesting family of lubricants are Ionic Liquids (ILs) which feature long-range electrostatic interactions and have been shown to have a positive impact in friction reduction. The Coulomb interactions tend to strengthen the ion layering in the transverse direction to the sliding and lead to near-wall phase transition, as seen both experimentally [2] and numerically [3]. At the same time, in-plane crystalline structures have been observed [4], [5], [6].

In this contribution, the IL ordering will be quantified via a proper generalisation of structure factors to ionic systems. Preliminary results have uncovered the formation of a rotated cubic crystal for the case of an IL consisting of spherical ions (Fig. 1). Different ion shapes and confinement conditions will be considered. It will be attempted to correlate the structure factors with local phase transitions and the tribological performance of the liquid, thus leading to best practices for new lubricant design.

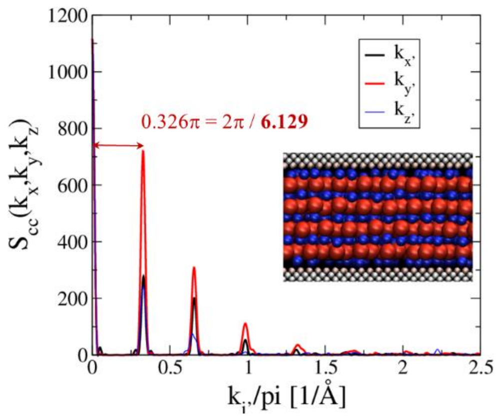

Fig.1 Structure factors of confined coarse-grained ionic liquid (configuration in inset) along the principal axes.

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TRIBOLOGICAL PROPERTIES OF HARD COATINGS UNDER LUBRICATION WITH LOW VISCOSITY FULLY FORMULATED OIL

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KEYWORDS
Coating; Lubricant additives; Tribofilms and 3rd bodies, in-situ Raman

ABSTRACT
To address environmental issues, automotive industries are in demand of developing fuel-efficient engine. Previous researches have shown that friction loss in engine parts account for 11.5 % of all fuel energy consumed. Moreover, a contact between piston assembly and cylinder liner is said to be the primary factor of the friction loss in automotive engine [1]. Therefore, reduction of the friction between piston assembly and cylinder liner is needed. One of the recent approaches to decrease friction between piston assembly and cylinder liner is a formation of hard coatings such as CrN and DLC on the piston ring surface. Such coatings are commonly lubricated with low viscosity oil, however, these oils are formulated on the assumption of steel/steel contact. Therefore, investigation on tribological properties of hard coatings under lubrication with low viscosity fully formulated oil is needed.

The friction and wear properties of CrN, ta-C, a-C:H coatings on AISI 52100 steel cylinder sliding against AISI 52100 steel disk under lubrication with low viscosity fully formulated oil (corresponding to 0W-8 on SAE standard) were investigated by using reciprocating test rig (SRV4, Optimol, DE). CrN coating showed low friction coefficient (between 0.05 – 0.06), followed by a-C:H (about 0.08) and the maximum friction coefficient was observed by ta-C (about 0.10). XPS analysis on steel disk confirm that there was a difference in a formation of MoS_2 tribofilm between these coatings. As shown in Fig. 1, MoS_2 / $MoS_{2-x}O_x$ atomic % ratio seems to have correlation with the average friction coefficient of each sliding surface.

Further investigation on a process of MoS_2 film formation and its real time effect on friction behavior was conducted using Raman spectroscopy. In this study, a laboratory built in-situ Raman tribometer, which was a combination of ball on disk configuration tribotester underneath the Raman spectroscopy, was used to observe the sliding surface of coated balls [2]. As can be cited on CrN case, MoS_2 film formation on coated ball was observed at 66 minute and the friction coefficient decreased from 0.15 to 0.06 at the same time.

Experimental results in case of hard coating/steel contact lubricated with low viscosity fully formulated oil suggest that, difference in the formation of MoS_2 tribofilm account for the difference in tribological properties of each sliding surface.

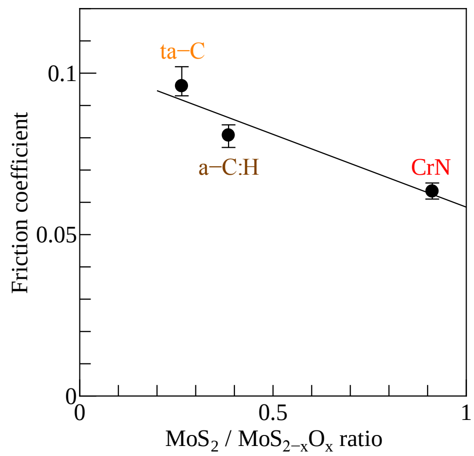

Fig. 1 Ratio of MoS_2 / $MoS_{2-x}O_x$ on surface of each hard films

ACKNOWLEDGMENTS
The authors are extremely grateful to Riken Corporation for their cooperation on this study.

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INVESTIGATION OF FORMULA ON ENTRAPPED EHL FILM THICKNESS UNDER VERTICAL MOTION - EXPANSION TO HIGH SPEED RANGE -

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KEYWORDS
EHL; Rheology; Experiments in tribology; Impact

ABSTRACT
In machine elements such as gears, rolling bearings and cam and followers, the film thickness and load change with time. In impact EHL, it is well known that the oil is entrapped between surfaces[1] because of the increase of the oil viscosity with pressure. The purpose of our study is to establish a formula on entrapped EHL film thickness under vertical motion.This paper reports the expansion to high speed range and effect of elastic modulus of contact material.

Figure 1 shows a schematic diagram of the experimental apparatus used in this study. The contact surfaces are composed of a steel ball and a glass disc. The lower surface of the glass disc has a semi-reflecting chromium layer. The lever arm is pushed by a piezo-actuator and impact speed v_{im} can be varied over a wide range. The final contact load is 50N. The shape and the thickness of the oil film were measured with the duochromatic optical interferometry technique and the fringe pattern is recorded with a high speed video camera attached to a microscope. All experiments were carried out at the temperature range of 25 ± 0.5 °C.

Figure 2 shows relationship of entrapped central film thickness h_c* and v_{im} for five types of oil. The viscosity at atmospheric pressure and pressure-viscosity coefficient for each oil are shown in fig. 2. The results make lines in the double logarithmic graph even if v_{im} is faster. And the angles of the lines are similar. It seems h_c* is proportional to $v_{im}^{0.54}$. Figure 3 shows relationship of h_c* and $\alpha^{1.8}\,\eta_0\,v_{im}$. All plotted points are on a single line. The line is expressed as $h_c^* = 1.24 \times (\alpha^{1.8}\,\eta_0\,v_{im})^{0.56}$.

The influence of the elastic modulus of the contact material on entrapped oil film thickness are also investigated. In the range of 84 - 285 GPa, equivalent elastic modulus does not affect h_c*.

Farther study is needed to make a formula on entrapped EHL film thickness under vertical motion.

ACKNOWLEDGEMENT
This work was supported by JSPS KAKENHI Grant Number JP16K06045.

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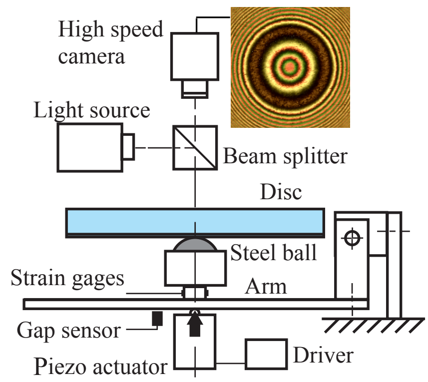

Figure 1 Experimental apparatus

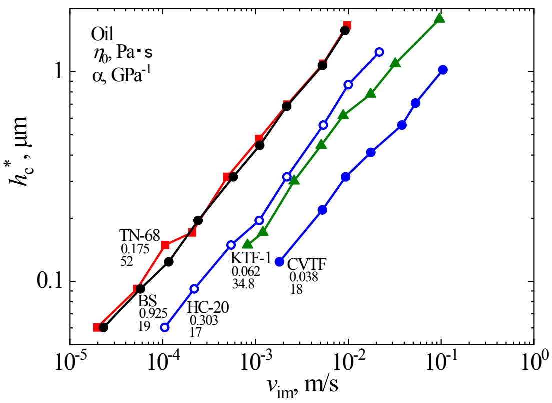

Figure 2 Effect of v_{im} on h_c^*

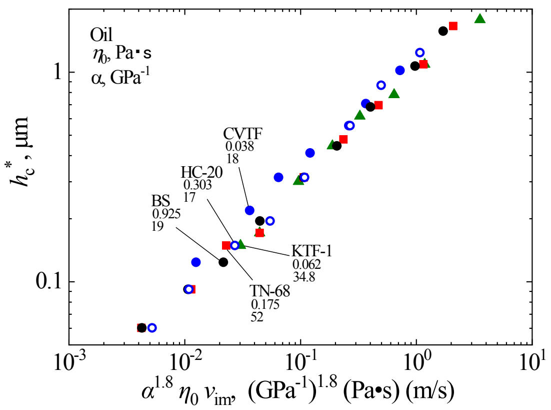

Figure 3 Relationship of h_c^* and $\alpha^{1.8}\,\eta_0\,v_{im}$

BEHAVIOUR OF GREASE FILM UNDER IMPACT AND SLIDING MOTION

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KEYWORDS
EHL; Friction; Rheology, Grease

ABSTRACT

Grease have been widely used and thickener have very large influence on the the grease film thickness. At low rolling speed, grease forms thick film [1] . We found very low speed vertical motion cause thick grease film[2]. The purpose of this study is to make clear the friction behaviour of grease thickener by direct observation of grease EHL film.

Figure 1 shows a schematic diagram of the experimental apparatus. The film thickness was measured using optical interferometry technique. The EHL contact was composed of the glass disc (E_D = 80 GPa) of 180 mm diameter with semi-reflective chromium coating and the steel ball (E_B = 206 GPa) of 25.4 mm diameter. Grease was filled in the gap between ball and disc. The ball was pushed by a piezo actuator with he final load of w = 50 N. In this study, several types of greases were used. The ambient temperature was 25 ± 0.5 °C for all experiments.

Figure 2 shows variation of friction coefficient with thick film caused by the thickener lump with very low speed impact v_{im}= 1 µm/s. At the beginning of sliding, the film thickness is over 1 µm. Under the low sliding speed, the thick film and low coefficient of friction are kept for long distance and time. On the other hand, for u_D = 200 µm/s, the film thickness becomes thin and friction coefficient rises at x = 2 mm. The behavior varies depending on the thickener type, and it correlates with the bearing torque. This method will be effective for grease test.

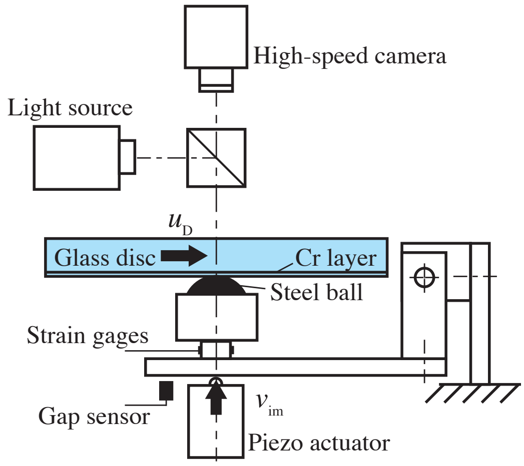

Figure 1 Experimental apparatus

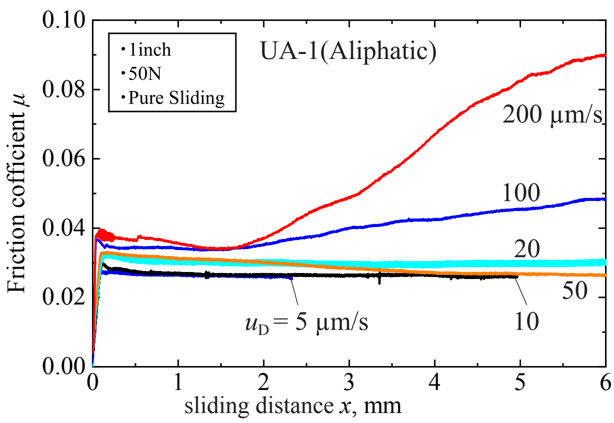

Figure 2 Effect of sliding speed on friction coefficient (Impact speed v_{im} = 1 µm/s)

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This work was supported by JSPS KAKENHI Grant Number JP16K06045 and JKA and it's promotion founds from KEIRIN RACE.

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NEW APPROACH OF LUBRICANTS BEHAVIOR IN HIGH LOADED CONTACT

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KEYWORDS
Fluid Lubrification; Experiments in tribology; EHL; Inelastic light scattering

ABSTRACT

Frictions in gears or pumping system is associated to energy lose due to mechanical contact. This effect can be reduce by a wise utilization of lubricant that endure extreme condition of pressure and shear stress. Friction curves in highly loaded lubricated contacts may exhibit a plateau regime at moderate Slide to Roll Ratios (SRR) related to the lubricant ultimate shear stress. In this well known regime, the shear stress becomes shear rate independent as shown in figure 1 and is identified as Limiting Shear Stress (LSS).

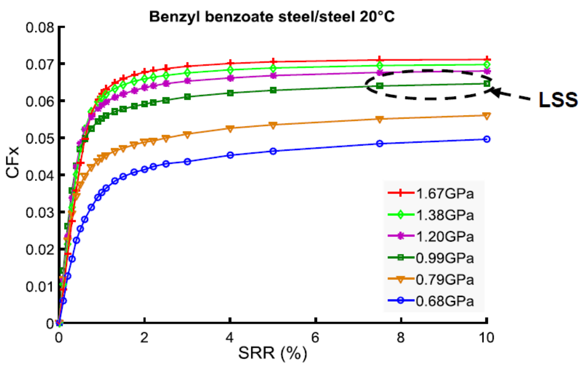

Fig.1 Friction coefficient versus SRR, U_e=1,3 m/s [1]

Yet, the physical mechanisms governing friction remain poorly understood and prediction of lubricant behavior in extreme conditions still empirical. Indeed, the extreme experimental conditions make any physical measurement of the fluid very strenuous. Moreover, the measured quantities are macroscopic, averaged over the whole contact area exhibiting a distribution of pressures and thicknesses. Therefore, they do not provide any local information on the dependence of the lubricant behavior with pressure and shear stress. Previous work suggest that the macroscopic plateau could be a result of one of the following mechanism: lubricant sliding at the wall interface, shear bands forming in the lubricant film or lubricant glass transition. Unfortunately, no experimental evidence has been provided from living highly loaded contacts to point out one specific scenario. Recent molecular dynamic simulations reveal homogeneous and linear lubricant velocity profiles in the lubricant film, even in the friction plateau regime, with no sliding at the walls [2]. This implies that the friction plateau results from an intrinsic property of the lubricant, which is reminiscent of the lubricant glass transition scenario. In this work, experiments have been performed on two different model fluids, squalane and benzyl benzoate. The fluids have been characterized in a high-pressure rheological set up, by using molecular dynamic simulations and Brillouin light scattering. This last technique turns out to be a powerful tool to investigate both the glass transition and the local physical properties (e.g. sound velocity) of the lubricant. Furthermore, visco-elastic properties such as elastic modulus, viscosity and relaxation time can be extracted by fitting the measured spectra [3]. In this field, Brillouin spectrum have been taken under hydrostatic pressure, up to the level of GPa in a Diamond anvil cell system. The results are compared to friction diagrams made in the same pressure and temperature conditions. This approach shows a strong correlation between the fluids glass transition and the onset of the friction plateau measured in a contact.

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TRANSITION FROM FULL-FILM TO MIXED LUBRICATION OF ANISOTROPIC ROUGH SURFACES UNDER EHL OPERATING CONDITIONS

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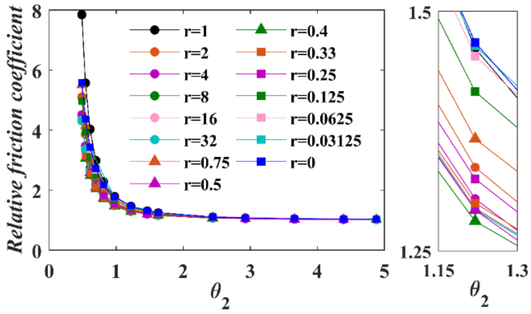
KEYWORDS

Friction; Surface topography; EHL; Onset of mixed lubrication regime

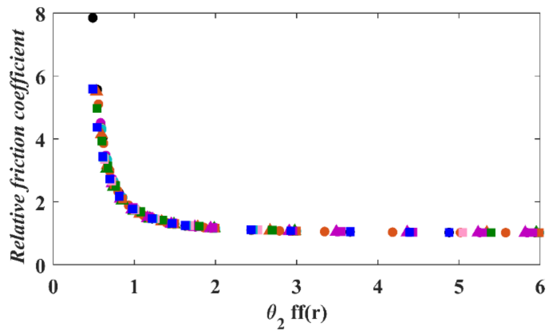
ABSTRACT

Early research [1] showed that the transition from hydrodynamic to mixed lubrication regime roughly occurs at a “lambda ratio” equal to 3, in which the “lambda ratio” is defined as the ratio of oil film thickness to the combined surface roughness. Previous work [2] on non-formal contacts found that the onset of the mixed lubrication regime depends on the operating conditions as well as the surface roughness wavelength, when only isotropic surfaces were considered. In reality, due to the machining processes the surface roughness of mechanical components is often anisotropic. A classical study [3] reported that the surface roughness anisotropy has an important influence on traction.

In this study, the relative friction coefficient, which is viewed as an indicator of the transition from full-film to the mixed lubrication regime, is re-computed by means of numerical simulations for anisotropic surface roughness cases. Simulation results can be unified by a surface roughness orientation function ff(r), when the same operating conditions are employed (Fig.1). It appears that besides the old “lambda ratio” parameter, both operating conditions and surface roughness anisotropy determine the onset of the mixed lubrication regime for highly loaded conditions.



(a)



(b)

Fig.1: Influence of surface anisotropy on the relative friction coefficient: (a) relative friction coefficient as a function of θ_2 , (b) relative friction coefficient as a function of θ_2 ff(r).

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STUDY ON LUBRICATION MECHANISM OF CONCENTRATED POLYMER BRUSH USING ULTRA-THIN FILM INTERFEROMETERY

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KEYWORDS
Friction; Coating; Mixed Lubrication, Polymer Brush

ABSTRACT
A CPB (concentrated polymer brush) is an assembly of polymer chains densely end-grafted on a solid surface. The CPB exhibits unique properties such as high elongation, high compression elasticity, and low friction properties when the CPB is swollen by a good solvent [1]. In this study, to elucidate the mechanism of the CPB's superlubricity, the relationship between friction and oil film was examined by simultaneous measurements of the friction coefficient and the film thickness.

The experiments were performed in a point contact between a steel ball (AISI 52100, dia.: 19.1 mm) and a glass plate (borosilicate glass, dia.: 25 mm). The glass plate, which was coated Cr film (thickness: 5 nm) and SiO_2 film (thickness: 580 nm), and the steel ball were used as a reference configuration (SiO_2/Steel). The glass plate, which was coated Cr film, and the steel ball, which is coated a CPB (PMMA, graft density: σ = 0.31 nm^{-2}, thickness: 220 nm @ dry), were used as a test configuration (Cr/CPB). The film thickness was measured by the ultrathin-film interferometry [2]. The friction coefficient and the film thickness were measured simultaneously under the lubrication of an ionic liquid (MEMP-TFSI) at a normal load of 5 N. The experiments were conducted in an environment with a room temperature of 25 ºC and a humidity of 40 %.

Figure 1 shows the effects of the entrainment speed U (0.1 – 1000 mm/s) on the film thickness h_{oil} for the configurations with/without CPB. h_{oil} is defined as follows: $h_{oil} = h - h_0$, where h is the distance between surfaces of Cr film and the steel ball and h_0 is the film thickness of SiO_2 film or CPB film. When $U \geq 30$ mm/s, h_{oil} of Cr/CPB showed larger values than those of SiO_2/Steel. On the other hand, when $U \leq 3$ mm/s, h_{oil} of Cr/CPB showed negative values, which mean the compressional deformation of the CPB film.

Figure 2 shows the effects of the entrainment speed U on the friction coefficient μ for the configurations with/without CPB. When $U \geq 100$ mm/s, μ of Cr/CPB showed similar values to those of SiO_2/Steel. On the other hand, when $U \leq 30$ mm/s, μ of Cr/CPB was much lower than those of SiO_2/Steel, such as $\mu \approx 0.001$.

The results of h_{oil} imply that an interface layer between the CPB film and the oil film increased h_{oil} effectively. The results of μ suggest that the interface layer still remained in the contact area at low speeds and provided the superlubricity of $\mu < 0.001$.

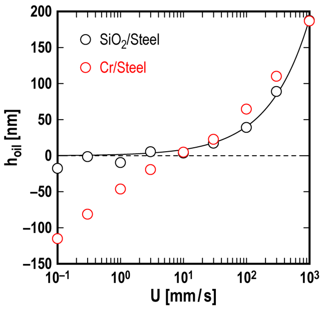

Fig.1 h_{oil} vs U

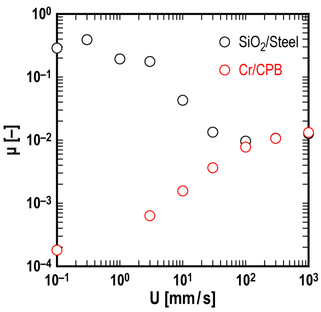

Fig.2 μ vs U

ACKNOWLEDGMENTS
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MODELLING BEHAVIOUR OF BOUNDARY LUBRICATING ADDITIVES WITH STRUCTURE ORIENTED LUMPING METHOD

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KEYWORDS
Lubricant additives; solid lubrication; modelling in tribology, Boundary lubrication

ABSTRACT

The durability of automotive engine tribopairs is often limited by the ability of their friction reduction and wear resistance. The ability to predict friction and wear, particularly for the comprehensive effects of lubricant, additive, and surface material including coating such as diamond-like carbon (DLC), would greatly aid the development process of both tribopairs and lubricants, especially, advanced environment friendly lubricants and additives.

The identity and composition of tribochemical system's countless molecular components may be beyond the resolution of analytical techniques. Nonetheless, models of tribochemical reacting processes must have a molecular basis to be useful in predicting the molecular composition of products and their physical, quality and quantity properties required by industry specifications. Strategies for solving this seemingly intractable problem are presented in this study. A kinetic model for boundary lubricating film formation by lubricating additives is intruduced, which considers representing reactant, intermediate and product molecules, and constructing reaction networks by the structure oriented lumping (SOL) for describing the compositions, chemical reactions, and properties of complex hydrocarbon mixtures approach in which all of the most important effects are included. This work addresses the development and function of boundary lubricating films on rough surfaces and their effect on surface friction and wear. Completely deterministic modeling of such films is possible based on the complex interactions between the numerous mechanical, thermal, and chemical variables over disparate magnitudes of time and length scales.

Density functional theory (DFT) in Materials Studio 2017 software is used for the calculation of the energies and structures of all reactants, intermediates and products, and transition states (decomposition, adsorption, oxidation and polymerization). Stated thus, for a given boundary lubrication system, it is important to understand thoroughly all the information on mechanisms of tribochemical reactions, and then to ignore minor reactions and retain key reactions. Applying a reaction rule to all molecules in the mixture generates a reaction class for the specific chemistry represented in the rule. In general, a reaction rule will find many reactants with the appropriate increments and each with a corresponding intermediate and product molecule. Further, each molecule may satisfy the criteria of more than one of the reaction rules. This would construct parallel reactions for a molecule. Application of all rules to all components of the mixture by using each reaction rule as the outer loop and each structure vector group as the inner loop generates the entire reaction network representing the chemistry of the process. Computer programs generating the entire network use sorting procedures to automatically construct the differential rate and energy balance equations for reactor modeling. Because all reaction is assumed as first order irreversible, the reaction network is equivalent to simple kinetic differential equations of the molecular lumps, which are solved with the approach, which is equivalent to the classical fourth-and fifth-order Runge-Kutta method and is very suitable for solving the dynamic model of SOL system. Seven different types of ZDDP, MoDTC, alternative lubricant and additive, steel and other metal surface, and DLC coating are employed to elucidate these processes at the atomic level. Results provide useful insight into the formation of boundary lubricating films. Accuracy, computational efficiency, and stability can be simultaneously achieved with the right numerical structure.

The model can be a useful tool to design tribopairs, the operating dynamics of a system, advanced environment friendly lubricants and additives.

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WATER CONTAMINATION AND ITS INFLUENCE ON ADDITIVE EFFICIENCY IN ENGINE OILS

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KEYWORDS
Wear, Lubrications additives, Fluid lubrication, and additive depletion.

Introduction

Water in lubricants is known as one of the most widespread and destructive contaminants. The presence of water can increase wear and oxidation of oil therefore increase the maintenance cost and oil drain intervals [1]. Water promotes the acceleration of ZDDP decomposition and decreases tribofilm thickness [2],[3]. Detergent and dispersant are attracted by water molecules and surround them due to polarity between molecules. Systems to remove water from oil can potentially remove all water-soluble species; this effect on oil performance is not well understood. This study focuses on the effect of additive depletion by water and the subsequent effect on wear and oil degradation.

Methodology and Results

The water saturation levels in Fully Formulated Oil (FFO) were initially evaluated at different temperatures according to ASTM D6304. For example, at the saturation point at 80°C more dissolved water existed compared to 60°C. When, the water reached saturation level in oil at fixed temperature, oil samples were taken for further analysis after centrifugation (C1) to remove the water. Additive depletion by water was chemically analysed using FTIR and ICP. The results showed a depletion of additive with the removal of water from oil accompanied with an increased in wear and formation of acids. The results also support the findings of other studies that incorporated water affects the function of the additives. Water had a significant effect on detergent/dispersant and anti-wear additive (ZDDP); shown as an example in the region 976 cm^{-1} of FTIR results as seen in Fig. 1 with formation of acids at region 1037 cm^{-1}. Removing the water caused additive depletion that promoted an increased in wear as demonstrated in Fig. 2.

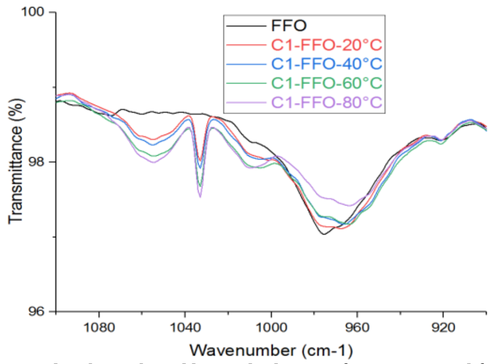

Fig.1 FTIR results show the additive depletion of anti-wear and formation of acids with increased removal water from FFO at different saturation points.

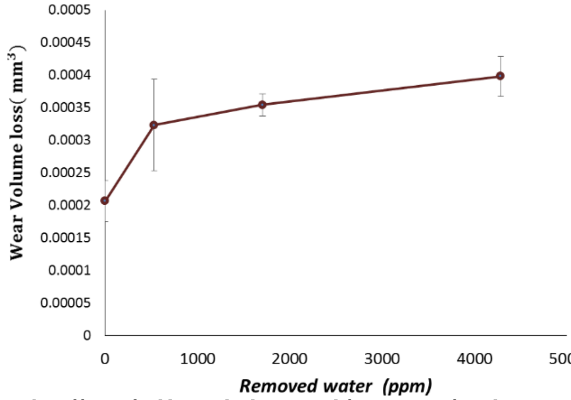

Fig.2 The effect of additive depletion and formation of acids on wear after removing the water from FFO.

Conclusion: Additive depletion is one of the most important factors that influences on the tribological performance and reduces the lifespan of oils. This study has determined the amount of additive that can be consumed and the effect on the tribological performance. Future work will focus on finding the relationship between the additive depletion and oil degradation to the level in which the lubricant is no longer fit for continued service.

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STRUCTURE COMPARISON USING COARSE-GRAINED MODEL FOR VISCOSITY INDEX IMPROVER

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KEYWORDS

Modeling in tribology; Lubricant additives; Rheology, Monte Carlo Brownian Dynamics

ABSTRACT

Molecular simulations are beginning to be used to analyze the behavior of viscosity index improvers in oil environments. The key difficulty to treat this system is the difference of the multi-physics nature, i.e. the size of the VII polymers are much larger than the size of the base oil molecules.

Due to the difference of the relative dielectric constant, interaction length between polar functional groups is longer in lubricating oil than in aqueous solution. Here we introduce Bjerrum length $l_B = e^2/4\pi\varepsilon_0\varepsilon_r k_B T$ to estimate long-range Coulomb interactions in solution. It is the length at which thermal energy and electrostatic energy are comparable.

In this study, a coarse-grained molecular simulation is used to analyze the structure of VII. The Monte Carlo Brownian Dynamics (MCBD) method [1] is used to simulate movements of a polymer chain in solution. Harmonic bond and angle interaction are applied to the neighboring segments. We assume polar segments which have a permanent dipole moment for the ester groups in PMA. Their long distance interaction has considered as $U_{dipole} = -2u^2/4\pi\varepsilon_0\varepsilon_r d^3$ where u is dipole moment, d is distance between segments.

The polymer segments are modeled as the Lennard-Jones particles instead of the hard core particles. 128 pieces of segments is modeled for the main chain of VII. Polar segments are set up at even interval, for N_{int}=4. Comparison between the LJ model and the hard core model has been done for a long time, however it is not known in models with functional groups.

The radius of gyration $R_g^2 = 1/N \cdot \sum_{n=1}^{N} \langle (R_n - R_G)^2 \rangle$ can describe the size of the polymer [2]. Fig.1 shows a snapshot of polymer in the LJ model. Fig.2 shows time developments of radius, both model gain equivalent radius. The fluctuation of radius is larger in the hard core model. In the LJ model, the arrangement between particles can be taken continuously. Therefore, the structural change proceeded gently.

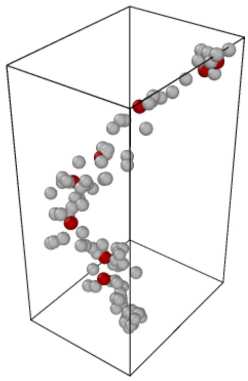

Fig. 1 Snapshot of polar polymer in LJ model (Perspective view, N=128, N_{int}=4).

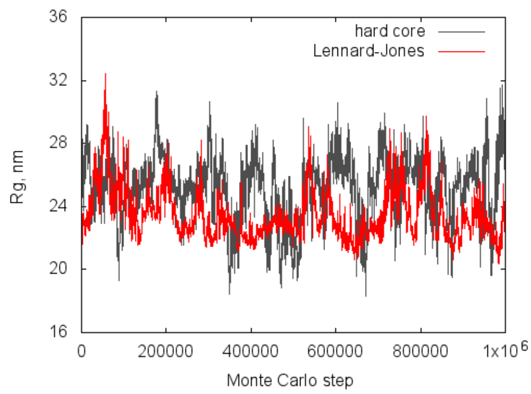

Fig. 2 Time developments of radius of gyration of polar polymer (T=313K, N=128, N_{int}=4).

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CHANGES OF THE COEFFICIENT OF FRICTION IN LUBRICATED SLIDING CONDITIONS DUE TO SURFACE TEXTURING

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KEYWORDS
Mixed Lubrication; Friction; Texturation; Unidirectional sliding,

ABSTRACT

Surface texturing is one of the basic methods of changing sliding conditions under lubrication. As a result of surface texturing a decrease of wear and better efficiency of mechanisms can be obtained [1]. In this work research was presented that corresponds to conditions of sliding crankpin bearing pad in race motorcycle engine. Such pads are usually threatened by severe wear, due to starved lubrication and high temperature. Investigations were carried out using an Optimol SRV5 tribotester equipped with pin-on-disc module. During tests friction force was monitored as a function of time. Standard types of samples were used in tests. Disc made of 42CrMo4 steel with 100 mm diameter acted as a sample. A counter sample was made of the same material, however its diameter was 20 mm. Samples and counter samples were heat treated to receive hardness of 40 HRC for sample and 35HRC for counter sample. Only the method of fixing the counter sample has been modified to ensure better aligning of the cooperating surfaces and eliminate fixing errors. Grooves were milled on the surface of sample grooves to change sliding conditions (fig.1.). Grooves had depth between 20 and 40 μm and had different bottom shape. Parts of discs were milled to make convergent geometry of groove bottom to the direction of sliding (fig.2.). Such solution leads to decrease of friction forces in comparison to untextured disc due to generation of the hydrodynamic lift. Some discs were textured to create rapidly ascending wall at the bottom of the groove. Such solution led to decrease of friction forces even more than convergent geometries of grooves.

Main goal of this research was to develop a simple method of texturing of crankpin bearing pads that can be made using CNC milling machines. Results also suggests that creating a hydrodynamic dam in some working conditions can lead to lower coefficient of friction and greater scatter than slowly converging bottom of the grove (fig.3).

Fig.1. Sample with milled grooves.

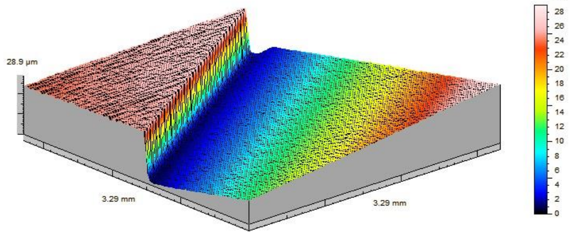

Fig.2. Axonometric view of the milled groove bottom of convergent geometry.

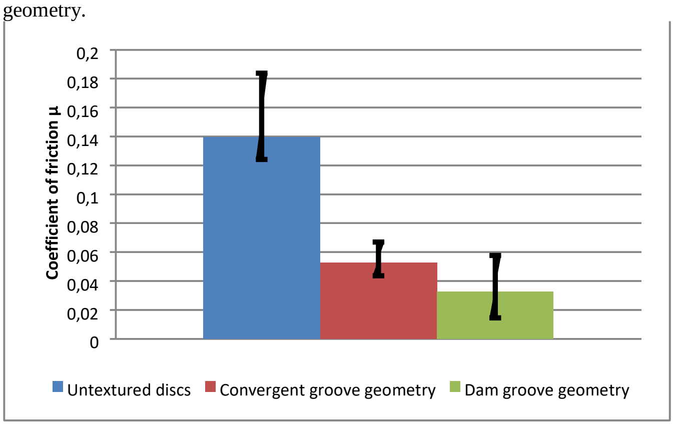

Fig. 3. Average values and scatters of the coefficient of friction for selected types of grooves

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A THERMO-GAS-DYNAMIC MODEL FOR THE BIFURCATION ANALYSIS OF REFRIGERANT-LUBRICATED GAS FOIL BEARING ROTOR SYSTEMS

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KEYWORDS

Modeling in Tribology; Friction;
Fluid Lubrication; Rotor Dynamics

ABSTRACT

During the last few decades, successful applications of refrigerant-lubricated gas foil bearings (GFBs) in air cycle machines of aircraft have confirmed the remarkable potential of this technology in the light of an increasing demand for energy-efficient and oil-free turbomachinery. Besides negligible power losses and low wear due to the absence of solid-to-solid contact between the gas-borne rotor journal and the bearing sleeve, the use of GFBs permits to overcome yet insurmountable speed, temperature, size, weight, and cleanliness limitations of conventional rolling-element or oil bearings. However, most GFB rotor systems are prone to undesirable self-excited vibrations with large amplitudes, which occur for elevated rotational speeds and may ultimately lead to machine failure [1]. As a countermeasure, the compliant and slightly movable bump foil and top foil structures in the lubrication gap of GFBs may dissipate some of the excessive energy by dry friction [3], hence providing a mechanism reducing detrimental rotor vibrations.

In current research on GFBs, sophisticated models and computationally efficient numerical tools are of major interest with regard to the complexity and costliness of experimental investigations. The presented work considers a nonlinear and fully coupled fluid–structure–rotor interaction model, which leads to an autonomous ODE system suitable for bifurcation and stability analyses as firstly discussed by the authors in [4]. Considering a Jeffcott–Laval rotor model, stationary operating points and periodic solutions can then be characterized by looking for instance at the rotor disk coordinates. The foil structure model is reduced to a reasonable complexity and it reproduces energy dissipation assuming a dynamic friction law applied to a spring–mass arrangement. To account for possible phase transitions in the lubricating hydrofluorocarbon refrigerant, the fluid pressure is obtained from an extended Reynolds equation for compressible non-ideal gases. Most importantly, knowing from previous studies that refrigerant-lubricated GFBs are rather sensitive to temperature fluctuations in the lubrication gap [2], the Reynolds equation is coupled to an energy transport equation governing the non-uniform temperature field. To this effect, the research presented on this poster is original in performing stability and bifurcation analyses of a refrigerant-lubricated GFB rotor system under non-isothermal conditions.

Summing up the main results to be presented on this poster, frictional energy dissipation reveals a remarkably beneficial effect upon the overall system dynamics and the consideration of realistic, non-uniform temperature fields has a significant influence on the predicted GFB performance. Finally, looking at some parameter studies, general recommendations for improving refrigerant-lubricated GFB rotor systems are given.

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A HOLISTIC APPROACH TO THE CHARACTERISATION OF ENVIRONMENTALLY ACCEPTABLE LUBRICANTS OVER A RANGE OF SHEAR RATES & PRESSURES

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KEYWORDS

Rheology; Fluid lubrication; Hydrodynamic Lubrication; Experiments in tribology

ABSTRACT

There is alot of effort ongoing to reduce the environmental impact of machines such as [1]. In 2013 the VGP regulation was introduced to promote the use of Environmentally acceptable lubricants (EALs). These are an exciting innovation that aim to minimise the negative impact of lubricants on our fragile and precious ecosystem. According to all standard testing methods, these EALs perform as well as their mineral oil counterparts. When they are used in marine propeller shaft bearing assemblies, they repeatedly underperform, displaying increased wear and failure. Many people are asking why is this the case.

There are a wide range of tools that can be used to characterise and qualify the viscosity and film forming behaviour of lubricating fluids. These vary from the standardised turnkey commercial off the shelf (COTS) tools that provide a highly repeatable measurement of a particular parameter, to the fragile research contraptions that are changing the way we understand tribological applications and that often require a PhD to operate.

When these large plain bearings experience misalignment and high loads, the result is an aggressive lubricated tribosystem with high temperatures, high pressures and high shear rates. There are no lab tools that exist to replicate these conditions in a controlled way.

To really understand what is happening to these new lubricants, a range of techniques have been applied including using a heavily instrumented miniaturised plain bearing test platform, low, medium, and high shear viscometers, high pressure viscometers, compressibility/bulk modulus characterisation tools, and some new and novel techniques.

A range of EAL products were tested and clear discrepencies were identified using the standard off the shelf characterisation tools. The main differences were in the fluid compressibility, the pressure-viscosity coefficient and particular products displayed some shear thinning behaviour.

The lubricant film thickness results from the jounal bearing test platform (Figure 1) showed that under low pressure and low shear conditions, lubricants of the same viscosity displayed similar fluid film forming behaviour when the fluid film temperature was kept constant. Additional discrepencies were identified during fixed inlet and high load tests. Fig. 1

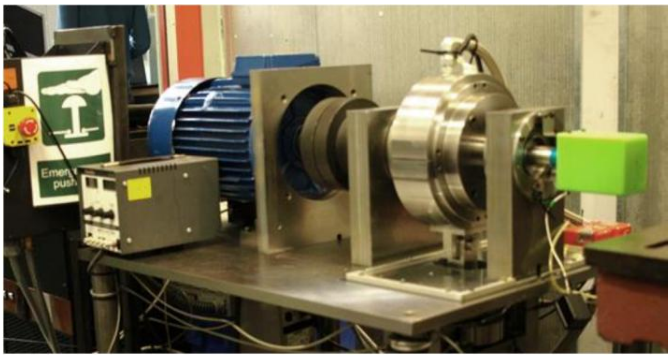

Fig. 1

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MODELLING CONCEPTS OF OPEN CLUTCH FLOWS – A THEORETICAL APPROACH

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KEYWORDS
Modelling in Tribology; Hydrodynamic Lubrication; Experiments in Tribology; Dimensional Analysis

ABSTRACT
Fuel saving trends of automotive industry remain highly important due to a strict regulation of vehicle CO_2-emissions. The development of multi-plate dual clutches, which are nowadays common in higher class automotive, leads to a speed difference in open clutch state, where induced oil is shearing in the clearance and causes an undesired drag torque. At a certain speed difference air is entering the clearance from the outer radius. Consequently, numerous research efforts aim at optimizing the lubrication flow between the clutch plate and rotating clutch disk, where various complex groove pattern have proven to result in a significant reduction of drag torque, due to earlier aeration onset.

The objective of the work is to contribute to the fundamental understanding of the aeration. A theoretical approach, based on a dimensional analysis is considered as can be found in related fluid mechanics text books, see e.g. [1]. The so-called Buckingham Pi-Theorem is applied to open clutch flows to provide a deeper insight into the comparison of different existing analytical, experimental and numerical results. Furthermore, the accordingly normalized scaling characteristics as derived from the clutch-flow parameter space are hypothesized to contribute towards predictive optimizing of lubrication flows in small gaps.

If the drag torque T_s and the volume flow rate $\dot{V}$ are described as dimensionless parameters ζ_m and $\dot{V}^*$ this leads to

$\zeta_m = \frac{\pi}{Re_l}$ and $\dot{V}^* = \frac{\pi}{20}$.

Those can be shown to depend on other dimensionless parameters of the system, such as the lubrication Reynolds number $Re_l = \frac{R_2 \omega h}{\nu}$. An example is shown in Figure 1 (a), where dimensional and normalized quantities are shown side by side. The curves collapse in non-dimensional scaling which demonstrates the appropriateness of the identified scaling parameters. At present the best results for prediction of aeration onset and drag torque in general are achieved with analytical models which do not capture the influence of surface grooves. Four different existing analytical models [2-5] are compared with respect to the respective simplifications and resulting torque predictions.

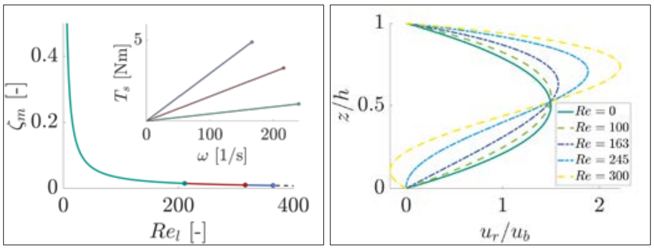

Figure 1 : (a) drag torque diagram; (b) radial gap flow profile

In addition to this comparison we consider how models for the aeration onset could be improved further. Figure 1 (b) shows the velocity distribution of the radial outflow for different Reynolds numbers. At lower speed the pressure driven Poiseuille flow is the dominant part, gradually predominated by the centrifugal flow at increasing angular velocities. Presently, the onset of aeration is typically predicted at the point, where the radial pressure gradient changes its sign. In the present approach we also consider additional flow, geometry and operating parameters that might be relevant for advanced drag torque and aeration onset predictions. Particularly, the challenge to cover various groove patterns is tackled on the grounds of the ratio between the radial through flow and the wetted perimeter, which will be elaborated in detail, both theoretically and by means of PIV experiments.

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INFLUENCE OF VELOCITY AND LUBRICANT VISCOSITY ON MICROSTRUCTURAL CHANGES DURING SLIDING OF FCC ALLOY SYSTEMS

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KEYWORDS
Friction; Fluid lubrication; Nanotribology, Microstructure

ABSTRACT

Recently, as analytical capabilities have improved in terms of resolution, interest in microstructural subsurface changes has increased. Which changes are beneficial or detrimental is still a subject of debate. Several groups focus on model alloys like Au-Au [1] or pure Cu [3], all in dry reciprocating sliding tests; a few on more complex microstructures like pearlite [2], but do not correlate the observed formations of newly formed microstructures to external loading conditions.

In the current work, the microstructural evolution of the subsurface volumes during lubricated sliding was investigated in a model sliding configuration (reciprocating ball on plate) of CuSn bronzes; an alloy system that is as simple as possible, but still commercially used. The examined lubricated steel-bronze pairing is representative of a wide range of bearings used in industrial or automotive applications. A deeper understanding of causal and quantitative dependencies on external loadings could enable action to improve wear resistance and decrease friction.

The CuSn bronze was subjected to an average Hertzian pressure of 317 MPa at various velocities (i.e. frequencies) and. In Fig. 1, an example is shown, where PAO8 and PAO20 are compared for 10 Hz. The effects of the lubricant viscosity are immediately obvious. The lower viscosity oil leads to grain refinement throughout the analyzed FIB cut up to depth of 5 µm, with a vortex structure near the surface, while the higher viscosity leads to only a very thin nanocrystalline layer and much larger grain sizes below.

The type of lubrication (droplet or oil circuit) also influences the microstructure considerably. With a droplet of PAO20, the grain refinement is more pronounced and the subsurface grains are heavily affected by twinning and intragranular residual stresses, as revealed by EBSD. Subsequently reducing the sliding velocity results in lower amounts of refined grains, but twinning still affects most grains. This shows the effect of different shear stress loadings.

Macroscopically, the different lubricant viscosities have – as expected – a large effect on the coefficient of friction, with the lower viscosity PAO20 leading to a substantial decrease in coefficient of friction and a much shorter running-in period.

The type of lubrication, has negligible effects on coefficient of friction with only a slight reduction in running-in, even if the microstructure is affected substantially. This could indicate that the differences in lubricant amounts in the contact itself, and thus its ability to take over part of the external shear loading, is compensated by the changing ability of the evolving microstructure to reduce the shear deformation by forming twins and grain boundary sliding.

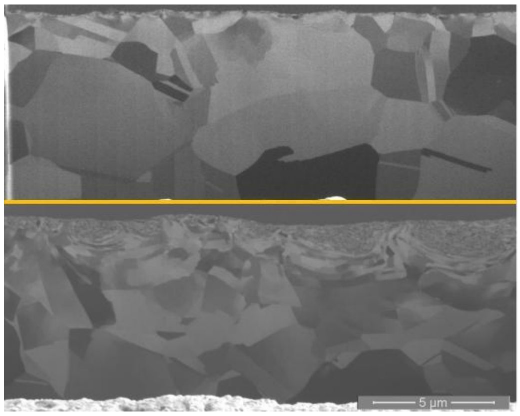

Fig.1 Subsurface microstructure of CuSn bronze subject to lubricated sliding with PAO20 (top) and PAO8 (bottom)

ACKNOWLEDGMENTS

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Poster group n° 3

Surface science, texturing

46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

BIO-INSPIRED SURFACE FABRICATED USING MICRO SLURRY JET METHOD AFFECTS EVERYDAY TRIBOLOGY

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KEYWORDS
Texturation; Surface topography; Everyday life tribology, Precision surface machining

INTRODUCTION

Surface texturing is an effective method for improving the tribological characteristics in everyday materials. The microstructure of natural surfaces, such as lotus leaves, moth-eyes, and Gecko skin, can be used as a template to design surface profiles. This study was performed to develop surface micromachining, a mechanical material removal process, for the creation of a bio-inspired surface on artificial materials. Practical applications were also demonstrated in various tribological fields.

MICROMACHINING PROCESS

A micro slurry jet was used for surface micromachining via mechanical removal. The micro slurry jet method involves wet blasting in which the slurry (water with alumina/diamond particles) is injected through a nozzle using compressed air. Photolithography or 3D printing technology was used to adjust the micro slurry jet removal rate to increase machining accuracy. The surface micromachining method achieved ultraprecision machining on the order of nanometres in the orthogonal direction on the material surface. Machining accuracy on the order of micrometres was realized in the parallel direction.

PLACTICAL APPLICATIONS

The bio-inspired surface of a Co-Cr-Mo alloy as a counterface material of polyethylene in an artificial joint increased the polyethylene particle size and reduced the total wear, preventing adverse tissue reactions [1].

The bio-inspired surface of a die used for molding a PET (polyethylene terephthalate) bottle reduced the adhesion of the PET material on the die surface, preventing the commingling of PET particles into the bottle material.

The wettability of a processed surface on a glass was changed to prevent the retention of sebum and fingerprints on the surface.

The developed process could remove microscopic cracks and other microstructural defects on a dental ceramic, resulting in improved bending properties and a smoother ceramic [2,3].

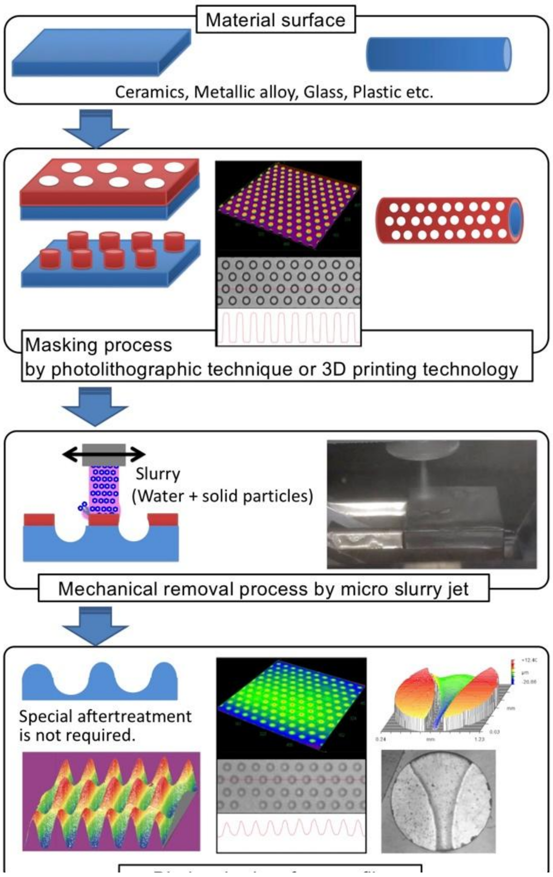

Fig.1 Micromachining processes for creating bio-inspired surface profile.

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

SURFACE ENGINEERING OF A TITANIUM ALLOY BY NANOSECOND-PULSED LASER

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KEYWORDS
Experiments in tribology; Texturation; Wear; Titanium alloy

ABSTRACT
Aviation is a vital part of our modern everyday lives, with both air travel and air freight transport increasing constantly throughout the last decades. Airline companies as well as customers ask for more fuel efficient airplanes, which are therefore more cost efficient and environmentally friendly.

Titanium alloys like Ti6Al4V have high specific strengths and can be used in aerospace structures to reduce their weight, which helps in meeting these demands. While titanium alloys also offer further advantages like an excellent corrosion resistance, their tribological properties are poor. Tribological systems using these alloys typically suffer from severe adhesive wear, which also can hardly be counteracted by the use of conventional hydrocarbon lubricants.

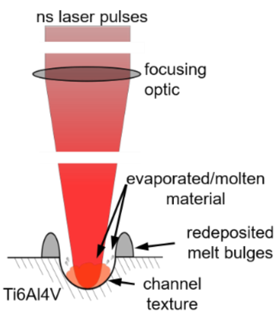

Fig.1 Laser surface texturing process

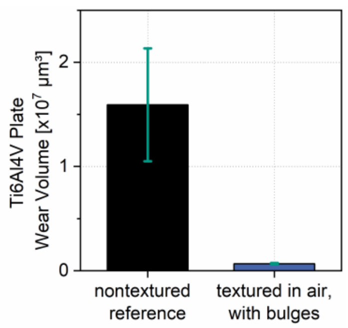

Fig.2 Wear volume of textured surface compared to non-textured reference

In order to overcome this drawback, linear, parallel channel textures were applied to the Ti6Al4V surface with a 20 W Yb-doped fiber laser. Due to operation in pulsed mode with pulse lengths of 26 ns, considerable amounts of material were molten and displaced to the sides of the texture in form of melt bulges (Fig.1).

Tribological tests were performed in cylinder-plane contact in a reciprocation fashion with a normal load of 20 N, stroke length of 0.2 mm and frequency of 20 Hz.

The laser surface treatment proved to be effective in increasing the wear resistance of Ti6Al4V significantly, as shown in Fig.2. By a variation in channel packing density, atmosphere during lasering and finishing procedure, tribological enhancing mechanisms were elucidated.

Further analysis was conducted on the melt bulges, using scanning transmission electron microscopy (STEM) and energy dispersive X-ray spectroscopy (EDX), showing a link between tribological properties, microstructure and chemical composition of melt bulges.

ACKNOWLEDGMENTS

The authors would like to thank the German BMWi for funding this work within the scope of the project FAWIBO (20Y1505C), headed by Liebherr-Aerospace.

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GREEN SYNTHESIS OF NANOLUBRICANT WITH COPPER OXIDE NANOPARTICLES BY ABLATION LASER

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KEYWORDS
Nanotribology; lubricant additives; friction; green synthesis

ABSTRACT

This work aims to evaluate the tribological performance of a nanolubricant mineral base oil with the copper oxide nanoparticles (NNP-CuO) synthesized by a green methodology. The NNP-CuO were produced by laser ablation into liquids technique using Nd:YAG pulse laser irradiation on mineral oil. The nanolubricant stability, as well as the optical absorption, morphology, particle size and dispersive state of copper oxide nanoparticles into the mineral oil, were analyzed by UV-VIS and SAXS techniques. This green technique provided highly pure nanomaterials and enhanced nanolubricant stability and dispersion. The tribological results showed antiwear properties.

INTRODUCTION

Because of its chemical and physical properties, the copper oxide nanoparticles have promoted friction and wear reduction when added in lubricants [1]. However, the main problem of its use as an additive is the easy formation of clusters because of their high surface tension and poor dispersion. A solution for this problem is to produce the NNP directly into oil by physical deposition sputtering [2], but it is an expensive and low production technique. On the other hand, the laser ablation technique shows major advantages because it combines the physical processes of the laser-matter interaction with chemical mechanisms due to the use of liquid solvents [3]. The laser ablation introduces a green method for manufacturing nanoparticles in solvents liquids with successful to solve the problem of agglomerate besides conferring long-lasting stability of nanoparticles in suspension. Also, it can be considered an easy experimental setup and environmentally friend, because it is not necessary the use of chemicals [4].

METHODOLOGY

The nanolubricant of NNP- CuO nanoparticles were prepared by a pulsed Nd:YAG laser with the wavelength at 532 nm, energy of 147 mJ/pulse and pulse length of 10 ns. The target was ablated at 50 cm from the laser focal spot. The laser was operated at a repetition rate of 10 Hz for 20 min. After ablation the UV–visible was used to chemical analyses of suspensions and SAXS to preview the morphology, size distribution, and dispersion. The tribological performance was evaluated using the high-frequency reciprocating rig at boundary lubrication conditions.

RESULTS AND DISCUSSION

The UV-VIS spectra present a band at around 240 nm wavelength. This band characterizes the presence of CuO nanoparticles [1] proving the success of the green synthesis. The profile of the SAXS curves for the CuO nanoparticles shows to a system of spherical particles and size around 10 nm. Finally, the absence of a second peak in the pattern of the curve indicates that there was no formation of agglomerates. The nanolubricant presented friction coefficient similar to mineral oil. However, it has antiwear properties.

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TEXTURATIONS AND SURFACE TREATMENTS INFLUENCE ON ALUMINUM GLUED JOINTS ADHERENCE

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KEYWORDS

Surface topography, Texturation, Contact and adhesion, Knurling

ABSTRACT

For glued joints efficiency surfaces morphology and physico-chemical properties have to be mastered. This is of major importance to control surfaces energies and the available surface in order to improve the mechanical joint strength. A lot of methods are used to functionalize surfaces at a micrometric scale: lithography, ion etching and molding (Ishino *et al.* 2004).

Surface preparation for bonding is almost done thanks to sandblasting as it allows cheap and efficient available surfaces increase. Laser texturing is more expensive but popular for its reproducibility and its attainable scales. However laser texturing can lead to changes in surface chemistry and then affect surfaces adhesion measurements such as wetting. (Bizi-bandoki *et al.*, 2013). In the following study, knurling is the texturing process highlighted (Fig.1). This is a well-known process in mechanical field but barely used for micrometric texturing. This is a fast and cheap alternative that does not modify surface chemistry (Divin-Mariotti *et al.*, 2019).

In this study, sandblasting, femtosecond laser and knurling texturing are made for surfaces bonding preparation and are compared. Samples in aluminum 1050 of 10x50mm and 1.5mm thickness are used. Aluminum 1050 is a ductile material of 34Hv easy to knurl. The chosen patterns for knurling and femtosecond laser are grooves around 3.5µm depth and 27µm period. In order to evaluate glued joints adhesion 3 points bending are made. A force is applied on the aluminum sample until glue and aluminum interface fracture (Fig.2). Knowing that femtosecond laser texturing affect surface chemistry during time, adhesion measurements are made during time and an aging cycle is also made.

Fig.1 Knurling surface experimental setup on a 5-axis machining center.

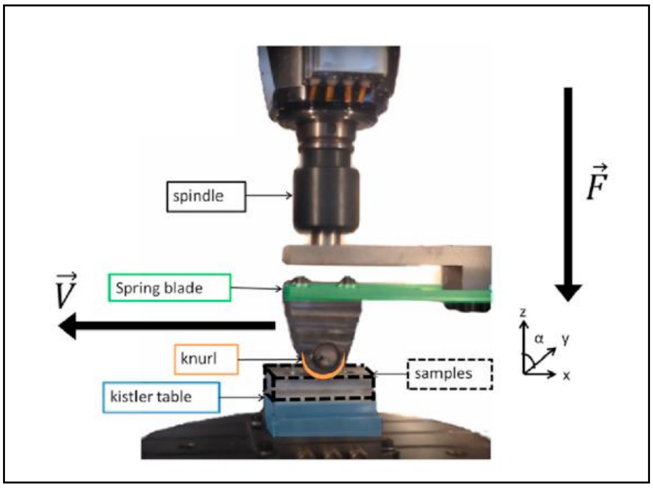
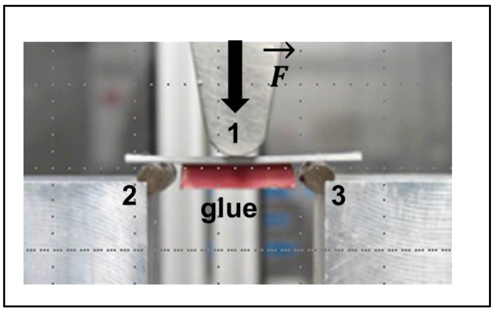


Fig.2 Adhesion tests by 3 points bending method.



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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

ELABORATION OF MODEL SUPER-HYGROPHOBIC SURFACES BY REPLICATION OF NATURAL SURFACES

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KEYWORDS
Contact and adhesion; Texturation; Surface topography, Bio-inspiration.

ABSTRACT
Understand the wettability and control repellency on surfaces is necessary in several industrial domains. The purpose of this work is the elaboration of model textured surfaces to study topographic contribution involved on super-hygrophobic properties. Many hygrophobic natural surfaces [1] have complex texturing (Multi-scale, re-entrant structure [2]), such as bamboo leaf (Fig 1). Replicate these topographies is an easy way to obtain hygrophobic model surfaces.

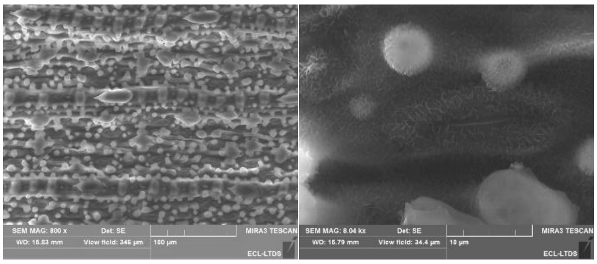

Fig 1 : Bamboo leaf underside multi-scale topography

A process has been developed to replicate the complex topography of natural surfaces with polydimethylsiloxane (PDMS) and without fluorinated compound. This replication process makes it possible to replicate precisely the micrometric scales and partially the nanometric scale.

In a first step, the natural surface is molded with PDMS to obtain a negative replica. In a second step of the process the negative replica is used as a mold for positive replication [3]. Thus, two model surfaces have been created by each replication step (Fig 2).

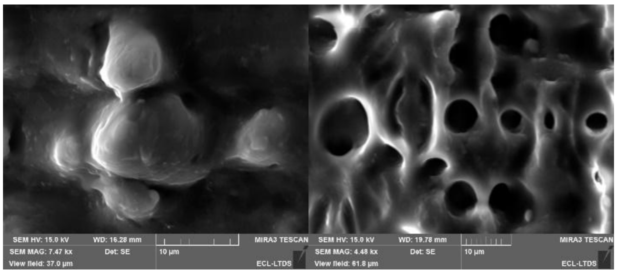

Fig 2 Positive (left) and negative (right) replicas

The contribution of the topography of the natural surfaces is quantified by a comparison of contact angles. On negative replica the contact angle is equal to 142° and for the positive replica it is equal to 130° (Fig 3). These values have to be compared with the contact angle on the real lower side of the bamboo leaf that is 137°. Compared to flat PDMS (contact angle equal to 110°), the contact angles on negative and positive replica indicate an effective contribution of the topography. The replication process has been applied on different plants to compare each topographic contribution.

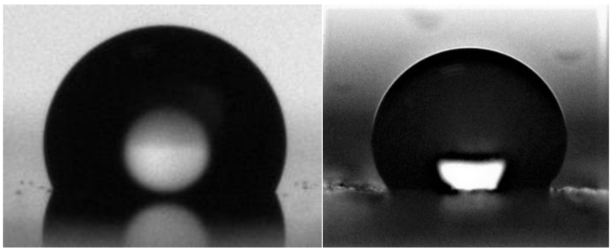

Fig 3 : Wetting on flat PDMS (left) and negative replica (right)

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DIFFERENT DIRECTIONAL ENERGY DISSIPATION OF HETEROGENEOUS POLYMERS IN BIMODAL ATOMIC FORCE MICROSCOPY

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KEYWORDS

Surface topography; Experiments in tribology; Physics of friction; Energy dissipation

ABSTRACT

Dynamic force microscopy (DFM) has become a multifunctional and powerful technique for the study of the micro-nanoscale imaging and force detection, especially in compositional and nanomechanical properties of polymers.[1] [2] However, the in-plane interaction cannot be detected by the commonly used tapping mode because of a sharp tip vibrating perpendicular to the sample surface.[3] Here a bimodal approach, where the first order flexural and torsional eigenmodes of the cantilever are simultaneously excited, was developed to detect the out-of-plane and in-plane dissipation and virial between the tip and the polymer blend of polystyrene (PS) and low-density polyethylene (LDPE). The amplitude and phase of the flexural and torsional response signals have been recorded and analyzed to calculate the contrast, energy dissipation power and virial at the various setpoint ratios. Three free flexural amplitudes have been used to explore the effects of amplitudes on the above physical quantities. In the end, the scanning images of different stages are displayed to confirm that contrast reversals occur within a small setpoint ratio range. The new findings are of great importance to the material components contrast, out-of-plane and in-plane energy dissipation, the non-contact ultrasensitive force detection for the soft matter, such as biological material, and the lateral micro-friction measurement in the future. [4] [5]

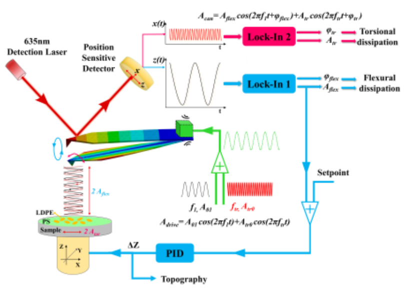

Fig.1 Bimodal schematic description and control system for the AFM, showing the two excitation signals are the first order flexural and torsional mode frequencies, respectively.

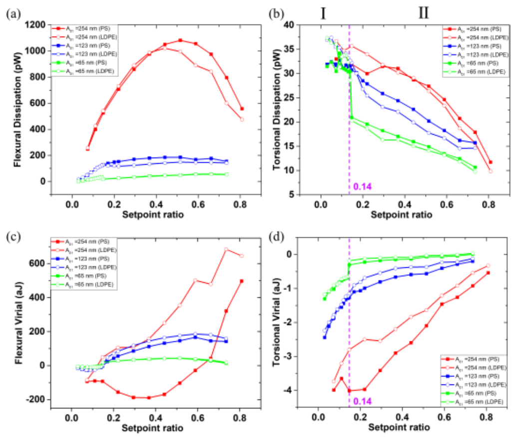

Fig.2 Energy dissipation power and virial curves under different free amplitude. Energy dissipation power of the first order flexural (a) and torsional (b) vibration mode. Virial of the first order flexural (c) and torsional (d) vibration mode.

ACKNOWLEDGMENTS

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

INFLUENCE OF SURFACE TEXTURING ON HEATED WALL ON COLLISION BEHAVIOR OF DROPLET

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KEYWORDS

Surface topography; Texturation; Contact and adhesion, Atomization

ABSTRACT

The atomization technology is progressing markedly the effect of it on environmental problem, energy conservation and resource saving is expected[1]. For example, improvement of cooling effect using heat of vaporization, or promotion of chemical reaction for purification of NOx. However, when droplets hit on the of high temperature 200~300℃, Leiden Frost phenomenon known to occur. This phenomenon can be a hindrance to the atomization technology. Therefore, it can be said that problem to be solved to improve atomization technology.

In this study, surface texture using wetting control[2] created on the test materials and then, it was heated to Leiden Frost temperature. In this way, improving atomization of microstructure under Leiden frost temperature is verified experimentally. As shown in Fig. 1, test materials of base and two kind of different groove are prepared. These test materials are heated to Leiden temperature using hot-plate and droplets are sprayed using injector. Also, the behavior of collision droplets was visualized by high-speed camera. Fig. 2 (a) shows the visualization result of dispersing droplets, (b) shows the visualization result of droplets. The particle size distributions after collision was calculated by measuring particle size of before and after collision to evaluate these visualization results quantitatively. Fig. 3 shows the particle distributions of after collision for particle size 50~60 μm of collision. From this figure, it is confirmed that atomization Leiden Frost phenomenon is improved by creating surface texture, and texture 2 is higher atomization performance texture1.

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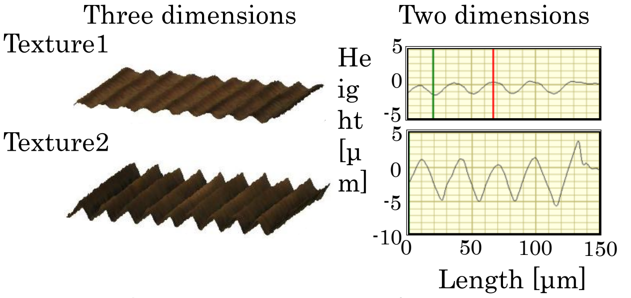

Figure 1. Observation results of texture materials

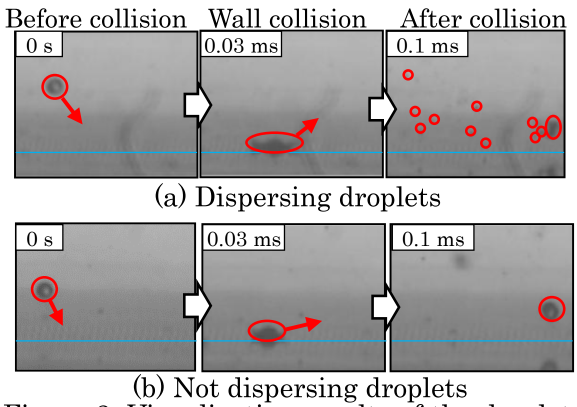

Figure 2. Visualization results of the droplets collision behavior

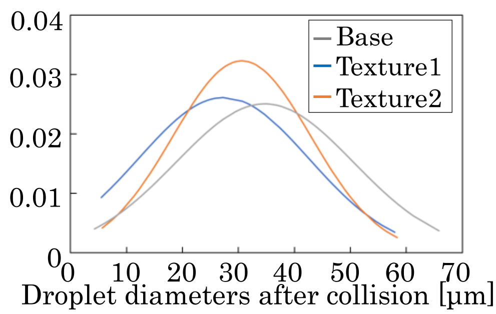

Figure 3. Particle size distribution of droplet diameter after collision

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

PERFORMANCE STUDIES OF FULLY FLOODED AND STARVED LUBRICATED TEXTURED SPUR GEARSETS

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KEYWORDS

Textured gear pair, Starved lubrication, Wear, Vibrations

ABSTRACT

Many mechanical devices use gear drives for achieving the precise velocity ratios and obtaining wide range of speeds and torques at given input power. Refer Fig. 1 for a gear drive system. Since recent past, there is growing demand for hard and efficient working gear sets possessing very high gear transmission density (large torque to volume ratio) for use in several mechanical systems. In this situation, improvement in the tribological performance at the gear teeth interfaces is very important for preventing the surface failures and controlling the vibrations of gearsets. It is worth noting here that effective lubrication at the gear teeth interface is necessary to avoid asperity-to-asperity interactions in the presence of starved lubrication at elevated loads and slow speeds.

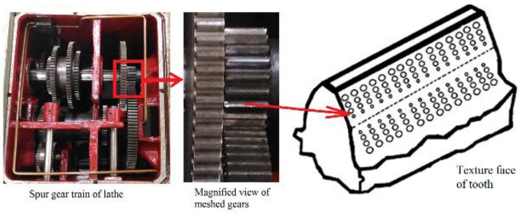

Fig. 1 Gear drive system with a textured teeth

Since recent past, the tribological performance in gearsets operating in boundary lubrication regime is being improved employing nano-lubricants, extreme pressure additives, increase in teeth surface hardness, super finished surfaces etc. The improvement in tribological behaviour at gear teeth interfaces leads to reduced dynamic problems and increased reliability of any gear transmission system. Since last two decades, it is found that worldwide researchers are exploring to improve the tribological features of conformal and non-conformal contacts using different surface textures [1-2]. This motivated the authors to conduct the tribo-dynamic performance behaviours of geared drive system using few promising surface textures. A schematic surface texture is shown on a tooth face in Fig.1.

The objective of this paper is to experimentally investigate the lubricating film formation feature, wear, and vibration behavior of spur gearset employing four different surface textures under fully flooded and starved lubricating conditions. Four different surface textures comprising of different dimple shapes (spherical, square, cylindrical, and elliptical) and grooves were employed in the exploration. The surface textures on faces of gear teeth were created through nanosecond pulsed Nd: YAG laser. The experiments were conducted on gearsets at various operating parameters. The schematic diagram of the test rig used is shown in Fig.2. Contact potential was measured for understanding the qualitative film thickness formation at the interface of conventional and textured teeth. Vibration signals were captured mounting miniature accelerometer at the location as shown in Fig.2. Signals were analyzed in time and frequency domains for understanding the roles of textures on gear vibrations.

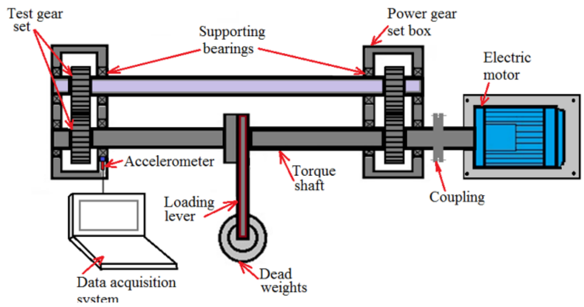

Fig. 2 Schematic diagram of test rig

The surface investigations of gear teeth faces were done using SEM and 3-D profilometer. Very encouraging results have been found with textured teeth faces.

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LOAD CARRYING CAPACITY AND FRICTIONAL TORQUE IN DIMPLED PARALLEL THRUST BEARINGS

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KEYWORDS

Fluid lubrication; Hydrodynamic lubrication; Texturation, Dimpled parallel thrust bearings

INTRODUCTION

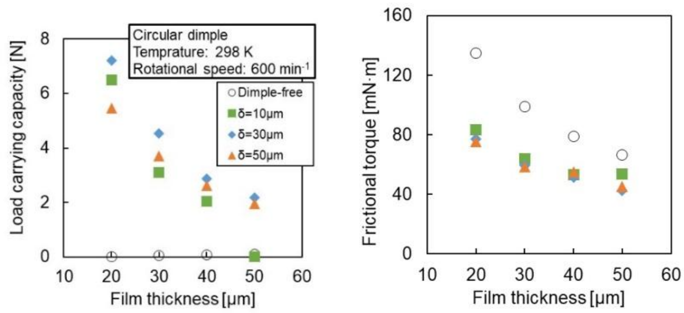
Parallel thrust bearings cannot generate the load carrying capacity to separate a rotor and a bearing. Therefore, dimpled or grooved parallel bearings have been investigated by many researchers to make clear the mechanisum of the hydrodynamic lubrication performance in such bearings [1, 2]. This study aims to clarify a dimple effect on the load carrying capacity, frictional torque, and cavitation phenomena.

MATERIALS AND METHOD

A dimple-free specimen and dimpled specimens (circular type and two rectangular types) are prepared in this study. Ten dimples (10μm-, 30μm-, and 50μm-depth) are etched on a lubricating surface. The load carrying capacity and frictional torque are measured under a constant load or a constant film thickness. In the latter measurement, a rheometer is used. In both measurements, cavitation occured around the dimples is observed.

RESULTS AND DISCUSSION

Figures 1(a) and 1(b) show the load carrying capacity and frictional torque, respectively, which are obtained under a constant film thickness. The measurement results for the circular dimple are shown here. Dimpled specimens show the larger load carrying capacity and lower frictional torque than the dimple-free specimen in all test conditions. The specimen with the dimple depth of δ=30μm shows the largest load carrying capacity in all film thickness tested. Figure 2 shows a result of visualization test. The cavitation appears in the entrance of each dimple.



(a) LCC (b) Torque

Figure 1 Load carrying capacity (LCC) and frictional torque

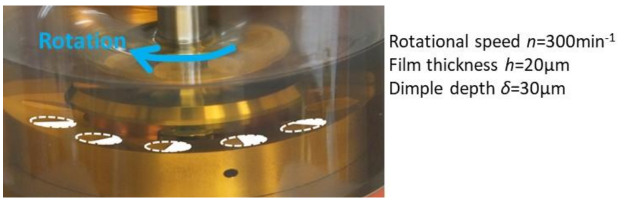


Figure 2 Picture of cavitation occurred the entrance of dimples

CONCLUSIONS

In this study, the load carrying capacity and fictional torque in the dimpled surface are discussed. The visualization test shows the occurrence of cavitation in the entrance of each dimple.

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

SENSITIVITY OF THE STRIBECK CURVE TO THE MACROSCOPIC GEOMETRY OF THE PIN-ON-DISC TRIBOMETER IN THE MIXED LUBRICATION REGIME

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KEYWORDS
Texturation, mixed lubrication, modelling in tribology, pin-on-disc tribometer.

ABSTRACT

A considerable part of the tribological research on surface textures relies on experimental set-ups based on pin-on-disc tribometers [1]. With these experimental devices the texture effects are investigated on a clearly defined contact region, allowing to study several texture patterns in a simplified and controlled way. Nonetheless, the typical process to obtain textured pins (through laser texturing and polishing) often leads to a considerable modification of the pin surface, which may differ from the nominal design, for example by getting rounded at the edges. The effects of the resulting macroscopic geometry changes can significantly affect the tribological performance of the applied texture. The present work aims to quantify the effects of such macroscopic modifications of the pin surface on the Stribeck curve.

The work is based on a numerical approach which combines different models in order to describe the mixed lubrication regime in pin-on-disc tribometers. The hydrodynamics part is modelled through the Reynolds equation with a mass-conserving cavitation algorithm [2], which has been extended to consider the influence of roughness through a homogenization approach [3]. Contact pressures are derived from an elasto-plastic simplification of the half-space model, while shear stresses are obtained via the Bowden-Tabor approach [4]. Hydrodynamics and contact mechanics are iteratively coupled to simulate mixed lubrication. The study focusses on the influence of the macroscopic pin geometry on the resulting friction coefficients for different operating conditions. Therefore, the pin surface profile is approximated by a parabolic function which is parametrized according to the height difference h_c between the center and the edge of the pin. The considered pin geometries are displayed in Fig.1 along with the corresponding fiction coefficients as a function of the sliding speed.

The results show that the friction coefficients and the operating conditions at which mixed lubrication occurs strongly vary for different pin profiles. Therefore, changes in the macro geometry that are introduced e.g. in the process of surface texturing, can have a strong impact on the obtained results. In consequence the (nominal) large-scale pin geometry should always be reported along with the small-scale surface geometries in corresponding studies in order to allow comparison and generalization of the obtained results.

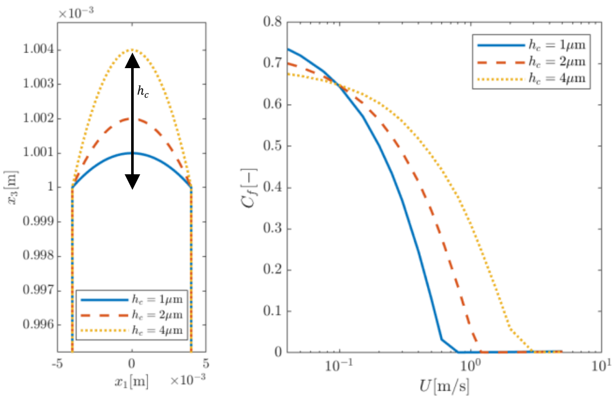

Fig.1 Pin profile and corresponding friction coefficient C_f as a function of the relative velocity U.

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COMBINED EFFECTS OF POCKET AND BIONIC TEXTURE ON THE PERFORMANCE BEHAVIOURS OF THRUST PAD BEARING

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KEYWORDS

Thrust pad, FEM, Pocket, Bionic texture, Energy efficient

ABSTRACT

Hydrodynamic thrust pad bearings are commonly employed in industries to transfer large axial load from rotating component to stationary pads through a thin lubricating film as illustrated in Fig. 1. It is found that great attempts are being made by the researchers across the globe to develop heavy load sustaining energy efficient fluid film thrust pad bearings by incorporating the modification in the pads' surface topographies (involving profiles, pockets, dimples, grooves etc.) at the macro/micro levels [1-4]. Looking the encouraging findings with textured surfaces, the authors got motivation to employ bionic texture as well for exploring and improving the performances of thrust pad bearings. Hence, the objective of this paper is to explore and improve the minium film thickness and friction coefficient in a thrust pad bearing through the synergistic effect of pocket and boinic texture (Labeo rohita fish).

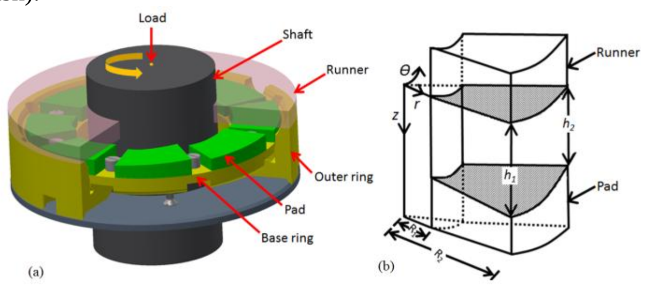

Fig. 1 (a) CAD model of thrust pad bearing; (b) Coordinate system used in FE analysis

Governing equations have been discretised employing FEM and solving the algebraic equations using Fischer-Burmeister-Newton-Schur (FBNS) algorithm [5]. The coordinate system employed in the mathematical model is shown in Fig. 1(b). Figures 2(a) and 2(b) show 3-D pressure profile and 2-D pressure distribution (along the circumference direction at mean radius) in the lubricating film, respectively, at the operating parameters mentioned in the plots. Based on the numerical investigations with pocketed and fished texture pad, encouraging results have been achieved. The minimum film thickness has increased about 19% and friction coefficient has reduced by 14%.

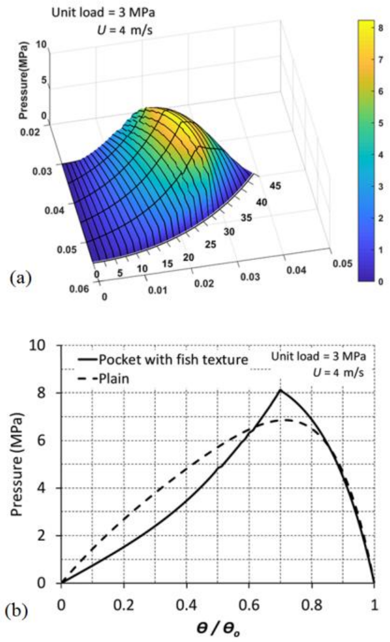

Fig. 2 (a) 3-D pressure profile in the film, (b) 2-D pressure profile along the circumference direction (at mean radius)

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MOLECULAR DYNAMICS SIMULATION OF INITIAL ADSORBING PROCESS OF ORGANOPHOSPHATE ON METAL SURFACE

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KEYWORDS
Lubricant additives; NanoTribology; Molecular Dynamics

ABSTRACT

Organophosphates are representative compounds of extreme pressure additives. They adsorb onto the metal surface and make a film by chemical reaction. Then, the film protects the metal surface. Although there are a plurality ester types in organophosphates, there is little knowledge about each ester single substance. Therefore, systematical comparison and evaluation of the friction and wear characteristics of organophosphates having different numbers of ester groups, different lengths and types of alkyl groups are needed. Molecular dynamics (MD) simulation is useful on elucidating the difference of dynamical behavior due to molecular structure. In this study, we carry out MD simulation to understand the physical adsorption characteristics and behavior in base oil in the difference of the structure of alkyl molecular chain.

Figure 1 shows the structures of mono-oleylphosphate, di-oleylphosphate and model base oil. LAMMPS [1] (Large-scale Atomic / Molecular Massively Parallel Simulator) is used for all atomic molecular dynamics simulation of organic molecules on the solid surface. The solid surface is a model metal having a lattice constant of α-iron, and the additive is adsorbed by charging the atomic charge of the outermost surface with +1e and the charge of the atom underneath with -1e [2].

Figure 2 shows simulation snapshots after 6 ns from the start of the simulation. The yellow molecules are the base oils, the red ones are the alkyl chain of the additives, and the pink atoms are the phosphate group. From figure 2, it can be seen that four molecules of the mono-oleylphosphate and the di-oleylphosphate form an association in the base oil. Neither mono-oleylphosphate nor di-oleylphosphate adsorbs to the solid surface even after 20 ns from the start of the simulation. This is because the molecular weight of the additive molecule itself is larger than that of the base oil molecule itself and additionally 4 molecules form an inverse micelle immediately after the start of the simulation, so that diffusion in base oil and physical adsorption to the surface are inhibited.

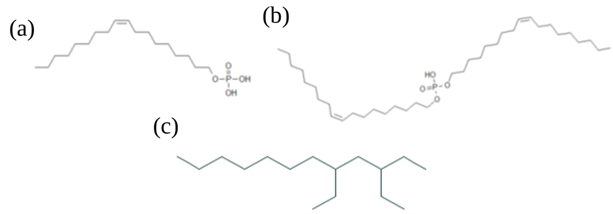

Fig.1 Oleylphosphate ((a)mono- (b)di) and model base oil. ((c)3,5-diethyldodecane)

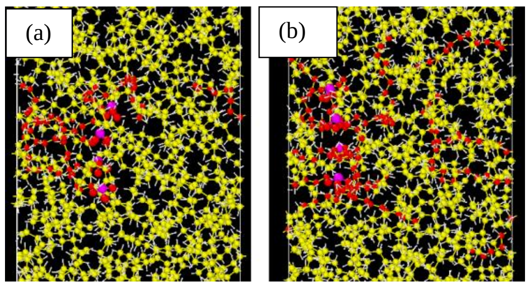

Fig.2 Snapshots of simulation after 6 ns. ((a)mono- (b)di-)

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THE EFFECT OF GRAPHITE SURFACE TEXTURING ON THE FRICTION REDUCTION IN A DRY CONTACT

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KEYWORDS
Friction ;Texturation; Experiments in tribology; Graphite,

ABSTRACT

Surface texturing is well known method of friction and wear reduction. Different techniques have been developed to modify surface topographies. Laser texturing is a common method used to make dimples and micro channels. Other techniques are also frequently used, like milling, EDM or burnishing (embossing). Abrasive jet machining, being an alternative texturing method, is presented in this paper. This technique has been used to texture graphite. Graphite is a very good material in terms of the friction resistance and the heat transfer. However due to great hardness and low fracture resistance it is difficult for machining. In this work graphite discs of 100 mm diameter were textured in a chevron pattern, and due to multiple stages of processing the bottom of a groove had convergent depth to produce aerodynamic lift (figure 1)[1], [2]. A counter sample was made of 42CrMo4 steel and its contact surface was polished. Tests were carried out using an OPTIMOL SRV5 tribotester, equipped with a pin-on-disc module. Tests were carried out at ambient temperature, a normal force was 1 N. A sliding speed was adjusted to 4.5 m/s. The contact area with a counter sample had 16 mm diameter. A friction radius was 38 mm. During test the friction force was measured as a function of time. No lubricant was used during tests. Various patterns of chevron grooves were made. The main difference among them was the angle between arms of chevron pattern (between 60° and 120°). Shapes of grooves bottoms also varied. Average values and scatters of friction forces for assemblies with untextured and selected textured samples are presented in figure 2.

It was found that surface texturing caused a reduction of the frictional resistance of the analysed sliding pair. The angle between arms of chevron layout was found to be substantial parameter .

Fig.1. Graphite disc with grooves made by abrasive jet machining, with 90° chevron pattern.

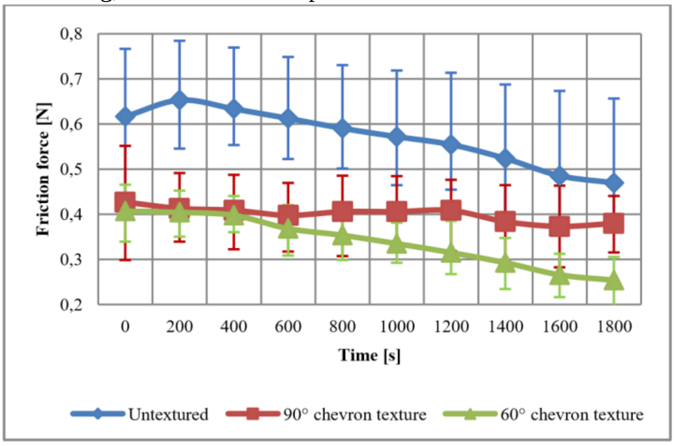

Fig. 2. Average values and scatters of friction forces for different types of graphite discs.

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LASER TEXTURE PREDICTION METHOD SELECTION WHEN RELATED TO A LUBRICATION MODEL

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KEYWORDS

Surface topography; Texturation; Hydrodynamic Lubrication; Modelling in tribology

ABSTRACT

Whereas the physic models of fluid lubrication should be able to provide quantitative predictions to industrial problems, it is somehow demanding to provide the input data to feed these high-level equation systems. The operating conditions are generally available, and the material properties can be obtained through thorough and costly independent measurements [1]. However, the surface topography characterization required in some cases comes with its own challenges.

In the present poster, the authors compare two different approaches to obtain the topography of laser texturation. Their aim is to demonstrate their strengths and weaknesses when being used as input data in a fluid lubrication model able to take into account non smooth surfaces [2]. The first method consists in including the height distribution stemming from topography measurements. The second is rather different and deals with the numerical predictions of the topography. Indeed, SIMTEC has developed a thermo-hydraulic model [3] to quantitatively predict the shape of the laser crater [4]. The output of such a model is a prediction of the topography.

The lubrication results obtained with the numerical predictions are presented in the poster, together with the strengths and difficulties of both methods. Whereas the experimental data may seem more easily available to the lubrication model developers, they actually require the making of a prototype surface. For its part, the numerical data provided by a thermo-hydraulic model may be different from the topography measurement. However, for the owners of such a model, the topography is available at a very early stage of the project. Moreover, it is possible to test a large among of laser operating conditions and directly evaluate their influence on the contact behaviour through the different surface shape they generate.

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Poster group n° 4

Wear, damage, fatigue

46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

TRIBOLOGICAL CHARACTERIZATION OF ALUMINIUM-BRONZE ALLOY SLM MANUFACTURED

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KEYWORDS
Friction; Wear; Surface topography, Additive manufacturing

ABSTRACT

The need for high performance materials assuming good behaviour in service is constantly increasing, especially in aggressive conditions such as tribological applications. Conventionally manufactured parts still lack effectiveness in fulfilling their requirements, thus, development of materials providing better properties become a necessity.

Efforts were made in order to respond to the market demand, using one of the most successful additive manufacturing techniques, viz: selective laser melting (SLM) [1], offering the ability to produce near-net shape parts in a short time reducing and even suppressing the post-processing treatments, thus minimizing production time, costs and stages. Besides its ability to produce highly refined microstructure due to the extremely short solidification time, thus, allowing production of high mechanical properties parts.

Aluminium bronzes SLM manufactured were physically, mechanically and tribologically characterized. Measurements of density using Archimedean method allowed determination of the optimized SLM parameters for this material. Mechanical tests such as hardness and strength measurements were also conducted. It is worth noting that the higher the part density, the better the properties obtained. Microstructure images were obtained using SEM and chemical analysis allowed determination of phases formed during the process. Wear tests and friction measurements provided optimistic outlook reflecting the readiness of our material to be industrially commercialized for the role it was designed for.

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TRIBOCHEMICAL PROPERTIES OF DIALKYL PHOSPHONOACETIC ACID IN ENVIRONMENTALLY ADAPTED BASE FLUID

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KEYWORDS

Lubricant additives, Friction, Wear, Dialkyl phosphonoacetic acid (DAPA)

ABSTRACT

Demands for environmentally adapted lubricants (EAL) have been increasing. Ester base fluids have been applied for EAL during the last few decades because of their good biodegradability. However, the performance of ester base fluids cannot be improved by lubricant additives generally used in mineral base fluids. In our previous study, it was found that dialkyl phosphonoacetic acid (DAPA) shown in Fig.1 provides superior antiwear performance compared to conventional phosphorus compounds in ester fluids [1-2]. In this work, the studies were carried out using four-ball test. X-ray photoelectron spectroscopy (XPS) was used in order to elucidate the action mechanism of DAPA in ester fluids.

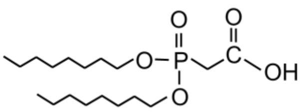

Fig.1 General molecular structure of DAPA

The ester base fluid used in this study is trime-thylpropane trioleate (TMPTO) which is well suited for EAL. Poly-α-olefin (PAO) was also used for comparison. Antiwear properties of DAPA in base fluids obtained from the four-ball tests are illustrated in Fig.2. DAPA in TMPTO improved wear resistance at all tested loads when compared to the base fluid alone. On the other hand, DAPA in PAO reduced wear only at lower load and had no effect at 392 N.

To understand this difference, XPS analyses were conducted. XPS depth profiles of the four elements detected on the worn surface after the four-ball tests at 392 N are shown in Fig. 3. The worn surface with DAPA in TMPTO has a higher relative concentration of oxygen (O1s) and phosphorus (P2p) than that in PAO after sputtering for 60 minutes. This result indicates that DAPA in TMPTO can form a thick tribofilm effectively at high load, therefore DAPA in TMPTO would show superior antiwear properties compared to DAPA in PAO.

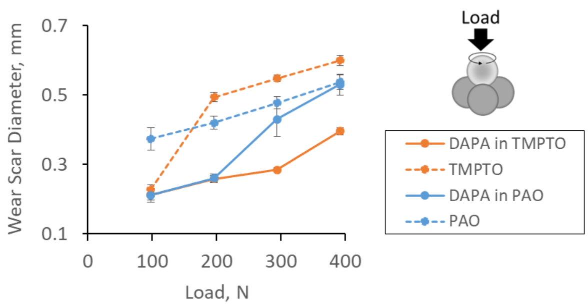

Fig.2 Effect of DAPA in base fluids on four-ball tests

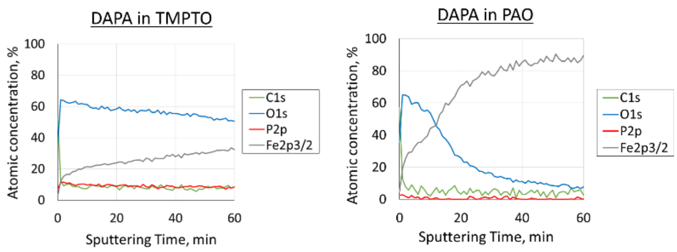

Fig.3 XPS profiles obtained on surfaces after four-ball tests at 392N with DAPA in TMPTO and PAO
(Ar+ ion sputtering condition: 250V 2×2 mm^2)

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SIGNIFICANCE OF THIRD BODY RHEOLOGY ON FRICTION DURING DRY SLIDING WEAR: MULTIBODY MESHFREE MODELLING

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KEYWORDS

Rheology; Friction; Modelling in tribology; Fretting

ABSTRACT

The third body approach, was first introduced to dry sliding by M. Godet in 1980s, brought tribology from volume to interfaces [1]. It focuses on the role of third bodies, whose chemical/phase composition, morphology, and rheology are critical when interpreting friction and wear of a material. In metal tribology of dry sliding wear, detached metallic particles often exhibit high adhesion and undergo severe plastic deformation, agglomeration, etc., resulting in large fluctuation in friction and usually high friction; while highly oxidized particles that present low adhesion yield smooth accommodation of the velocity difference between two first bodies, leading to stable and low friction [2]. In the present study, using multibody meshfree modelling [3], we report influence of surface property, specifically adhesion and shear strength, of third body particles on third body rheology, and eventually on friction.

In the model, third body particles in the contact was described as a mix of spheres and ellipsoids were defined, and the ellipsoids held sizes that was twice as large as the spheres whose diameter ranged 0.3-0.5 µm. Normal pressure and sliding velocity were set at 1 GPa and 100 m/s, respectively, and applied onto the upper first body. The surface property of third body particles when they are in contact was defined by adhesion strength and shear strength; by varying them from 0 GPa to 20 GPa, their influence on third body rheology was examined.

As shown in Fig. 1, the average friction increased linearly at low contact strength, achieved the peak value at 2 and 3 GPa, then started decreasing slightly with increasing contact strength. The friction behaviour with contact strength can therefore be divided into two zones: low friction zone (before the peak) and high friction zone (after the peak). According to third body rheology, in the low friction zone, due to low contact strength between particles, the velocity difference was accommodated smoothly through some easy-shear path; yet in the high friction zone, the high friction and their large fluctuation was driven by frequently formation and breakdown of large agglomerates and this phenomenon became more and more significant with increasing contact strength (see standard deviation in Fig. 1). The results were also discussed in detail by measuring the activated third body thickness, which was the thickness of third bodies that carry the velocity gradient between two first bodies.

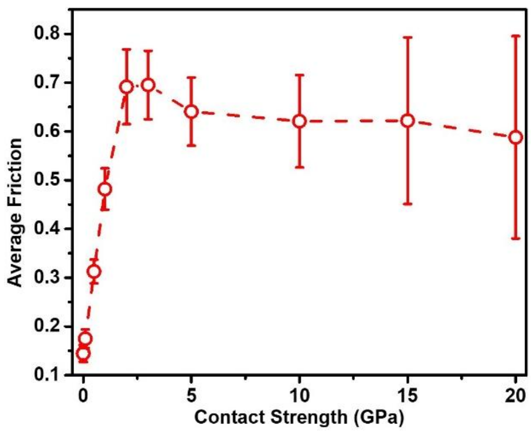

Fig.1 Average friction vs. contact strength

ACKNOWLEDGMENTS

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Microstructure, nano-mechanical characterization and fretting wear behavior of plasma surface Cr-Nb alloying on γ-TiAl

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KEYWORDS

Coating; Wear; Fretting; Double glow plasma surface metallurgy technology

ABSTRACT

The dovetail and groove connection of a turbine blade and rotor which are made from the TiAl intermetallic compound are exposed to damage by fretting wear. A surface strengthening process: Cr-Nb plasma surface alloying was implemented on the TiAl alloy to improve its anti-fretting wear performance based on double glow plasma surface metallurgy technology [1]. A Cr-Nb coating (Cr:Nb=1:4 wt%) was prepared in the process, which consisted of a deposited layer and diffusion layer. The surface morphologies, microstructure, phase composition and nano-hardness were analyzed in details. The fretting wear behaviors of the TiAl substrate before and after plasma surface alloying were comparatively analyzed under different number of cycles. The results showed that: 1). The Cr-Nb coating deposited on TiAl substrate is dense and homogeneous without defects. The thickness of deposited layer and diffusion layer were 16μm and 2μm, respectively. 2). The Cr-Nb coating consist of Cr_2Nb and Nb, which contribute to the high hardness. 3). The nanohardness of TiAl substrate increased from 5.65 to 11.61GPa and the elasticity modulus increased from 167.75 to 194.12 GPa after plasma surface alloying. The H/E and H^3/E^2 ratios of Cr-Nb coating were 1.77 and 6.48 times of TiAl substrate, respectively. 4). Coefficient of friction remains at stable level over tested number of cycles: 2500, 5000, 7500 and 10000 and for the Cr-Nb coating it was 0.8, which was slightly lower than that of the 0.9 for uncoated TiAl substrate. The fretting wear depth of the Cr-Nb coating was significantly lower than that of the substrate over a range of tests with different number of cycles. And the Cr-Nb coating did not show any obvious signs of wear or delamination before 5000 cycle. The adhesion and abrasive type of wear were found on both the TiAl substrate and the Cr-Nb coating. 5). The results indicate that Cr-Nb plasma surface alloying based on double glow plasma surface metallurgy technology is a feasible and effective method to improve the fretting wear resistance of TiAl alloy.

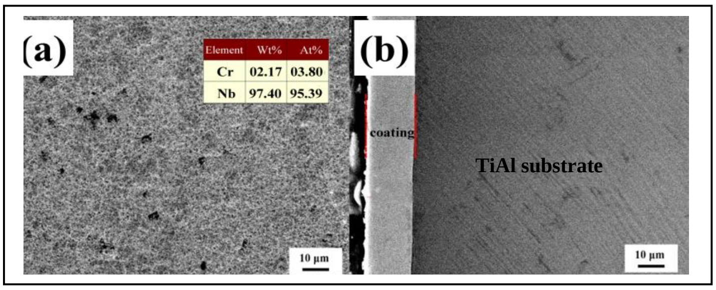

Fig.1 SEM of Cr-Nb coating on TiAl substrate : a) surface view and b) cross-section view.

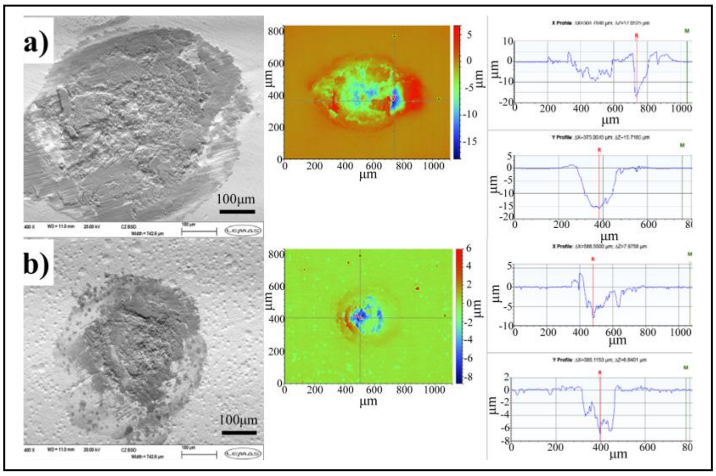

Fig.2 Surface morphologies and profile curves of wear scars after 5000 cycle a) TiAl substrate b) substrate with Cr-Nb coating.

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INFLUENCE OF HUMIDITY AND SULFUROUS GASES (H_2S, SO_2) ON FRETTING WEAR BEHAVIOR OF SILVER-PLATED ELECTRICAL CONTACTS

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KEYWORDS

Fretting; Wear; Tribolfilms and 3rd bodies; Sulfurous gases

ABSTRACT

Electrical connectors need to keep a low and stable electrical contact resistance (ECR) to avoid micro-interruptions of signal. Due to their working environment (car engine), they are subjected to vibrations inducing fretting in the contact. This phenomenon induces wear and the formation of oxide debris layer in the contact increasing the electrical resistance. The aim of this work is to study the effects of pollutant sulfurous gases present in the exhaust gas: sulfur dioxide SO_2 and hydrogen sulfide H_2S, versus the relative humidity rate, on silver plated electrical contacts.

A previous study [1] shows that the relative humidity tends to increase the ECR endurance (i.e. Nc when $\Delta R > 4m\Omega$) (Fig.1). Above RH=50% the humidity modifies the rheological properties of the debris layer so that the wear rate is highly decreased leading to a linear increase of Nc.

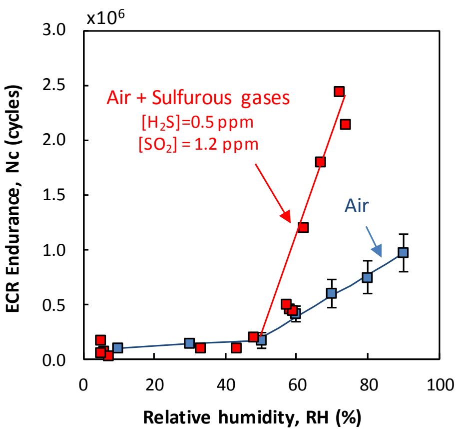

Fig. 1 : Evolution of the ECR endurance versus RH in air and in the presence of sulfurous gases.

The present investigation suggests that H_2S and SO_2 combined with humidity extends again the ECR endurance by a factor 3 (Fig.1). This was explained by a lubrication phenomenon of the interface due to the formation of silver sulfide Ag_2S when RH > 50% (Fig. 3) and leads to a reduction of the coefficient of friction (Fig.2). Such lower friction response reduces the adhesive wear and promotes longer endurances.

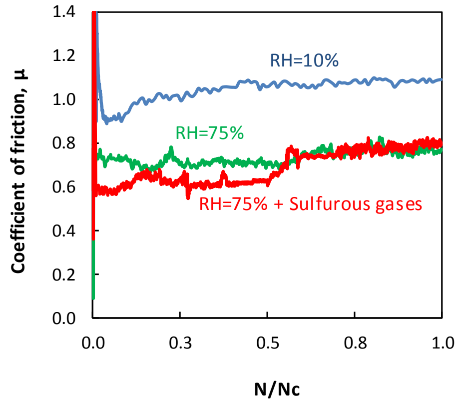

Fig. 2 : Coefficient of friction (µ=Q*/P) vs a normalized scale N/Nc.

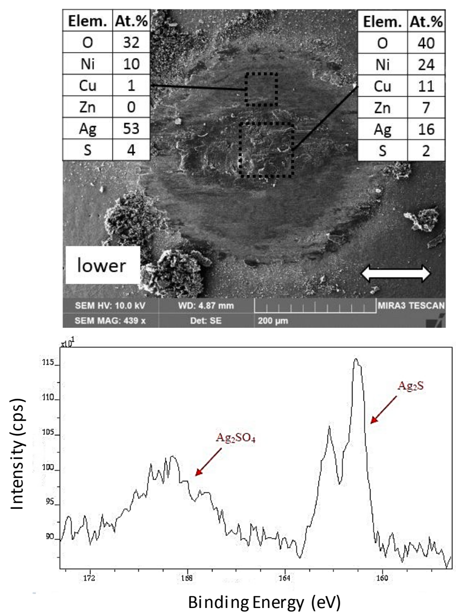

Figure 3 : SEM observations and EDX and XPS analyses of the fretting scar at Nc/2 for RH=75% with sulfurous gases ($[H_2S]$ =0.5ppm, $[SO_2]$ =1.2ppm)

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DEFORMATION OF PEARLITIC STEELS DURING NANOTRIBOLOGY

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KEYWORDS
Wear; Nanotribology; Experiments in tribology; Pearlitic steels;

ABSTRACT

Pearlite is a microstructure which can enhance the strength of steel while preserving its ductility. Therefore it is commonly used as structural material for many engineering applications. One of the challenges of nanotribology is to investigate their microstructure evolution during microasperity wear, which would be the basis of fundamental analysis of tribological behavior of pearlite on the macroscale.

Plasticity of pearlite is claimed to be one of the crucial factors in the formation process of the white etching layer (WEL) on the rail tracks [1, 2]. In the previous work, the occurrence of extensive plastic deformation in hypereutectic pearlite below the wear track was shown. The wear mechanisms of brittle cementite lamellae included bending, winding, shearing and fracture and were accompanied by ferrite grain refinement as well as pile up around the wear track edges.

In the current study, we focus upon the microstructure evolution of pearlite as well as cementite plasticity and its dissolution under a tribological load. For this purpose, indentation and single-pass scratching tests were performed both on the samples of hypereutectic pearlite and pure cementite.

After testing, scanning electron microscope (SEM) with energy dispersive x-ray spectroscopy (EDX) and X-ray diffraction analysis (XRD) were used to analyze samples structurally and chemically both inside and outside of the wear tracks. As the result, the effects of initial microstructure, phase composition, and normal forces were taken into account while investigating the wear mechanisms of pearlite and cementite at the microscale.

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FRETTING WEAR RATE EVOLUTION OF A FLAT-ON-FLAT LOW ALLOYED STEEL CONTACT: A WEIGHTED FRICTION ENERGY FORMULATION

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KEYWORDS

Fretting; wear; third bodies; flat-on-flat contact

ABSTRACT

Fretting wear resulting from micro-displacement oscillatory movements is a serious problem for many industrial applications. It is accompanied by remarkable surface degradation which has adverse consequences on the durability of contact assemblies. Real contact configurations of industrial components are very complicated and practically difficult to reproduce at laboratory scale. As a result, simple non conformal configurations including sphere-on-flat and cylinder-on-flat are usually investigated. Yet, few are the researches that examined fretting wear using flat-on-flat geometry due to its high sensitivity to alignment issues although it allows the analysis of quasi-constant pressure condition. Hence, the objective of the current study is to broadly investigate fretting wear of flat-on-flat contact by applying wide range of loading conditions. This work aims also at predicting wear kinetics by using an extended form of friction energy approach that takes into account the influence of the loading parameters.

Fretting wear rate evolution of a steel alloy (35NCD16) in dry flat-on-flat configuration is probed extensively by varying several parameters including test duration, contact pressure, sliding amplitude, and frequency. Wear kinetics is assessed by the energy wear rate (α) which is estimated using friction energy wear approach by computing the ratio of the wear volume (V) to the cumulated dissipated friction energy ($\sum Ed$). Post-mortem analysis (SEM, EDS) is done to follow surface damage evolution.

Numerical simulations of flat-on-flat geometry reveal a homogeneous mean pressure profiles after a fast honing of the contact borders induced by fretting wear process. Results of the parametric experimental study showed that wear rate depends on the contact pressure, sliding amplitude and frequency. Two main phenomena significantly control the observed wear kinetics, namely contact oxygenation [1] and third body flows [2]. Depending on the loading conditions and the surface exposure to oxygen, adhesive or abrasive wear processes are activated. In the condition where oxygen concentration is high, abrasive wear dominates inducing high wear rate. This is not the case when interfacial oxygen concentration is low where adhesive wear is favored causing lower wear rates. Besides, the rate of creation and ejection of third bodies affects wear rate which is higher in the condition where debris ejection is larger revealing a protective role of the third bodies.

By compiling all the loading conditions, a weighted energy wear formulation is introduced. Using a very basic power law approach (Fig. 1), a reliable prediction of wear volume is obtained.

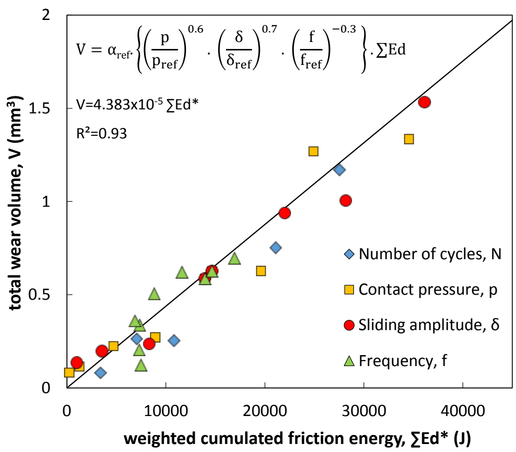

Fig.1: wear volume evolution versus weighted cumulated dissipated friction energy

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EVALUATION OF HISTORY OF STRESS CHANGE IN GEAR SUBSURFACE DURING RUNNING-IN BY MIXED LUBRICATION ANALYSIS

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KEYWORDS
Keyword - Rolling contact fatigue; Mixed Lubrication; Wear, Running-in

ABSTRACT
Gears used in construction machines have potential to cause pitting fatigue and improvement of their fatigue strength is required. The final goal of this research is to improve the strength by finding better running-in condition. In this study, stress distribution in subsurface of twin-disk test specimens with various surface roughness were obtained by mixed lubrication analysis method.

Methods of mixed lubrication analysis considering asperity contact was used by Jiang et al. [1], Evans et al. [2] and other authors, that combines EHL analysis by Reynolds equation and asperity contact analysis by discretized Fast Fourier Transform. In this research, we also analyzed using this method. The Reynolds equation was discretized using a finite difference method and implemented. Stationary analysis was conducted on the cylinder contact problem assuming a two-cylinder test that frequently used for testing gear materials.

Figure 1 shows the analysis result of the von Mises stress distribution in subsurface in the roughness condition of the two-cylinder test piece before operation. In the Hertzian contact problem assuming a smooth surface, the maximum stress is generated at a position about 100 μm from the surface, whereas in the present analysis considering the protruding contact, it is found that the stress distribution has a high stress at a depth of about several μm. The observation result by Mallipeddi et al. [3] that the influence due to running-in is a depth of about 10 μm under surface coincides with high stress regions of the analysis result, and strongly suggests the necessity of considering asperity contact to evaluate the running-in process. Moreover, the order of depth is comparable to that of wear depth, thus it is also important to investigate whether highly stressed region in running-in remains after the process or removed due to wear.

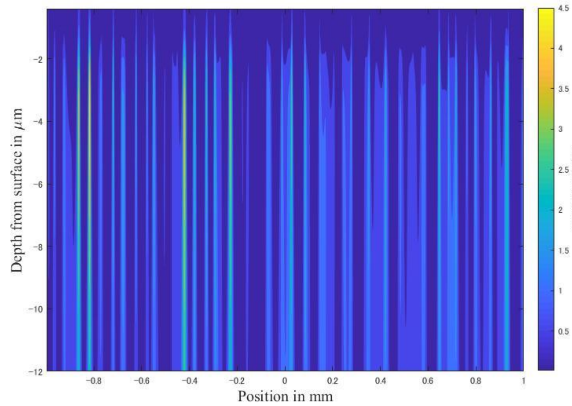

Fig. 1 von Mises stress distribution in subsurface of a twin-disk test specimen with high-roughness condition before running-in process.

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DEVELOPMENT OF ON-MACHINE INSPECTION SYSTEM FOR TWIN DISC TEST

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KEYWORDS
Rolling contact fatigue; On-Machine inspection

ABSTRACT

Pitting fatigue occurs on the tooth surface of gears operating with high surface pressure. Twin disc test is widely used for Pitting fatigue strength and characteristics. The test simulates the rolling-sliding contact condition of gears by rotating and contacting small and large discs under high contact condition with different circumferential speeds. In order to study the pitting fatigue strength and characteristics in details, microscopic surface observation of the disc during the test is important. In most conventional tests, small disc is removed from the testing machine and the surface is observed by microscope. However, the contact position between two discs may change when reinstalling the small disc to the two disc fatigue test machine. Thus, the on-machine inspection system that can observe small roller surface without removing it from the machine is required. In this study, we developed on-machine inspection system for this purpose. The on-machine inspection system consists of a digital microscope for surface observation, a stepping motor for shaft rotation and positioning, and a proximity sensor indicating the origin of the disc was developed. By controlling these on the LabVIEW 2018, it is possible to observe entire circumference microscopic images on the small roller surface by connecting the small images observed on various positions on the small disc.

Figure 1 shows the state of pitting fatigue evolution obtained by developed on-machine inspection system. In this case, micro cracks of several tens of μm in length occurred locally in various places on a small roller surface at 3.0×10^6 cycles. At 5.0×10^6 cycles, micro-pitting with a width of about 0.8 mm was observed from the region where micro-cracks locally occur. In addition, micro cracks of about 0.2 mm were generated at both ends of micro pitching, and the test was continued to observe this progress. The crack developed further and similar micro-pitting occurred in other places at 5.5×10^6 cycles. Ultimately, micro-pitting coalescence was observed at 6.0×10^6 cycles to form one large pitching.

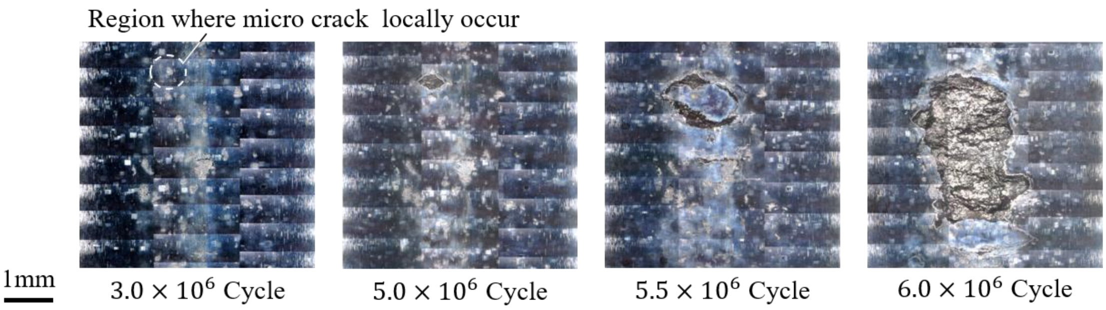

Fig.1 Progress of pitting fatigue

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DESIGN OF THE OPTICAL SENSING COATING FOR IN-SITU WEAR MEASUREMENT

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ABSTRACT
The main driving force for developing in-situ wear monitoring coating system is to reduce the degree of over-engineering and pre-mature replacement of key components in high-end equipment since the coating system could provide an indication of service life and sufficient warning before failure. Wear detection also provides valuable insight on wear mechanisms of coatings, which can lead to new coating and lubricant designs. In this work, we aim to develop a coating system with optical sensing capability for in-situ wear measurement. The coatings with different optical properties were synthesized by combing Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD). The relationship between optical properties and Raman signals was also established which provides insight on designing the optical sensing coatings for in-situ wear measurement.

KEYWORDS
Coating; Wear; Solid lubrication; Sensing film

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Effect of lubrication on electrical performance of Au plated contacts subjected to fretting wear

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KEYWORDS

Wear; Fretting; Fluid lubrication; Electrical contact

ABSTRACT

Modern automotive and aviation industries require an intensive use of electrical connectors for transmitting direct current (DC) and radiofrequency (RF) signals. These connectors can be exposed to severe environmental vibrations inducing fretting wear damages. Wear debris and related formation of an oxide debris layer promotes an increase of the electrical contact resistance (ECR) and RF signal attenuation, *i.e* insertion loss (IL) until electrical failure [1]. To increase the lifetime of connectors, lubrication can offer a viable solution as it reduces friction coefficient and wear rate. Recent research studies have demonstrated the benefits of grease lubrication on DC endurance of Sn and Ag coated electrical contacts [2-3], though the effect and the potential benefits of lubrication in RF domain are still open questions.

The aim of this work is to study the effect of grease lubrication on DC and RF electrical endurance of Au coated electrical contacts. A dedicated workbench was developed to study a double sphere/plane contact under fretting solicitations in dry and lubricated conditions. To characterize the evolution of DC ECR, a common 4-wire sensing method was adopted. In addition, a vector network analyzer (VNA) was used to inject a high frequency signal through the device and to measure the insertion loss (IL) at 2.4 GHz.

Endurance test were performed to estimate the antiwear and antifriction properties of grease and their effects on DC and RF endurance of the contact. The test conditions were the following: a normal load of $F_n = 1.5$ N per contact (i.e total normal load $P=2\times F_n=3$N) and a cyclic displacement of $\delta=\pm 40$ µm at a frequency $f = 33$ Hz were applied for a number of fretting cycles $N=2\times 10^6$ cycles in dry conditions and $N=10^7$ cycles in lubricated conditions. Three different greases were tested: a high-temperature multi-purpose grease (G1), a conductive rolling bearing grease (G2) and a carbon conductive grease (G3). Displacement and frequency of the test were chosen to ensure hydrodynamic lubrication condition.

To compare the performance of grease, the DC contact endurance N_c is determined thanks to the following failure criterion: for each fretting cycle greater than N_c, the contact is assumed to be faulty if $\Delta R>0.1\Omega$ where $\Delta R=R-R_0$ with R_0 the initial resistance of the contact. This threshold corresponds to a drastic change in RF domain. Below $\Delta R<0.1\Omega$, IL is rather constant. Above $\Delta R>0.1\Omega$ IL shows a slight rise with sharp fluctuations. Figure illustrates the evolution of ΔR and IL obtained in dry conditions.

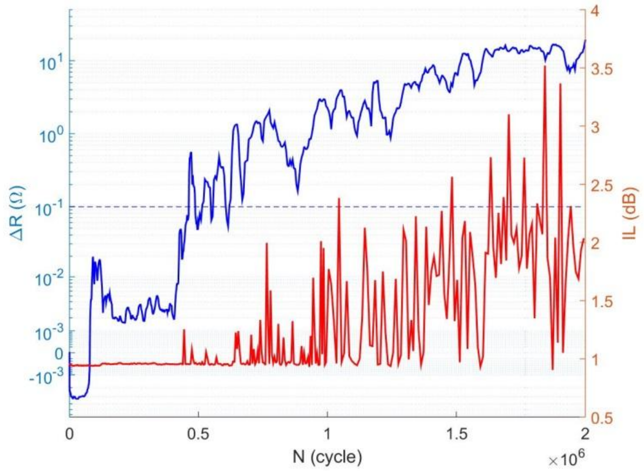

Figure 1: Evolution of ΔR and IL versus fretting cycle in dry conditions

The strong correlation between ΔR and IL is also observable in lubricated conditions. Grease lubrication permits to significantly increase contact performance in DC domain as contact lifetime N_c is extended at least 9 times compare to the dry conditions. In RF domain, grease lubrication permits to maintain stable insertion loss. However, the choice of lubricant is crucial since undamaged dry contacts could exhibit better RF performance. Additional tribo-chemical analysis of the fretted zone and resistivity measurement within the fretting scars performed after endurance tests emphasized the protective effect of the grease against wear and oxidation.

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EXPERIMENTAL AND NUMERICAL INVESTIGATION ON THE WEAR OF MICROSTRUCTURE OF DIAMOND IMPREGNATED TOOLS FOR CUTTING CONCRETE

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KEYWORDS

Rheology; Wear; Modelling in tribology; Diamond tools

ABSTRACT

Metal bonded tools include circular and frame sawblades, wire saws and core drill used in stone cutting and construction industries, road repair, petroleum exploration and mining, etc. … All of them are composed by abrasive segments fixed to a steel support by brazing or welding [1]. Segments consist in diamonds retained by a metallic matrix. Diamonds constitute the cutting edges and are able to indent and cut the stone. This process generates a debris flow of the cut material which is abrasive for the matrix and is in turn able to abrade it. To optimize the tool life and guarantee efficiency in the process, the matrix wear has to be adjusted to the wear speed of diamonds [2].

The wear of the matrix is the result of a complex tribological behavior affected by several factors at different scales; therefore, a numerical multiscale approach is necessary.

The role of microstructure properties (porosity, grains size, bulk properties and composition of metallic powder) is investigated by experimental and numerical tools.

An innovative multibody meshfree technique coupled with a Discrete Element Method (DEM) approach is used to study wear and damage at the microscopic scale [3]. This method allows to control both microstructure and debris properties (shape and size distribution). The intergranular fracture is modelled as a phenomenon of progressive separation at grain boundaries by a traction-separation law. The response of the metal bond is written in terms of local wear law and material loss from the surface and then is compared with micro-scratch test and erosive tests respectively. At the scale of debris flow, the rheology of that slurry is studied to obtain an empirical constitutive law. This model is validated with results obtained by rheometer.

Both rheology and wear law are implemented in the macroscopic model. Here the matrix wear is studied at the scale of diamond.

This model is qualitatively validated with observations made by

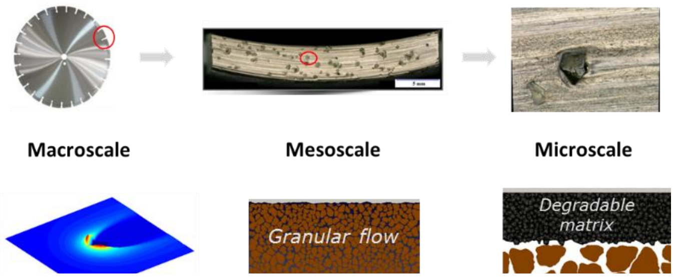

Fig. 1 The multiscale approach in modelling

optical microscope and quantitatively in terms of protrusion and clearance wear rate.

Table 1 Size of main features

Material	Main size
Diamonds	40/50 mesh (300-375 µm)
Debris	1 -100 µm
Matrix grains	1-2.5 µm

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GREASE LUBRICATION IN AERONAUTICAL HEAVILY CHARGED OSCILLATING BEARINGS

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KEYWORDS
Rolling contact fatigue; Grease lubrication; Wear; High contact load.

ABSTRACT

The worldwide emission reduction policy imposes industries to overcome system efficiency to reduce both power consumption and maintenance operations and costs. Extreme operating conditions, imposed in aeronautical application, push researches to the understanding of the accommodation mechanisms, accounting for both mechanical and physiochemical interactions, to enhance performances.
Within this framework, high-loaded oscillating bearings are here investigated. Such extreme working conditions are encountered in special applications as aeronautics (ailerons, flaps, actuators, etc.), manufacturing (repetitive robot motions), space engineering, etc. In all those systems, while the oscillating motion imposes a starved lubrication regime, loads to transmit can be very high, inducing high contact pressures.
Preliminary researches have given a reconstruction of the bearing life evolution and comprehension of the contact morphological evolutions [1]. Coupled with finite element simulations, which provided information on surface and subsurface contact stress distributions [2], a degradation scenario has been identified, for the investigated high loaded oscillating bearings [1, 3].
Results have proved that the grease response and its interaction with the bearing components is a key point to preserve the bearing integrity and to improve their performances [1, 3], although the lubrication regime is starved [4].
In the present analysis, the role of the grease in affecting the accommodation mechanisms is focused, accounting for several different parameters such as the grease composition and the geometry of the contact. While different commercial greases will be tested to investigate the effect in modifying the physiochemical evolution of the contact, the modification of the bearing geometry will allow for investigating the effect of a different contact and stress distribution.
To fulfill those comprehension, endurance tests on a laboratory test bench are accompanied by both topological and chemical analyses of the interacting surfaces, in order to investigate the evolution of the greased interface along all the life of the bearing, under high loaded oscillating movement.

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THE STUDY OF THE QUANTITATIVE RELATIONSHIPS BETWEEN TRIBOCHEMISTRY AND WEAR OF THE FULLY FORMULATED OIL

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KEYWORDS

Lubricant Additives; Wear; Tribofilm and 3rd bodies.

ABSTRACT

The background of this work is based on the swash-plate type piston pump used in the hydraulic systems. Due to the existence of the swash-plate tilting angle during operation, a portion of the piston/cylinder interfaces will be a lack of lubrication, resulting in wear and even failure. In order to extend the lifetime of the hydraulic pump, the understanding of the antiwear property of the lubricant is of importance.

In response to the above problem, many researchers have conducted a lot of experimental studies on antiwear-additives such as zinc dialkyldithiophosphate (ZDDP) under different test conditions [1]. The antiwear tribofilm formed by ZDDP can effectively reduce the wear on the steel surfaces. There are also many researchers who studied the tribochemistry models of ZDDP by using the Arrhenius equation and have made good progress [2]. However, the previous experimental results showed that the tribofilm formation and anti-wear performance of ZDDP will be influenced by other additives, especially detergents which can also form the tribofilm on the surface [3]. Thus, when ZDDP and detergents are present at the same time, the competitive effects on the surface will affect the antiwear performance of ZDDP. In addition, the previous tribochemistry and wear model based on the tribofilm of ZDDP cannot be applicable to the lubricant containing detergents. In the hydraulic pump, the lubricant used is the fully formulated oil (FFO) containing ZDDP, detergents and dispersants so it is important to study the quantitative relationship between tribochemistry and wear mechanism of FFO, which is significant for predicting wear and failure in applications. Therefore, this work attempts to explore and further summaries the quantitative relationships between tribochemistry and wear, based on the experimental studies of how each additive in FFO influences the tribofilm and wear.

The lubricants involved in the experiments, besides of FFO, are the base oil with ZDDP or detergents respectively as the same mass concentration as that in FFO. The tribo-tests were conducted on the steel surfaces by the Mini Traction Machine (MTM) which can measure the in-situ tribofilm thickness through the 3D Spacer Layer Imaging method (SLIM). Then, the White Light Interferometry was used to measure the amount of wear after removing the tribofilm. Energy-dispersive X-ray spectroscopy (EDX) and Secondary ion mass spectrometry (SIMS) are used to analyse the chemical compositions of the tribofilm to understand how each additive works on the surface.

The results obtained from experiments show that the tribofilm growth process of FFO has a similar trend as ZDDP under different temperatures, that is, the tribofilm thickness increases with temperatures. However, the wear curve (vs time) shows a linear trend with a very short running-in period at moderate temperatures. This may result from the faster formation of the tribofilm, compared with ZDDP, due to the presence of detergents. After FFO forms a stable tribofilm, when it was replaced by base oil with ZDDP only to continue the test, the amount of wear was no longer increased. Further EDX analysis showed that the contents of Ca and S in the FFO-tribofilm are higher than the contents of P and Zn which are the main elements of the ZDDP-tribofilm in the oil-change test. It indicates that the FFO-tribofilm has different wear characteristics and chemical compositions.

The highlights of this work are 1) the quantitative study of in-situ tribofilm formation of the FFO and the corresponding wear evolution at different time periods and 2) the qualitative analysis of the reasons of the different wear characteristics of the FFO. The quantitative relationships provide not only the reference data for the application of the FFO in the hydraulic pump but also the guidance for the study of the tribochemistry model and wear prediction of FFO in the future.

ACKNOWLEDGMENTS

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46th Leeds-Lyon Symposium on Tribology - September 2-4, 2019, Lyon, France

MULTIBODY MESHFREE MODEL WITH THERMAL MODEL AND ADAPTIVE MASS SCALING FOR SIMULATION OF FRETTING CONTACT

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KEYWORDS

Fretting; Modelling in tribology; Tribofilms and 3rd bodies, Granular Materials.

ABSTRACT

In this study, a multibody meshfree model with thermal model and adaptive mass scaling is proposed. Simulations of contacts - like fretting - can use this model of granular materials. The implementation is done in an open-source software called MELODY (Multibody ELements-free Open code for DYnamic simulation) developed in LaMCoS [1].

The first objective is to implement in MELODY some mass scaling. Mass scaling allows faster computation by reducing the propagation speed of mechanical waves in some critical nodes. The critical time step is proportional to:

$$\Delta t \propto \sqrt{\frac{m}{k}}\Delta x$$

With k the stiffness between two nodes, m mass of the node (in deformable models) and Δx the average length between two nodes. If the mass of all nodes is bigger, the time step can be larger and simulation is faster. This is global mass scaling. However, this global mass scaling modifies the physical behavior of particles. A better way to speed up simulations is to add mass only on nodes that slow down the simulation. If we add some mass on these nodes, the error is reduced. It allows us to use a larger time step.

The main difficulty of the implementation of mass scaling in MELODY is that this software uses an adaptive time step, which can lead to a competition between the adaptive time step and the mass scaling. Like the time step, the mass scaling is proportional to normalized error of each nodes. Multiple tests are done to determine the best parameters of mass scaling leading to the largest time step, without losing accuracy of simulation.

The second objective is to add in MELODY a thermal model. The friction between particles themselves and with boundaries produces shearing, then heat. This heat generates an increase of the temperature, which can lead to a modification of properties of materials.

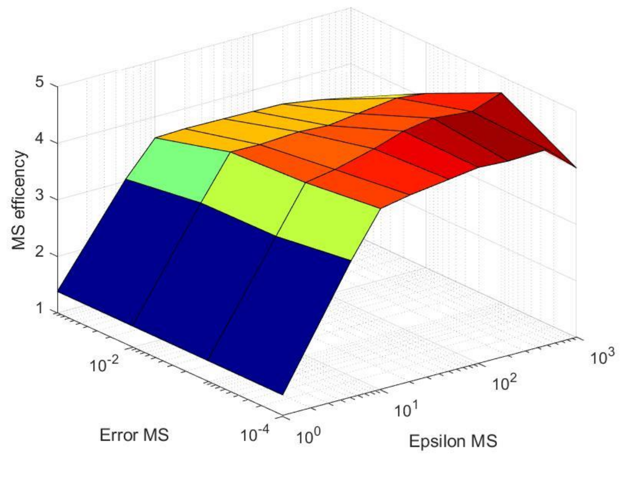

Figure 1: Example of couple of parameters tested for mass-scaling

The strategy for implementing this thermal model follows 4 steps:

1. Creation of heat by dissipation of the mechanical energy
2. Propagation of heat in bodies by thermal conduction and creation of boundary conditions
3. Validation of model on simple cases
4. Updating of temperature-dependent mechanicals properties of the materials

This improved model is applied to the study of wear in mechanical parts subjected to fretting.

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Understanding the coated abrasive/work piece interactions & developing strategies to control metal capping

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1. Introduction

Due to the nature of metal grinding, coated abrasives have a very short life span. Several factors contribute to the efficiency of the abrasive including: grain fracture, grain removal, blunting of grains, clogging and metal capping (1). Metal capping is the process of the workpiece material adhering to the surface of the grain during the grinding process (2). Due to the adhesion between the work piece material and the grain a new interface of metal against metal is created and as a result the rate of metal cutting is severely diminished. To ensure that the lifetime of coated abrasives is extended as much as possible it is important to understand the mechanism by which cutting rates are reduced.

To investigate this process a series of experiments have been developed, looking into the life cycle of coated abrasives. These experiments will show how discrete areas of metal transfer occur and they extend to fully encompass the grain. This reduces the efficiency of the grain to cut the metal. The grain becomes invisible during TEM (Transmission Electron Microscope), SEM (scanning Electron microscope) and EDX (Energy Dispersive X-rays) analysis carried out to understand the material transfer and bonding between the alumina and stainless steel.

2. Methodology

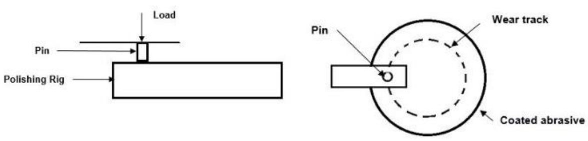
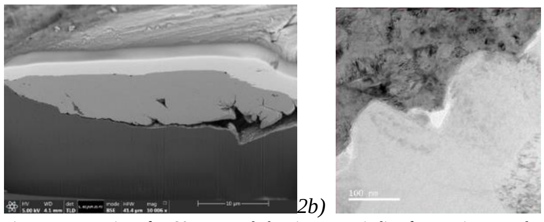


Figure 1: Schematic drawing of experimental apparatus.

Figure 1 shows the experimental schematic used to replicate grinding within the lab. A single speed polishing rig of 250 RPM used to rotate the coated abrasive. The work piece material in in contact with the abrasive by applying a dead weight as shown on the figure.

For the experimental testing, a 1 kg weight was chosen as the load against F980 36 Norton blaze coated abrasives. The work piece material, of a 6 mm diameter 304L stainless steel pin was chosen due to its known high metal capping tendencies. Grinding experiments from 30 seconds to 15 minutes were conducted in an attempt to understand how the abrasive deteriorates over time and the amount of metal capping observed during the efficient life cycle of the abrasive.

3. Results



2a) 2b)

Figure 2a) FIB cross section of F980 36 coated abrasive post grinding for 15 minutes under a 1 Kg load – Scale 10 um, 2b) HADDAF TEM image of the Abrasive grain Stainless steel metal cap post grinding for 15 minutes under a 1 Kg load – Scale 100 nm

Figure 2a) shows an example cross section of a metal capped alumina grain. As can be seen, a thick layer of stainless steel has built up on the surface of the grain. Gap between the grain and the adhered metal cap have shown capping of grain to be in localized areas on the grain rather than constant throughout as initially thought. This gap indicates a potentially week bond between the alumina grain the stainless steel metal cap.

Figure 2b) shows at high magnification, the high conformation of the stainless steel to the alumina grain. This high conformity indicates the mechanical interlocking of the metal cap to the abrasive grain beneath.

4. Discussion

Results show the bonding of metal cap is caused by the mechanical interlocking to the rough surface of the abrasive grain. Within the contact due to the continuous abrasion of the workpiece, the temperature increase is significantly larger in comparison to the abrasive grain. This temperature increase is enough to liquefy the workpiece hence results in the high conformity observed in figure 2b). As individual grains are in contact with the work piece for fractions of a second at a time, the heat increase of the grains is minimal in comparison to the workpiece. Hence this reduces the likelihood of chemical bonding taking place. This paper will detail the current findings regarding the bonding mechanisms metal caps to abrasive grains through added analysis such as EELS (Electron Energy Loss Spectroscopy) and EDX (Energy Dispersive X-Rays)

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A MORPHOLOGICAL STUDY OF RESTORATION OF DAMAGED HAIR FIBER WITH CHEMICAL TREATEMENTS USING MICROSCOPY TECHNIQUES

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KEYWORDS

biotribology; wear; surface topography; hair fiber.

ABSTRACT

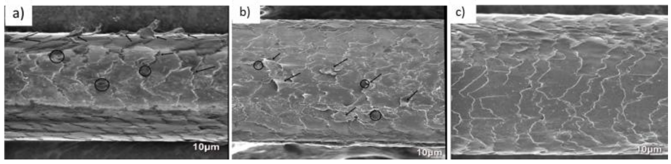
People seeking hair chemical treatments, such as dyes and relaxers, include beauty for many reasons including beauty and social acceptability. However, these treatments are responsable to cause damage to hair fiber that can be related to protein loss [1]. As the cuticle is the most external layer of human hair, it is more susceptible to chemical and environmental damages. They provide chemically resistant protection to internal hair componentes, such as the cortex and de medula [2].

Concerning the changes in hair morphology and structure due to the restoration of hair fiber with cosmetic, only a few studies are addressing this topic. In the present work, the three approaches were used to investigate the damage ans restoration on the morphology of hair cuticles: AFM, SEM and Raman spectroscopies techniques.

For this study, it was select a virgin hair in good condition of a healthy 26-year-old female. She had not used hair care products excessively nor experienced any chemical treatments likely to induce hair injury. This hair was submitted to straightening or dyeing processes. After this, they were treated with two different cosmetics (in chemical composition) indicated to restore damage hair fiber. The first product has in its composition arginine, cysteine and Keratin, and it has low cost, and the second has coconut oil and glycerol in its composition, and it has a high price. All hair samples were characterized by X-ray diffraction, SEM, AFM and Raman spectroscopy before and after the restoration treatment.

This research demonstrated, through vibrational spectroscopy, an absolute difference between virgin and chemically treated hair. After the treatments, it was possible to observe that several important bonds were modified, such as the S-S, SO_3, C-H, C = O bonds as well as the secondary structures of proteins that changed their conformations. The results demonstrate that the chemical processes modified the conformational structure of keratin and damaged the hair fiber, altering the its structure. Although such products are intended to change the structure and appearance of the hair positively, they result in some undesirable damage (Fig. 1a). Vibrational spectroscopy together with scanning electron microscopy was useful tools for the analysis of the level of hair fiber wear. It is inferred that the electron microscopy confirmed that the chemical treatment that stood out in the performed analyzes is the professional product more specifically in the process of more significant degradation of the fiber that was the dyeing followed by straightening (Fig.1). The results demonstrated that the high cost treatment caused a different restoration in hair fiber surface.

Fig.1 Hair fiber morphology: a) after dyeing and straightening treatments; b) treated with low cost product, and c) treated with high cost product.



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AN EXPERIMENTAL APPROACH TO EVALUATION WIND BLADE DEGRADATION IN MARINE ENVIRONMENT

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KEYWORDS

Friction; wear: experiments in tribology; wind blade

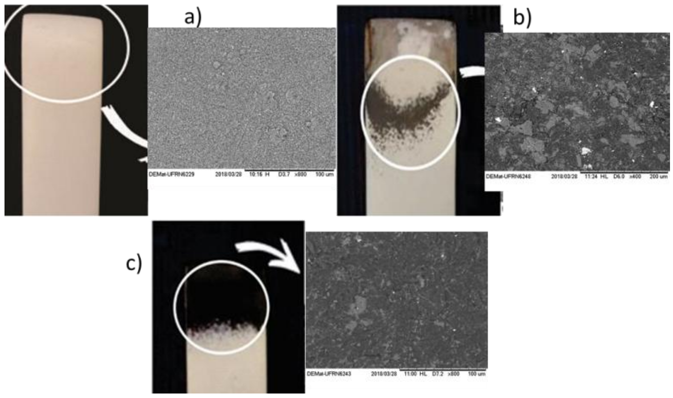
ABSTRACT

The wind energy has fast grown in the world, as a good option of the clean and renewable energy source. In December of 2018, the Brazilian installed generation capacity was 162.5 GW, around 8% of electricity matrix [1]. For 2022, the estimated growth for the Brazil wind industry figures to reach 840 GW; nowadays Brazil l is the eighth largest generator of wind energy in the world. Composites materials, such as fiber reinforced plastic and glass fiber reinforced plastic, have been used to manufacture wind blade, because of its low weight. However, these materials are exposed to hostile environment conditions, such as rain, icing, lightning, etc., that can provoke many damages [2,3]. Thus, to understand the action of environment conditions on wind blade materials is essential to estimate its life and avoid failure and accidents. In this sense, this work aimed to develop an experimental approach to evaluate the marine environment conditions on the surface of wind blades.

The methodology consisted of simulating the marine environment in a wind tunnel. Salt and sand particles, together and separately, were added to the air in order to verify their effect on blade wear. For the tests, we manufactured samples with a section according to were used specimens based on the model of NACA 7715 from glass fiber reforced plastic coating with epoxy paint. The chord is 17 cm, and the height of the blade is 2.5 cm. Also, three attack angles were studied at 0 °, 45 °, and 90 °, and the test time was 12 hours. Before and after the tests all samples were characterized in terms of mass loss, roughness, and morphology, this last by scanning electron microscopy. The air velocity was set up in 20 km/h.

The attack angle was found to be the most critical parameter for initiation blade damage, in the angle of 45 ° was observed higher mass loss, as well as increase the surface roughness. The SEM images (Fig.1) showed the potential failures on the blade surface, the presence of sand and salt in the air accelare the composite failure, such as cratering, pitting, penetration to the substrate, adhesion loss of coatings and delamination of them. The combination of these particulates increase the failures on coating and composite structure. test only air flow

Fig.1 Blade failures after wind tunnel test at 45 °: a) only air flow, b) air flow + sand; and c) air flow + sand + salt



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INFLUENCE OF TANTALUM CARBIDE CONTENT, ANGLE OF IMPINGEMENT AND TEMPERATURE ON EROSIVE WEAR BEHAVIOUR OF SILICON CARBIDE COMPOSITES

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KEYWORDS

Erosion wear, Tribofilms, Third bodies, Experiments in tribology.

ABSTRACT

In present study, dense SiC-(10, 20 or 30 wt%)TaC composites were prepared via spark plasma sintering (SPS). Mixtures of SiC-TaC powders were sintered inside a graphite die-punch system under an axial pressure of 50 MPa at 1800°C for 5 minutes in argon atmosphere. The sintered composites showed almost equi-axed grains for all the composites with a small change in grain size by incorporating TaC in SiC. Further, solid particle erosion test was performed on the spark plasma sintered composites against a stream of SiC particles (45-75 µm size) eroding with an impact velocity of 50 m/s. Mass flow rate of SiC erodent was kept as 3 g/min throughout the test. Effects of impingement angle of erodent:30, 60 or 90°, erosion test temperature: ambient and 400°C and TaC content in the composites were studied It is found that the erosion rate of the SiC-TaC ceramic composites decreased with increase in TaC content from 10 to 30 wt%. The composite with higher fracture toughness and less hardness exhibited less erosion. Furthermore, with change in test parameters as increasing angle of impingement from 30° to 90° and temperature to 400°C, erosion rate increased. A minimum erosion wear rate of 25 mm^3/kg was obtained for SiC with 30 wt% TaC at 30° in ambient condition (*see Fig. 1*), while a maximum erosion wear rate of 166 mm^3/kg was obtained for SiC with 10wt% TaC at normal impingement and 400°C. Fracture of SiC grains and pull-out of TaC particles were dominant mechanisms of material removal for the SiC-TaC composites in the selected erosive wear conditions.

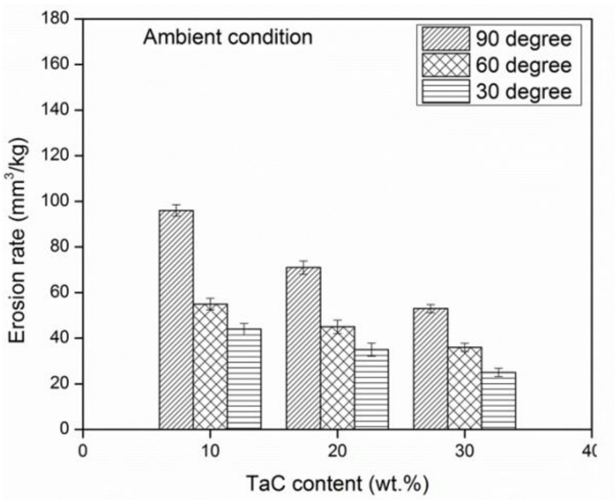

Fig.1 The effect of TaC content and angle of impingement on erosion rate of SiC-composites in ambient erosion test condition

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TRIBOLOGICAL PERFORMANCE OF POLYIMIDE AND PTFE COMPOSITES UNDER DRY SLIDING, DRY & SLURRY EROSION AND HIGH- STRESS ABRASIVE CONDITIONS

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KEYWORDS
Wear; friction; experiments in tribology; plastics

ABSTRACT
From basic home appliances to advanced engineering & medical applications, polymers (plastics) have made them visible everywhere. The global market for plastics is predicted to grow at rate of 3% per year of which engineering plastics alone are projected to reach CAGR of 7% approximately until 2023. With the increase of plastics in technologically driven world, arise its need to be tribologically efficient and its fitting for use in applicable areas.

Tribological contact results in total of 23% of the world's total energy consumption, of which 20% is lost to overcome friction and 3% to re-manufacture and replace the worn out parts [1]. Use of engineering plastics as lightweight, strong, thermally stable, low- frictional, chemical & heat- resistant materials have made them of large use in our day to day lives. Well, not all the plastics show such properties; a particular plastic may have excellent wear characteristics under one condition but may have poor wear behaviour under other. Moreover, virgin plastics when mixed with fibrous fillers (such as, carbon, aramid, glass) are usually proven to perform better.

The aim of current research is to fill the unstudied gap and bring into light the comparison between two high performance polymers; polyimide (PI) and polytetrafluoroethylene (PTFE) also called as 'teflon' with and without the effect of additives of aramid, carbon, glass and basalt fibres under dry sliding, dry and slurry erosion and high- stress abrasive conditions. The results are represented through wear mechanism maps drawn for PI and PTFE to bring out the worst to best tribological conditions for each material. The comparison with conventional Hardox 400 wear resistant steel and AISI 316 stainless steel is provided. The characteristic features of wear mechanisms are presented and discussion is supported by scanning electron microscope images.

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GRADIENT TRIBO-METALLURGICAL BEHAVIOR OF IN-SITU LASER SOLID FORMED (α+β) TI-MO ALLOY

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KEYWORDS

Friction; Wear; Everyday life tribology, Additive manufacturing

ABSTRACT

Given to the high mechanical strength, low density and desirable high bio-combability, pure Ti has been widely used as bio-medical replacement materials[1]. However, the low wear resistance of pure Ti limits it further application [2]. The paper investigates the unique metallurgical features of additive layer manufacturing of TiMo based alloy for assessing its potentials as a biomaterial [3]. First, the tribo-metallurgical behaviour of laser solid formed Ti-Mo alloys, from the powder mixture of pure Ti and pure Mo, is investigated with focus on the thermalcycling induced gradient microstructure in as-deposited condition. Titanium exhibits indeed an allotropic transformation at the transformation temperature from a hexagonal close-packed structure (α) to a body-centered cubic structure (β). The thermal conductivity and volume specific heat of Titanium alloys are unusually low, which account to a large extent of its thermal anisotropic behavior. The microstructures of the in-situ laser solid formed Ti-Mo alloys are hence characterized by optical and scanning electron microscopy and indicated that a gradient microstructure from pure α at top to α+β at the bottom is obtained. The tribometallurgical behavior of the as-deposited samples is studied using ball-on-disc tests at different altitude of the in-depth asdeposited microstructure. The results show that the sample obtained from top region possesses slight lower friction coefficient, about 0.4, than that of sample from bottom regions (0.5). Interestingly, in case of wear rate, they presents an opposite results. The wear rate of bottom region is just half of the sample from top region, which decreases from 6.91E10-6 g/(N*m) to 3.68E-6 g/(N*m). This work give a novel highthroughput tribological results of bio-medical Ti-based alloy with a wild range of microstructure.

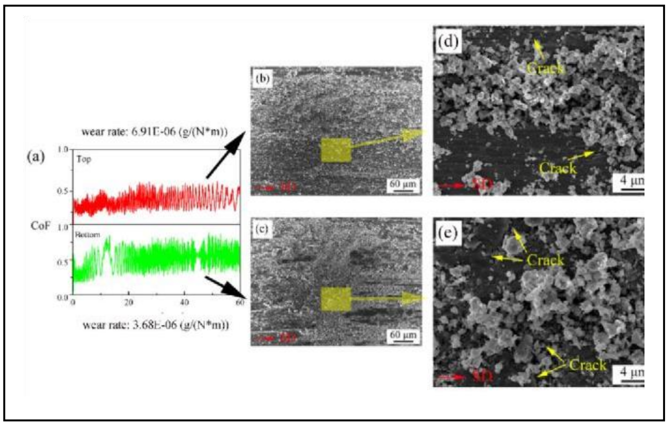

Fig.1 The ball-on-disc (a) friction coefficient (CoF) and wear rate, worn traces of LSF processed Ti-Mo alloys at (b and d) top and (c and e) bottom regions.

ACKNOWLEDGMENTS

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TRIPLE HEAT TREATMENT EFFECTS ON THE MICROSTRUCTURE AND FRETTING WEAR BEHAVIOR OF INCONEL X-750 ALLOY

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KEYWORDS

Heat treatment; fretting; friction; wear

ABSTRACT

Unlubricated fretting wear characteristics of self-mated Inconel X-750 nickel-chromium superalloy are presented at room temperature (25 ℃), intermediate (315 ℃) and high temperature (650℃) conditions in an ambient laboratory air with ~55% relative humidity. High temperature Optimol SRV 4 tribosystem was employed to run the fretting tests with a pin-on-disk contact configuration. Specimens were undergone the triple heat treatment process (THT: solution annealing at 1149 ℃/2 h + equalization treatment at 843 ℃/24 h + precipitation treatment at 704℃/20 h, all cooled down in air), then the microstructure characterization and the hardness tests were performed on the heat treated material to compare with as-received alloy material. Experimentations show that the heat treated alloy material obtained higher bulk hardness and more precipitated γ' phases in the interior of grains and Cr-rich carbides along the grain boundaries. The average grain sizes for the as-received and the THT specimens were found to be 21.2 µm and 67.4 µm, respectively. Post-fretting worn surface morphologies indicate that the formation of tribo-oxidation or "glaze" layer prevails on the wear scar at the elevated temperatures, harnessing significantly lower friction coefficient and wear volume than at room temperature. Severe material transfers from pin to disk or vice versa, and galling were the dominant wear mechanism on as-received friction pairs at 650℃ with the combination of abrasion on the worn surface, while the THT specimens exhibited stable wear characterization in the same fretting condition.

Table 1 Fretting wear parameters

Parameters	Value
Load	16 N
Stroke length	100 µm
Frequency	50 Hz
Duration	1 h (N=180 000)
Temperature	25℃, 315℃, 650℃
Disk	As-received and THT specimens
Pin	Solution annealed at 1080℃/2 h, A.C

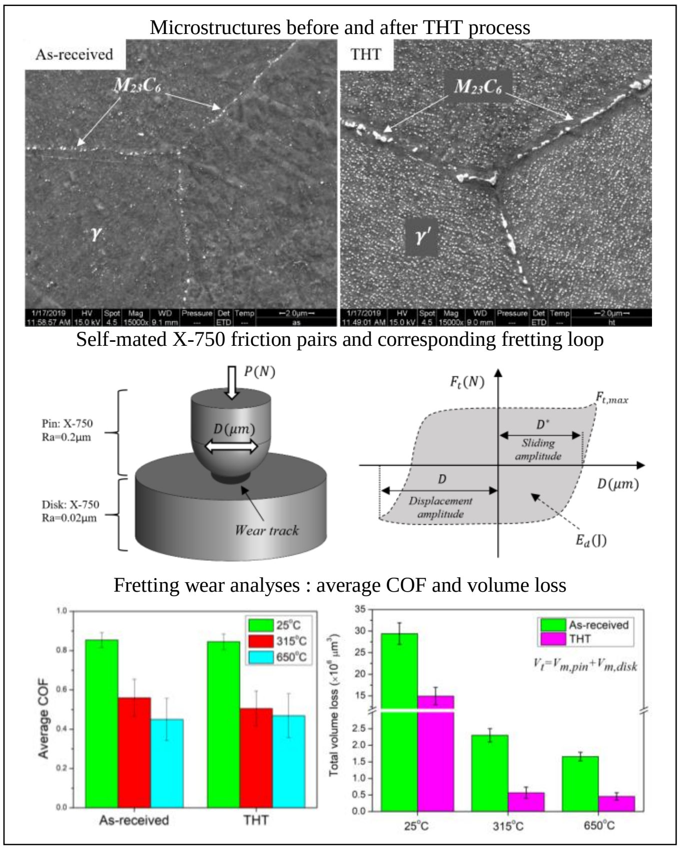

Fig.1 Microstructural characteristics and fretting wear results

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