Discussion

BIO-TRIBOLOGY AND THE OPERATING ENVIRONMENT

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Dr I C Gebeshuber *(AC^{2}T Reseach GmbH, Austria, and Technische Universität Wien, Austria)*. Thank you very much for this most interesting presentation. I want to add two remarks.

1. Living systems also constantly sense the environment and react to it. They have evolved adaptive and smart materials. However, their sensitivity, e.g. to temperature, limits their applicability in many important synthetic materials applications. For effective transfer from biology to technology, we have to understand the basic building principles of living and the function, which are optimized at different length scales in living systems.

2. I want to introduce the organisms I work on in tribology: diatoms. Diatoms are microorganisms that offer a thesaurus to micro- and nano-tribologists. These organisms make (at ambient conditions) nanostructured glass surfaces of intricate beauty; some diatom species have evolved strong, self-healing underwater adhesives. I suggest them as model organisms for tribological studies on the microscale.

Reply by the authors. We are grateful to Dr Gebeshuber for her observations. The first point she makes is an interesting one and we certainly agree that to achieve successful transfer from biology to technology we must understand the building blocks for living organisms. Specifically, with respect to diatoms, they have a very complex and intricate structure. It is difficult to see at this stage how their remarkable characteristics could be adopted in engineering tribological situations, but their properties are certainly interesting and intriguing from the tribological point of view. Dr Gebeshuber's work on diatoms at the nano-scale is fascinating and we look forward to further integration of biological and tribological studies in this field.

Professor H A Abdel-Aal *(University of Wisconsin, USA)*. In you presentation, you touched upon a very important unified natural design principle, the 'economy of effort'. This principle is in essence a manifestation of thermodynamic principles in natural functional designs and natural systems interactions. In the opinion of the authors would thermodynamic approaches play a role in optimizing the tribological aspects of humanly designed systems? Moreover, would thermodynamics help bridge the gap between understanding modes of tribo-operation in natural systems and implementing these modes in humanly designed systems.

Reply by the authors. The possibility of exploiting thermodynamic principles evident in nature in human designed systems is important and we are grateful to Professor Abdel-Aal for his remarks. To some extent this issue is already addressed by designers. For example the selection of bearing forms with minimum energy dissipation is well known, as is the role of this principle in solving free-boundary problems in cavitation. The concept has also been discussed widely in the field of biomimetics, with comparisons being made between natural and engineering systems.

FRETTING WEAR OF TI(C_xN_x) PDV COATINGS UNDER VARIABLE ENVIRONMENTAL CONDITIONS

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Mr M Maillat *(Haute Ecole, Arc le Locle, Switzerland)*. Could you please given an example of practical use of alumina sliding against a hard coating?

Reply by the authors. Materials like alumina, sapphire or corundum are rare in engineering practice and they are used in experimental programmes mainly to limit impact of tribochemical interactions at the interface. For this study, alumina ball has been selected as a counterbody, which allowed us to exclude one variable from a complex tribo-system controlled by changeable environmental conditions and as a result focus on fretting wear mechanism under different RH conditions.

Professor H A Abdel-Aal *(University of Wisconsin, USA)*.
1. In fretting, as in any other sliding situation, and due to energy release, the contact spot will entertain a high temperature rise. This temperature rise will affect the true relative humidity of the contact spot and its immediate vicinity, in a way that is not

likely to be captured by sensors. This discusser wonders if the values of wear rates shown in the figures have been corrected for temperature effect on RH? If not, would the authors expect different wear behaviour if such corrections are performed?

2. In the opinion of the authors, would considering the temperature effects remedy some of the inadequacies of the energy dissipation approach?

Reply by the authors

1. It is important to mention that contrary to classical pin on disk situation the sliding velocity was very slow in our experiments: around 1 mm/s. The impact of local temperature has been extensively investigated by Attia research group and it reports significant effect of temperature for a couple of similar materials. However it has been observed for much higher frequencies related to sliding velocity around 10 mm/s. Based on this conclusion, the impact of local flash temperature has not been considered in the present study.

2. The energy approach is a global approach and the dissipated energy will activate numerous phenomena which can not unfortunately be investigated separately. However, similar loading conditions has been applied in this study and it could be argued that the given energy approach is adequate to evaluate the impact of the relative humidity on the wear process. As discussed in the paper, humidity plays a critical role on the oxidation phenomena and modifies the rheology of the third body, which indirectly modifies the dissipation processes (energy can be dissipated at the interface of the first bodies but also through the third body).

TRIBO-ASSISTED REORIENTATION OF NANOMETER-THICK AG FILM IN ULTRAHIGH VACUUM ENVIRONMENT

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Dr A Erdemir *(Argonne National Lab., USA)*. Why silver? Could similar results be obtained from thin Au and In films?

Reply by the authors. Silver atoms do not diffuse into silicon substrate and diamond slider, that the deformation during sliding is limited only in the Ag layer. And also, interaction of Ag to diamond is so weak whereas to Si substrate is strong covalent bond. Ag layers does not transfer or disperse from the Si surface. Au films were easily removed from cleaned Si surface and we have no experience about In. These are the reason we chose Ag. In this condition, Ag layer yields due to the shear stress and reform the crystal form parallel to the pin sliding direction. The tribo-assisted reorientation of Si/Ag/diamond system occurs under the condition extremely thin film of FCC metal.

However, it would be possible if we can find out the substrate and slider that do no form solid solution to Au or In maintaining good adhesion.

Mr M Maillat *(Laboratoire Dubois, Switzerland)*. The reorientation would be easier and faster with continuous sliding compared to alternative sliding (see one of my papers on friction of Ag coatings at high temperatures).

Reply by the authors. Yes, I think so. Tribo-assisted reorientation would be easier under unidirectional sliding, although we have no experience of unidirectional sliding. The SOR-XD experiments proved that reorientation occurred by 10 cycles at least and at the room temperature. We can not compare the orientation rates with other experiments.

EFFECT OF GAIT INITIATION UPON TRANSIENT ELASTOHYDRODYNAMIC LUBRICATION OF METAL-ON-METAL TOTAL HIP REPLACEMENT

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Z M Jin, D Dowson
Institute of Tribology, University of Leeds, UK

Dr B Bou-Saïd *(INSA LaMCoS, France)*. What is the initial condition for the starting phase? Velocity different from zero?

Reply by the authors. A non-zero starting velocity was chosen as 0.01 m/s and the corresponding load was 2000 N. The non-zero velocity was chosen such that the corresponding predicted lubricant film thickness was of the similar value to the surface roughness of the metallic bearing surfaces.

Dr D Najjar *(ENSAM Lille, France)*. What is the minimal film thickness that may be reached for MOM components to have a well functioning prosthesis at start-up conditions and over time? How does this minimal value evolve in the case of component scratching over time?

Reply by the authors. The minimal film thickness should be as large as possible to achieve a full fluid film lubrication, for example the lambda ratio should be equal to or greater than 3. However, such an ideal lubrication condition is not always easy to achieve, for example under start-up conditions. Nevertheless, it is reassuring from the present study that the time to reach a steady cyclic film thickness is rather short. Furthermore, the metallic material used for metal-on-metal hip joints is cobalt chromium alloy, which has the ability to self-polish and self-heal, and is further protected by the boundary lubricant film of proteins. So even if a scratch is produced, it can be polished subsequently. Under steady walking conditions, at least a mild mixed lubrication regime towards full fluid film is required in order to reduce the asperity contacts. However, this is further complicated by the fact that the surface roughness of the cobalt chromium alloy exhibits non-Gaussian distribution, predominantly in the form of valleys. It has been shown by Dowson (2003) that a minimal film thickness of the order of 10 to 20 nm is required to produce a minimal wear rate in these man-made bearings.

[Dowson, D (2003) The relationship between steady-state wear rate and theoretical film thickness in metal-on-metal total replacement hip joints, in *Tribological Research and Design for Engineering Systems* (Edited by D Dowson *et al.*), Elsevier, Amsterdam, pp.273–280.]

THE WEAR EFFECTS AND MECHANISMS OF SOOT CONTAMINATED AUTOMOTIVE LUBRICANTS

D Green, R Lewis, R S Dwyer-Joyce
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Professor M Priest *(University of Leeds, UK).* I was surprised to discover plastic deformation in your experimental results at modest soot levels. Does this give rise to concerns about the validity of your tribometer simulation versus the real engine?
In this regard, I would like to know more about the contact geometry, new and worn, and lubricant supply of the engine compared to your tribometer simulation.

Reply by the authors. The plastic deformation occurs in regions where the contact has become starved of lubricant. The results appear to be valid as recent work; testing real engine component produces similar features. The engine contact (elephant's foot) appears to be flat but is actually slightly radiused. The component when used only gets worn in the centre of the elephant's foot, where the contact pressure between the elephant's foot and valve tip is highest. Therefore lubricant (and soot) enters the contact as in a ball-on-flat test as they are similar but with slightly different geometries.

Dr R Coy *(University of Leeds, UK).* What evidence do you have for your statement that the morphology of carbon black is the same as soot generated in diesel engines?

Reply by the authors. Previous papers (i.e., Clague, 1999) state that particular types of carbon black (similar to the one used in these tests) are the best commercially available surrogate for diesel engine soot found in the lubricant. I have recently discovered that real engine exhaust soot is available commercially – using a soot generation cycle. Further test may be performed using this for comparison, but exhaust soot is chemically very different to soot contained in the lubricant, in particular its chemical volatility and carbon content.

THE EXTRACTION AND TRIBOLOGICAL INVESTIGATION OF TOP RING ZONE OIL

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R I Taylor
Shell Global Solutions, Chester, UK

S Chung
Infineum UK Ltd, UK

Dr D Green *(The University of Sheffield, UK).* Could the authors discuss the influence of variation of the viscosity on the results?

Reply by the authors. It is unfortunate that the time allocated for presentation at the conference did not allow the chemical and rheological analysis of the samples to be discussed. They are, however, presented and discussed in this paper. As such this question pertains to the effect of the viscosity on the traction and friction results obtained from the tribological testing, as presented at the conference.
The viscosity has clearly had an effect upon the results obtained and viscosity values are directly linked to the level of volatiles contained within the sample; i.e. samples with higher volatile content have returned lower viscosity values. The general trend in the results is that the higher the viscosity of the sample the higher the friction or traction coefficient values obtained. However, as surface film formation and the chemical composition of the samples will also have had an effect on these values, it is not surprising to see individual discrepancies

from this general trend in the three tribological tests undertaken.

INVESTIGATIONS ON THE POWER LOSSES IN HIGH SPEED GEARS

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Dr G W Roper *(Shell Global Solutions, UK)*. How do you deal with thermal coupling between the various power-loss mechanisms?

Reply by the authors. So far, the coupling between the various sources of power loss has not been included. The temperatures used for evaluating the losses by gas trapping, windage and tooth friction are average temperatures in the gearbox. Research is currently under way to account for the interactions between thermal effects and power losses; a first set of results is presented in Changenet *et al.*, 2006.

[Changenet, C, Oviedo-Marlot, X, and Velex, P Power loss predictions in geared transmissions using thermal networks – applications to a 6-speed manual gearbox, *ASME J. Mechanical Design*, 2006, to be published].

Dr H P Evans *(Cardiff University, UK)*. Does the compression healing analysis of the trapping mechanism include heat transfer to the tooth material?

Reply by the authors. In the simulations of gas trapping by the teeth, adiabatic flow is assumed and consequently the energy transfer to the environment, i.e., the teeth, is not considered. However, it is known from experience that uneven thermal distortions can be generated by gas trapping in wide-faced helical gears and that the above assumption should be relaxed for analysing thermal deflections of the teeth.

HIGH PRESSURE CHAMBER MEASUREMENTS

B Jacobson
Lund University, Sweden

Professor G Poll *(University of Hannover, Germany)*. How can temperature be correctly represented when modelling the shear-pressure relationship in the ‘solid’ state?

Reply by the author. That question was not treated in this paper, but in a paper from 1987 [A model for the influence of pressure on the bulk modulus and the influence of temperature on the solidification pressure for liquid lubricants, *J. Tribology*, 1987, **109**, 709–714] the author found that the pressure needed for solidification increases with temperature such that the volume at solidification is constant and independent of the temperature. This is the same as saying that the thermal expansion of the solidified oil has to be cancelled by increased compression to keep the oil in the solid state.

At high shear velocities in the solid state, the shear stress normally has straight line proportionality between stress and pressure, but the shear stress often decreases with increasing shear rate.

Dr S Grundei *(Klueber Lubrication, Muenchen KG, Germany)*. Greases contain air, and filling into chamber might also lead to air enclosures. How does this influence the measurement? Did you observe grease combustion?

Reply by the author. The compression is so slow that the small air bubbles present at room pressure have ample time to dissolve in the grease. The air does thus not influence the measurements, and the author has never seen any trace of combustion in the high pressure experiments.

MODELING THIN FILM LUBRICATION IN EXTREME CONDITIONS: CONTINUUM VERSUS MOLECULAR APPROACHES

J Tichy
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Dr R Coy *(University of Leeds, UK)*. You indicated that the time frame for the lubrication/thin film events was such that you could consider the fluid to be isotropic. However MD of long chain molecules (C_{16} hydrocarbons) show that the perturbing forces (shear rates) at typical EHD conditions are greater than the time constant (relaxation time) of the molecule thus leading to anisotropic fluids. Can you take this effect into account in the models you presented?

Reply by the authors. Indeed there is a highly developed continuum theory of anisotropic liquids, liquid crystals being a well-known example. In the case of simple shear, there is an additional unknown unit vector quantity (the director) that roughly represents the molecular orientation. Thus, an additional equation is required, which is the equation of angular momentum. The angular momentum equation is trivially satisfied for isotropic liquids when $\tau_{xy} = \tau_{yx}$, etc. The theory is discussed in *The Structure and Rheology of Complex Fluids*, by R. G. Larson, Oxford University Press, 1999. However, in anything other than the simplest flows, the anisotropic theory probably becomes too complicated to be useful.

HIGH ORDER FINITE ELEMENT SOLUTION OF EHL PROBLEMS USING THE DISCONTINUOUS GALERKIN METHOD

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Professor T Lubrecht *(INSA LaMCoS, France)*. The authors are to be congratulated with this precise solution using only 200 points, but could they comment on the computing time of the FEM solution?

Reply by the authors. Since we use automatic *h*-adaptivity, for steady-state line contact problems the computing time depends on both the number of the unknowns and how many times the initial grid is adjusted. Normally, it takes no more than 5 minutes to obtain a fully converged, highly accurate solution if the number of the elements is no more than 40.

For 1D transient problems, more elements are usually required since the solutions at some time steps are more complicated (particularly when another pressure spike is captured). Therefore, it might take longer time at each step, compared to the steady-state cases.

At the moment, we are using Gaussian-elimination to solve the resulting linear system when updating the unknowns at each sweep of our nonlinear iteration. Of course, the computational efficiency can be improved significantly if more sophisticated numerical methods are used to solve these linear systems (for which only an approximate solution is required anyway). Furthermore, we currently update all of the values of the kernels introduced to calculate the film thickness after the grid is adjusted. But in fact, only the kernels related to the new or modified elements need to be recalculated. The efficiency could be therefore be much better if these two issues are considered. In the 2D case, we use an alternative method to solve the resulting linear system at each sweep and the recalculation of the kernels is optimized. We will give these details in another paper, currently in preparation.

WATER CONTAMINATION EFFECTS OF THE LUBRICANT ON THE HYDROGEN ABSORBING TENDENCY OF DEEP GROOVE BALL BEARINGS

T Imran, B Jacobson
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Dr S Grundei *(Klueber lubrication Munchen KG, Germany)*. What is the influence of different lubricants on hydrogen content in steel?

Reply by the authors. We have not investigated differences in hydrogen content in steels as a function of which oil types have been used in the experiments. The amount of water possible to dissolve in lubricants is a function both of the oil molecule type and the oil additives used. A clean paraffin oil can only dissolve about 100 ppm water, but a polyglycol lubricant can dissolve many percent water. The oils we have tested are usual mineral oils which have all water saturation points well below 500 ppm.

PREDICTION OF LOSSES IN BELT-TYPE CVT DUE TO SLIDING BETWEEN BELT AND DISCS

G Poll, A Sue, T Kruse, C Meyer
University of Hannover, Germany

Dr C Coy *(University of Leeds, UK)*. The deformation of discs seems critical to the operation of the CVT; what strategies have you developed in the design to minimize friction losses due to these deformations?

Reply by the authors. We studied several options to reduce the losses due to radial sliding motions by optimizing the geometry of variators, both theoretically and experimentally. We investigated the influence of disc thickness as well as additional features like collars and ribs which were meant to increase disc stiffness with little additional weight. We also looked at the free bending length of the shaft between the disc fixtures, the distance of the supporting bearings and the clearance between the movable disc and the shaft.

It turned out that increasing stiffness against particular modes of deformation does not always yield higher efficiency. For example, a collar counteracts the umbrella like bending of the discs but allows for a tilting of the complete sheave, leading to a pronounced spiral motion of the chain and high losses. On the other hand, large bending deformations evenly distributed around the circumference lead to an umbrella shape with little spiral motions.

As long as the bearing distance is so small that shaft bending further expands the wedge between the discs caused by the axial clamping forces, increasing shaft stiffness and reducing the free bending length is beneficial.

The amount of clearance between the shafts and the moveable discs should be as small as possible in order to minimise the tilting of the discs as a whole. However, the free axial motion of the discs may not be impaired. Therefore, it is more advisable to extend the guiding length.

In general, every measure to minimise clamping forces reduces losses due to deformations and the amount of power consumed by the hydraulic system. If the clamping system is able to adapt precisely and quickly to the needs smaller safety margins are acceptable.

LUBRICATION IN REFRIGERATION SYSTEMS: A NUMERICAL MODEL FOR PISTON DYNAMICS CONSIDERING OIL-REFRIGERANT INTER-ACTION

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M Priest
University of Leeds, UK

A T Prata
Federal University of Santa Catarina, Brazil

Dr E Ciulli *(University of Pisa, Italy).* Did you take into account the friction torque between piston and pin in your model? Do you intend to validate your model with experimental tests in the future?

Reply by the authors. Opposite to internal combustion engines, for compressor assemblies it is common to have a tight fit between the piston and the dudgeons pin, so that relative movement is unlikely to occur between these components. However, the adjust between the pin and connecting rod is loose and usually responsible for most of the rotation of the assembly.

Despite being acknowledged as the component most susceptible to wear, the power consumption for piston/connecting rod bearing is usually small compared to the frictional power loss in the piston-cylinder clearance, especially due to the small area of contact of the former compared to the latter.

In regard to the validation of the model with experimental tests, it is definitely expected for the near future. It is currently being developed at Federal University of Santa Catarina (Brazil) a test rig for a journal bearing, with capabilities to simulate conditions previously tested with the numerical two-phase model. With successful validation for this case, further developments will include a complete experimental study for the piston assembly. So far, the results obtained with the two-phase model for this geometry have agreed with the expectations of predicting higher friction compared to single-phase models considering cavitation.

However, future experimental works should not focus only in measuring performance variables, but also in understanding better oil–refrigerant mixture properties and having them controlled during practical experiments.

ROUGHNESS IN ROLLING-SLIDING EHL CONTACTS

C J Hooke
University of Birmingham, UK

Dr F Ville *(INSA LaMCoS, France).* What is the influence of the rheological model (Ree–Eyring, τ_o = constant) on the method you propose to 'rebuild' the pressure field?

Reply by the author. The method can be used for any value of the Eyring stress, τ_o. The results presented in the paper are for a value of 4 MPa. However, all the components of the clearance and pressure curves (amplitude and phase of the attenuated roughness and the amplitude, phase, wavenumber and decay rate of the complementary wave) vary with τ_o. This means that the final pressures (and stresses) can be expected to depend, to some extent, on the Eyring stress. This is inconvenient since the value of the Eyring stress may vary with pressure and temperature and is, in any case, generally not well defined for many lubricants. However, the relationship between the Eyring stress and the maximum stress under a rough surface was explored for two surfaces in ref 1 and for those surfaces the maximum stress increased by about 30% as the Eyring stress was increased from 1 MPa to 10 MPa. This suggests that the actual value of the Eyring stress adopted may not be critical and that it might be possible to get reasonable estimates of pressure and stress with some estimated median value for τ_o.

Mr H Xu *(Glacier Vandervell Bearings, UK).* Thanks for the interesting presentation. Your work is based on sinusoidal surface roughness. Is this method readily transferable to the case of surface roughness of complex profile? (for example, the one from real machined surface from practice).

Reply by the author. Where the complementary wave decays rapidly it is straightforward to estimate the pressures and clearances using discrete Fourier transforms and ref 1 gives some examples of this process. If the complementary wave is significant then the procedure becomes more complicated but it does appear possible to use the results obtained from low amplitude sinusoidal roughness to estimate the clearances and pressures in general rough surfaces. The major problem is to allow for the differing velocities of the rough surface(s) and the complementary wave and it is hoped to publish details of how this may be done in the near future.

EFFECTS OF SOOT ON WEAR IN EHL CONTACTS

M Kaneta, T Irie, H Nishikawa, K Matsuda
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Dr R C Coy *(University of Leeds, UK).* In you beautiful videos in the case of pure sliding with the ball stationary you showed a build up of soot in the inlet of the contact. Did this lead to starvation and hence lower oil film thickness and higher wear? Also, did it lead to high roughness on the wear scar?

Reply by the authors. Yes, a build up in the inlet of the contact led to starvation and lowered oil film thickness. However, in the case of disk sliding, it was difficult to observe wear scar.

Dr F Ville *(INSA LaMCoS, France)*. In the past we conducted experiments with solid contamination. We never observed embedded particles in the surfaces even under sliding conditions. It seems that there are two different mechanisms in your experiments leading to wear depending on the slide-to-roll ratio, contacting body hardness: starvation and abrasive wear.

For the last mechanism, did you observe embedded soot particles and what was the particle size?

Reply by the authors. As seen from Fig. 23, EPMA analysis showed us that soot particles adhered to the surface of the soft steel roller. However, we could not measure the aggregated particle size.