

Selected Publications on Research Work carried out on the EHL Ultra Thin Film Measurement System

Contents

Orientation and Film-Forming Properties of Thermotropic Liquid Crystals in EHD Contacts.....	3
A Study of Parched Lubrication.....	4
Film Thickness Measurements of Lubricating Greases Under Normally Starved Conditions.....	5
Techniques for Studying the Behaviour of Lubricants in Elastohydrodynamic Contacts.....	6
The Elastohydrodynamic Properties of Some Advanced Non Hydrocarbon-Based Lubricants..	7
In-Situ Measurement of ZDDP Films in Concentrated Contacts.....	8
EHD Film Formation and Starvation of Oil in Water Emulsions.....	9
The Film-Forming Properties of Polyalkylene Glycols.....	10
The Lambda ratio - A Critical Examination.....	11
The Influence of Basestock Type on Polymer Solution Rheology in EHD Contacts.....	12
The Behavior of Polymer Solutions in Concentrated Contacts: Immobile Surface Layer Formation.....	13
Thin Film Optical Interferometry in the Study of Grease Lubrication in a Rolling Point Contact.....	14
Measurement of Elastohydrodynamic Film Formation in Rolling Contacts at Very High Pressures.....	15
Behaviour of Lubricants in the Mixed Elastohydrodynamic, Boundary Regime.....	16
Boundary Film Formation by Lubricant Base Fluids.....	17
The formation of Viscous Surface Films by Polymer Solutions: Boundary or Elastohydrodynamic Lubrication.....	18
The Influence of Temperature on the Lubrication Behaviour of a Lithium Hydroxystearate Grease.....	19
The Rheology Of Thin Lubricant Films.....	20
Boundary Film Formation by Viscosity Index Improvers.....	21
The Role of Surface Tension and Disjoining Pressure in Starved and Parched Lubrication.....	22
The Influence of Slide/Roll Ratio on the Film Thickness in EHD Contact Operating in the Mixed Lubrication Regime.....	23

Starvation and Reflow in a Grease Lubricated Elastohydrodynamic Contact.	24
The Thickness and Rheology of Boundary Lubricating Layers.	25
The Lubricant Film-Forming Properties of Modern Fire-Resistant Hydraulic Fluids.	26
Measurement and modelling of boundary film properties of polymeric lubricant additives.	27
Optimizing Film Formation by Oil in Water Emulsions.	28
Direct Measurement of Boundary Lubricating Films.	29
An Experimental study of Film Thickness in the Mixed Lubrication Regime.	30
Friction and Wear Reduction by Boundary Film-forming Viscosity Index Improvers.	31
Fractionation of liquid lubricants at solid surfaces.	32
Friction behaviour of ZDDP Films in the Mixed, Boundary/EHD Regime.	33
Prediction of the influence of lubricant formulations on Fuel Economy, from Laboratory bench test.	34
The Control of Friction by Molecular Fractionation of Base Fluid Mixtures at Metal Surfaces.	35

Orientation and Film-Forming Properties of Thermotropic Liquid Crystals in EHD Contacts.

Cann P.M., Aderin M., Johnston G.J. and Spikes H.A.
Proc. 18th Leeds-Lyon Symposium on Tribology, (1992).

There is growing evidence from infrared and from computer simulation work that the very high shear stresses associated with elastohydrodynamic (EHD) contacts result in the partial alignment of lubricant molecules. Such an effect has important implications with respect to the lubricants EHD film forming and traction behaviour. In this paper, the film formation and alignment of thermotropic liquid crystals are studied in an EHD point contact. Two complementary experimental techniques are employed, in-contact, infrared -reflection absorption spectroscopy and polarised, thin film optical interferometry. The work shows the extent and direction of orientation of liquid crystal molecules in EHD contacts and indicates how similar effects can be studied in more conventional lubricants.

A Study of Parched Lubrication.

Guangteng, G. Cann, P.M. and Spikes, H.A.
Wear, 153, pp 91-105 (1992).

The elastohydrodynamic regime of lubrication is now quite well understood, to the extent that theoretically derived equations for lubricant film thickness are used routinely in engineering design. The boundary lubrication regime, which occurs at slow rubbing speed and in which the surfaces are separated only by a chemically formed layer, is less clearly understood but many of the underlying concepts, such as the formation of a monomolecular adsorbed film or a thicker, reacted glass-like layer, have been both demonstrated and modelled. Between these two regimes there remains, however, a territory about which very little is known. This is the regime where a concentrated contact is heavily starved, permitting no conventional elastohydrodynamic film, and yet there remains between the surfaces a film of lubricant whose presence is governed by its rheology rather than its ability to bond to the rubbing surfaces. Such films exist in applications such as gyroscope bearings and probably in many grease-lubricated systems. This regime has been called "parched lubrication" (E. Kingsbury, Trans. ASME J Tribol., 107 (1985) 229). Up until the present it has not been possible to do much more than speculate upon the behaviour of this lubricant regime because such very thin films could not be directly measured. It was possible to deposit lubricant films of known thickness onto surfaces and to measure properties such as friction and wear but it was not possible to relate this to the thickness of such films under operating conditions. This paper describes an experimental study of parched lubrication which addresses this problem. A recently developed technique for measuring very thin films in concentrated contacts is employed to monitor the occurrence and persistence of thin lubricant films within highly starved, concentrated contacts under a range of conditions. This is combined with IR reflection-absorption spectroscopy to measure the oil film thickness on the out-of-contact surfaces. The main factors which determine the behaviour and performance of this type of starved film are discussed.

Film Thickness Measurements of Lubricating Greases Under Normally Starved Conditions.

Cann, P.M. and Spikes, H.A.
NLGI Spokesman, 56, pp 21-31, (1992).

The primary role of a grease is to act as a reservoir to providing sufficient oil to a lubricated contact to form and maintain a separating film. Elastohydrodynamic (EHD) film thicknesses obtained with greases are dependent upon both base oil rheology and gellant structural properties (1). However most experimental (1)(2) and theoretical (3) studies of grease lubrication maintain or assume fully-flooded conditions whilst in practice many machine elements are known to operate in a starved or "parched" lubrication regime (4). The problem of grease performance when there is only a restricted supply to the inlet has never been fully addressed.

Techniques for Studying the Behaviour of Lubricants in Elastohydrodynamic Contacts.

Spikes, H.A. and Cann, P.M.
Acta Trib., 1, pp 33-48, (1992).

The main role of a lubricant is usually to separate rubbing surfaces with a low shear strength film. The extent to which this is achieved is determined in elastohydrodynamic contacts by the physical and chemical response of the lubricant basestock and additive molecules to the conditions in the inlet and interior of the contact. Generally, the film thickness is determined by lubricant response to the inlet conditions whilst the shear strength is controlled by the way molecules behave in the contact centre. Clearly it is important to understand how lubricants behave in contacts. This is not straightforward however, since the conditions, especially in concentrated contacts, as found in gears and rolling element bearings, are very severe, involving very high pressures, strain rates and rates of energy dissipation. It is difficult to predict the behaviour of molecules under such conditions and it is also difficult to reproduce these conditions in macroscopic test equipment. Therefore the behaviour of lubricants in contacts tends to be inferred from indirect information, such as measurements of scuffing or wear performance, or from analysis of surface films after rubbing has taken place. The obliquity of this approach has tended to limit our fundamental understanding of how lubricants behave. One way of addressing this problem is to treat the contact itself as a test chamber and to devise ways to directly study the behaviour of the lubricant therein. This ensures that the conditions to which the lubricants are subjected are realistic whilst focusing directly on generic aspects of lubricant behaviour such as film thickness and rheology rather than on secondary measures of performance such as wear. This paper reviews methods to directly study the behaviour of lubricants in concentrated contacts. It then goes on to describes in more detail three specific techniques recently developed by the authors, ie:

1. Ultrathin film interferometry to measure film thickness of lubricants in contacts.
2. infrared thermal microscopy to determine shear stress profiles of lubricant films in contacts.
3. infrared reflection absorption microspectroscopy to examine molecular composition of lubricant films in contacts.

The Elastohydrodynamic Properties of Some Advanced Non Hydrocarbon-Based Lubricants.

Aderin M., Johnson G.J., Caporiccio G. and Spikes H.A.
Lubrication Engineering 48, pp. 633-638, (1992).

As the temperatures encountered in advanced engineering systems increase, a growing interest in the availability and use of non hydrocarbon-based oils, which have the potential for operating at significantly higher temperatures than conventional lubricants, develops. When considering the application of such fluid, it is important to know their lubricating properties at the very high temperatures for which they are required. This study uses a newly-developed ultra-thin-film interferometric system to measure and compare the elastohydrodynamic film-forming properties of several different types of non hydrocarbon-based lubricants over a wide temperature range, up to 200°C. The results are discussed in terms of the way that the fluids pressure-viscosity coefficients and temperature-viscosity coefficients vary with temperature and composition.

This paper describes the results of measurements of both pressure- and temperature-viscosity coefficients of advanced non-hydrocarbon lubricants at a range of temperatures. Pressure-viscosity coefficients were determined from optical interferometric film thickness measurements in an elastohydrodynamic contact and temperature-viscosity coefficients were calculated from conventional viscometry.

The first aim of the current work was to provide an overall comparison of the pressure and temperature viscosity coefficients of different lubricant types of the same viscosity under the same conditions. To do this, lubricants within each structural class were blended to have the same viscosity at one fixed temperature, and were then compared.

The second aim of the current work was to explore how the pressure and temperature coefficients of each lubricant type correlated and varied with temperature. For this, fluids in each structural class were taken, and each was examined over a wide range of temperatures, especially at high temperatures.

In-Situ Measurement of ZDDP Films in Concentrated Contacts.

Gunsel, S., Spikes, H.A and Aderin, M.
Trib. Trans. 36, pp 276-282, (1993).

The film formation behaviour of lubricating oils containing zinc dialkyldithiophosphate (ZDDP) additives has been studied in rolling, concentrated contacts using ultra-thin-film interferometry. It has been shown that ZDDPP-containing oils form chemical films which are additional to the elastohydrodynamic (EHD)) films produced by the base oil. ZDDP film formation occurs at elevated temperatures and begins in the range of 130°C to 170°C, depending upon the base oil type. The thickness of the films increases with temperature and test time. The ZDDP films formed are typically 5 to 25nm thick and appear to be solid-like surface coatings.

EHD Film Formation and Starvation of Oil in Water Emulsions.

Barker, D.C., Johnston, G.J., Spikes, H.A. and Bunemann T.
Trib. Trans., 36, pp 565-572, (1993).

The elastohydrodynamic film-forming properties of oil-in-water emulsions in rolling point contacts have been investigated using a combination of ultrathin film interferometry and short duration TV microscopy.

It has been shown that at slow rolling speeds, all the o/w emulsions tested formed EHD film comparable to those of their water-free components. Above a certain critical rolling speed, which depended upon the emulsion composition, the film thickness started to decrease. This was due to EHD starvation, and the film thickness/inlet oil meniscus relationships developed for starved oil systems were found to apply to emulsion starvation.

At high rolling speeds, the EHD film thickness did not collapse to zero, but instead leveled off at a low value, typically 10 to 30nm, which persisted to the highest rolling speeds attained.

The Film-Forming Properties of Polyalkylene Glycols.

Aderin, M.E., Johnston, G.J., Balson, T.G., Emery, M.G. and Spikes, H.A.
J. Synth. Lub. 10, pp 23-45, (1993).

It is now recognised that, for many practical applications, an important property of a lubricant is its ability to generate thick elastohydrodynamic (EHD) films in concentrated contacts. This paper describes a study of the EHD film forming properties of polyalkylene glycol lubricants. A wide range of polyglycol structures have been examined, with different monomer types, initiators, and molecular weights. Film thickness has been measured at several different temperatures using both conventional and ultra-thin film interferometry. From the measured film thicknesses, the effective pressure-viscosity coefficients of the lubricants have been evaluated. This has enabled a systematic investigation of the effect of polyalkylene glycol structure on both pressure viscosity coefficient and EHD film formation.

The Lambda ratio - A Critical Examination.

Cann, P.M., Ioannides, E., Jacobson, B. and Lubrecht, A.A.
Wear, 175, pp. 177-188, (1993).

The reliable performance of heavily loaded contacts can only be sustained over long periods when a lubricant film fully separates the two bodies and asperities do not interact. Engineering surfaces do have a certain degree of roughness and this would then determine the required lubricant film thickness. Unfortunately thick lubricant films have disadvantages such as high power losses (oil churning) or may not be attainable because of prescribed lubricants or high operating temperatures.

In order to optimize bearing selection against these conflicting parameters or in order to design specific surfaces for extreme operating conditions a thorough understanding of the mechanisms of micro EHL or asperity lubrication is required. This required level of understanding goes beyond the current one which employs λ , the ratio between film thickness and combined surface roughness. When detailed analysis of the behaviour of surface asperities in heavily loaded elastohydrodynamic contacts includes non-Newtonian effects, two phenomena become evident. One phenomenon is the possibility to describe theoretically the collapse of an oil film and to determine when a lubricated rough surface in contact with another surface can come into solid contact through the lubricant film. The other phenomenon, which is closely related to the first one, is the explanation of the well-known fact that the oil film thickness needed to separate two elastohydrodynamically lubricated surfaces is strongly dependent on the structure of the surface roughness and not only on the values of the different surface roughness parameters. Both of these phenomena can only be explained if the pressure distribution in the lubricant film has such high frequency variation that local asperities in the lubricant film become elastically deformed by the pressure distribution, making the contact surfaces conform much more than in the unstressed state outside the high pressure contact zone.

The analysis should include details of the surface topography, the amount of lubricant present on the track, the rheological behaviour of the lubricant, the thermal behaviour in the contact, the transient behaviour of non-smooth contacts and the degree to which the asperities are flattened under these conditions. These aspects are addressed in this paper.

The Influence of Basestock Type on Polymer Solution Rheology in EHD Contacts.

Cann, P.M. & Spikes, H.A.
Proceedings 20th Leeds-Lyon Symposium, (1993).

Whereas elastohydrodynamic (EHD) film thicknesses for simple base stocks can be predicted with some confidence from their bulk properties this is not so for polymer-containing fluids. The behaviour of such fluids in an EHD contact is extremely complex and can include elements of shear thinning, viscoelasticity and boundary properties. In this paper polymer solution behaviour in a concentrated contact has been investigated through detailed EHD film thickness measurements. A series of model polymers; polyisoprenes in the molecular weight range 27-86,000, have been studied in two different basestocks, the intention being to examine the effect of base stock rheology and solvation properties on polymer behaviour.

The Behavior of Polymer Solutions in Concentrated Contacts: Immobile Surface Layer Formation.

Cann, P.M. and Spikes, H.A.
STLE Trib. Trans, 37, pp 580-586, (1994).

The film-forming properties of solutions of low-to-medium molecular weight polyisoprenes in synthetic hydrocarbon have been studied using thin film interferometry. It has been shown that the lubricating films formed in rolling, concentrated contacts have two components. At very slow speeds, the polymer forms an immobile film of thickness equivalent to two radii of gyration of the polymer molecules. This film thickness is independent of speed but is gradually squeezed from the contact when motion is halted. The film is likely to represent two monolayers of polymer, one on each surface, and can be regarded as a boundary lubricating film. As the rolling speed is raised, a conventional elastohydrodynamic film is formed which is superimposed on the immobile film.

The immobile films formed are similar to those detected using a force balance apparatus and reported elsewhere in the literature.

Thin Film Optical Interferometry in the Study of Grease Lubrication in a Rolling Point Contact.

Cann, P.M. and Spikes, H.A.
Acta Trib. 2, pp 45-50 (1994).

In recent years significant advances have been made in our understanding of fluid lubrication so that film thicknesses in elastohydrodynamic (EHD) contacts can now be performed from simple lubricant parameters. This is not the case for greases where our understanding on the mechanisms of lubrication is still very limited. One of the reasons for this is the paucity of experimental techniques available for studying and measuring the very thin films formed by greases in EHD contacts. In this paper the application of thin film optical interferometry to the study of grease films in a rolling point contact is described. This new technique has removed some of the limitations inherent to the old methods and is providing fresh insights into fundamental mechanisms of grease lubrication.

Measurement of Elastohydrodynamic Film Formation in Rolling Contacts at Very High Pressures.

Smeeth, M., Cann P.M. and Spikes, H.A.

Presented at the 21st Leeds-Lyon Symposium on Tribology, Leeds, Sept 1994, "Lubricants and Lubrication". Publ. Elsevier 1995.

A modified optical interferometry technique was used to measure the EHD central film thickness of two oils up to pressures of 3.6GPa. In order to generate such pressures a tungsten carbide ball was loaded against a hardened steel disc with a sapphire window insert. The results showed that the film thickness generated was slightly lower than that predicted by the Dowson-Hamrock equation and the load exponent lay between that predicted by Dowson-Hamrock and recent high pressure computed solutions.

Behaviour of Lubricants in the Mixed Elastohydrodynamic, Boundary Regime.

Guangteng, G. and Spikes, H.A.

Presented at the 21st Leeds-Lyon Symposium on Tribology, Leeds, Sept 1994, "Lubricants and Lubrication". Publ.. Elsevier 1995.

A range of lubricant base fluids have been chosen and their film-forming properties measured in the mixed elastohydrodynamic regime in pure rolling conditions. The Dowson-Hamrock elastohydrodynamic film thickness equation was found to remain valid over a large film thickness range for the tested base fluids. For hexadecane, the film thickness equation remains valid down to a film thickness of about 0.5 nm, a size equivalent to a molecular monolayer on each solid surface. However thicker films than predicted by elastohydrodynamic theory were found for all the other tested fluids at low speeds in the very thin film regime. This effect can be interpreted as boundary film formation by the fluids. The origins of these boundary films are still being explored but may be due to adsorption of molecules of the fluid on the solid surfaces and/or enhancement of viscosity due to the presence of a solid surface. This study has shown that full film lubrication is still possible for smooth surfaces in pure rolling in the very thin film regime where the film thickness is far smaller than the composite surface roughness.

Boundary Film Formation by Lubricant Base Fluids.

Guangteng, G. and Spikes, H.A.

Accepted for publication, Tribology Transactions, May 1995.

The measurement of lubricant film thickness in a rolling steel ball on glass flat contact down to one nanometer is now possible by using ultrathin film interferometry. This technique has been used to study the film-forming properties of a range of synthetic base fluids in the mixed elastohydrodynamic and boundary lubrication regimes.

For a very highly purified sample of hexadecane, it was found that classical EHD theory was obeyed down to less than one nanometer, indicating that any boundary film formed by this fluid was less than 1nm thick. Most other synthetic fluids tested gave thicker films than predicted from EHD theory under very thin film conditions. This deviation from theory occurred at between 1 and 10nm for different fluids. The effect can be interpreted as resulting from the presence of boundary layers, one or two molecular layers thick of the fluid on each solid surface, which are more viscous than the bulk lubricant.

The formation of Viscous Surface Films by Polymer Solutions: Boundary or Elastohydrodynamic Lubrication.

Smeeth, M., Gonsel, S. and Spikes, H.A.

Accepted for publication, Tribology Transactions, May 1995.

The film-forming properties of a range of polymer solutions have been studied down to very thin film thickness using ultrathin interferometry. It has been found that, at very slow rolling speeds, some polymers generate much thicker films than predicted from theory. It appears that these polymers form adsorbed layers between 3 and 15 nanometers thick on the two solid surfaces. These layers have a viscosity many times higher than that of the bulk solution. Therefore, under slow speed, low film thickness conditions, the contact effectively operates within a viscous boundary layer, generating an elastohydrodynamic-type film much thicker than predicted from the viscosity of the bulk lubricant. As the speed is raised the contact emerges from this boundary layer and reverts to elastohydrodynamic behaviour based upon the viscosity of the bulk polymer solution.

The Influence of Temperature on the Lubrication Behaviour of a Lithium Hydroxystearate Grease.

Cann, P.M.
Eurogrease, Jan/Feb, pp 25-32, (1995).

This paper reports a fundamental study into the lubrication behaviour of a lithium hydroxystearate grease in a rolling point contact. In an earlier presentation (1) the development and use of test methods for research into grease lubrication were reported and in this paper these have been used to study the lubricating film thickness and film composition for a single grease. The intention is that this approach will provide an insight into general mechanisms of grease lubrication in bearings.

Bearing operation has been simulated in two ways: firstly lubricant film thickness has been measured at three temperatures 20, 50 and 80°C which represents a typical working range for a bearing grease Secondly the grease supply condition has been made similar to bearings in that there is no external mechanism to supply grease to the contact so that film thickness is measured under fully "starved" conditions. The results show that film thickness decays with time as observed in earlier work (1), however at high temperatures the film thickness recovers as the test proceeds.

Some general observations can be made about the nature of the separating films. There are two components; a "residual" film which is composed of shear degraded thickener deposited within the rolling track and a hydrodynamic component due to oil either in the track or supplied from the grease reservoir. The recovery of the film thickness at high temperatures has significant implications for bearing lubrication as the resultant film thicknesses exceed those for the base oil alone. Such recovery is presumably due to improved supply of the lubricant to the contact facilitated by structural, and hence viscosity, loss in the grease due to the combined effects of temperature and working.

The Rheology Of Thin Lubricant Films.

Spikes, H.A.

Solid-Solid Interactions the Proceeding of the First Royal Society-Unilever Indo-UK Forum in Materials Science and Engineering, ed. M J Adams et al., copubl. The Royal Soc., Imperial College Press, 1995.

The most important role of a liquid lubricant is to form a low shear strength separating film between rubbing solids in contact. Ideally, the thickness of this film should be several times greater than the roughness of the two surfaces, so as to prevent any significant interaction between adjacent high points. The lubricant film thickness generated in contacts is strongly dependent upon the viscosity of the lubricant present and an important stage in designing rubbing systems is to calculate the film thickness using the viscosity of the lubricant at the prevailing temperature. When carrying out such calculations, the assumption is always made that the viscosity of the lubricant is homogenous and thus does not vary with distance from the solid surfaces. In the last few years, however, a good deal of research has been carried out using force balance techniques which suggests that many liquids form layers a few molecules thick on solid surfaces which are less mobile than the bulk and thus have enhanced viscosity. Clearly such a phenomenon could have a considerable influence on the lubricant film thickness developed in rubbing contacts. This paper first examines previous work on the rheology of thin layers of lubricants on solid surfaces. It then describes a new approach to investigating the rheology of very thin layers of liquid lubricants and the consequent effect of lubricant film thickness. Film thicknesses down to one nanometre are measured in lubricated, rolling, concentrated contact. It is shown that some lubricants form thicker films than predicted from elastohydrodynamic theory. This is interpreted as resulting from the presence of a viscous layer of fluid on each solid surface of thickness equivalent to about one to three molecular layers. With some polymer solutions, a pronounced step is observed in the measured film thickness/rolling speed relationship. This is believed to result from the formation of an adsorbed layers of polymer on each solid surface one radius of gyration thick. These layers mean that at very slow rolling speeds the contact inlet is immersed in viscous, polymer concentrate whilst at high speeds the system operates in the lower viscosity, bulk solutions.

Boundary Film Formation by Viscosity Index Improvers.

Smeeth, M., Gonsel, S. and Spikes, H.A.

Accepted for publication in Tribology Transactions, preprint no. 95-3B-TC-1.

Ultrathin film interferometry has been used to measure the film-forming properties of a range of viscosity index improver (VII) solutions in rolling, concentrated contacts. It has been shown that some VIIs form boundary lubricating fluids of thickness 10 to 30nm in contacts. These films result from the presence of highly concentrated and thus very viscous layers of polymer solution formed on the two rubbing solid surfaces by polymer adsorption. These boundary films are formed only by some types of VII and can persist up to temperatures in excess of 120°C. The possible implications of this type of boundary lubrication are discussed.

The Role of Surface Tension and Disjoining Pressure in Starved and Parched Lubrication.

Guangteng and Spikes, H.A.

Accepted for publication in Proc. I. Mech. E., Aug. 1995.

The starvation of a rolling, elastohydrodynamic contact has been examined both experimentally and theoretically. It has been shown that starvation occurs at a critical rolling speed which is determined by the rate of flowback of lubricant into the out-of-contact track due to oil/air surface tension forces. Above this speed, however, complete collapse of the oil film in the contact does not occur. Instead a film of approximately 10-20 nm thickness persists even to very high speeds. It has been shown that this behaviour can be explained by considering the flowback into the out-of-contact track due to solid/liquid van der Waals forces. Thus a combination of oil/air and oil/solid surface forces can fully explain the phenomena of starved and parched elastohydrodynamic lubrication.

The Influence of Slide/Roll Ratio on the Film Thickness in EHD Contact Operating in the Mixed Lubrication Regime.

Smeeth, M. and Spikes, H.A.

Presented at 22nd Leeds/Lyon Symposium on Tribology, "The Third Body Concept", Lyon, Sep. 5th-8th, 1995, to be published by Elsevier, 1996.

Ultra-thin film interferometry is used to measure the film thickness of an elastohydrodynamic point contact under mixed sliding and rolling conditions in the thin film regime. By maintaining a fixed entrainment speed and varying only the slide/roll ratio, the precise influence of the sliding speed on the lubricant film thickness can be determined. The results clearly show that the film thickness falls under high amounts of sliding. A degree of asymmetry is observed in film thickness versus slide/roll ratio plots, which is tentatively attributed to the different materials used in the contact. A number of different possible explanations for this behaviour are suggested and discussed.

Starvation and Reflow in a Grease Lubricated Elastohydrodynamic Contact.

Cann, P.M.

23. STLE Trib Trans, 39, pp 698-704, (1996).

The lubrication mechanisms of a grease in a rolling-element bearing has been studied through the measurement of film thickness in a polling point contact. To simulate bearing conditions the contact runs under fully starved conditions; there is no attempt to maintain bulk flow of the grease in to the inlet using an external supply. In consequence the film thickness drops off rapidly as the contact progressively starves. After a few minutes rolling (at constant speed) and equilibrium film thickness is attained which has two components: a residual film (h_R) comprised of degraded grease thickner and a hydrodynamic component (h_{EHD}) due to the liquid phase from the grease. The hydrodynamic contribution represents a balance between lubricant lost from the contact and replenishment from the grease close to the track. The ability of the grease to replenish the rolling track has been inferred from measurements of lubricant reflow around the static contact. These results are discussed in light of current starvation and grease lubrication models.

The Thickness and Rheology of Boundary Lubricating Layers.

Spikes, H.A. and Cann, P.M.

presented at International Tribology Conference, Yokohama, October 1995. Accepted for publication in the Proceedings.

Using an advanced form of optical interferometry it is now possible to measure lubricant film thickness in rolling, concentrated contacts down to 1 nm. This enables a direct study of the presence and properties of boundary films in such contacts. It is shown that simple hydrocarbon fluids show no boundary effects down to 1 nm, obeying elastohydrodynamic theory down to this thickness. Some base fluids and additive solutions form boundary films up to 20 nm thick. Using film thickness measurements it is possible to explore the rheological properties of these films.

The Lubricant Film-Forming Properties of Modern Fire-Resistant Hydraulic Fluids.

Ratoi-Salagean, M. and Spikes, H.A.

Presented at ASTM Symposium on the Tribology of Hydraulic Pump Testing, Houston, Dec. 1995.

Fire resistant hydraulic fluids tend to show significantly poorer tribological performance in hydraulic systems than conventional mineral oil based fluids. There have recently been performance problems associated with increases of operating temperatures of mining hydraulics. This paper describes measurements of the elastohydrodynamic and boundary film-forming properties of a range of different hydraulic fluid types at temperatures up to 80°C. These are compared with friction and wear results obtained using the same fluids.

Measurement and modelling of boundary film properties of polymeric lubricant additives.

Guangteng, M. Smeeth, P.M. Cann, & H.A. Spikes
proceedings IMechE, 210, pp 1-15, (1996).

Experimental work using ultrathin film interferometry has shown that some polymer solutions in oil form much thicker films at slow speeds in rolling, concentrated contacts than predicted from elastohydrodynamic (EHD) theory. This behaviour can be interpreted as resulting from the polymers forming adsorbed, surface layers of enhanced concentration on the two solid surfaces. Such layers, which are typically 20 nm thick, would be significantly more viscous than the bulk solution and thus produce thicker EHD films. This concept has been supported by modelling the elastohydrodynamic point contact using control volume analysis with a layered surface viscosity. The film thickness behaviour predicted computationally using this technique is quite similar to that found experimentally using polymer solutions.

Optimizing Film Formation by Oil in Water Emulsions.

Ratoi-Salagean, M., Spikes, H.A. and Rieffe, H.L.

to be presented at STLE Annual Conference, Cincinnati, May 1996 and to be published in STLE Trans.

Oil-in water (O/W) emulsions are widely used in metal rolling and cutting and also as fire-resistant hydraulic fluids. For both of these applications, they require a reasonable degree of lubricating ability; in metal rolling to protect the surfaces against wear and seizure and to provide a controlled value of friction; in hydraulics to limit the extent of wear, scuffing and fatigue of rubbing pump components. The lubricating properties of O/W emulsions are significantly poorer than those of most water-free oils and this deficiency can give service problems, such as excessive wear or rolling contact fatigue of hydraulic pumps or the uneven rolling or heat streaking of metal strip. Considerable work has gone into the design of O/W emulsions which have acceptable lubricating properties combined with satisfactory emulsion stability and corrosion resistance. Much of this work has been empirical although there have been a number of more fundamental studies of the film-forming and friction properties of emulsions. The latter have shown that the ability of O/W emulsions to form films in rubbing contacts is very dependent on the rolling speed of the contact and also the composition of the emulsion. This paper describes a study of the relationship between the composition and properties of O/W emulsions and the extent to which they form elastohydrodynamic films in contacts over a range of speeds. By applying surface chemical principles to maximise the tendency of the oil in O/W emulsions to wet the surfaces, it is shown how the composition of an O/W emulsion can be optimized to yield satisfactory film formation and, thus, low friction and wear over a wide range of speed conditions.

Direct Measurement of Boundary Lubricating Films.

Angheli, P.M. Cann & H.A. Spikes

29. Proceedings 23rd Leeds-Lyon Symposium on Tribology, to be published, (1996).

Using an advanced form of optical interferometry it is now possible to measure lubricant film thickness in rolling, concentrated contacts down to 1 nm. This enables a direct study of the presence and properties of boundary films in such contacts. It is shown that a simple hydrocarbon fluid exhibits no boundary effects down to 1 nm and obeys elastohydrodynamic theory down to this thickness. However solutions of long chain surfactants, such as stearic and oleic acid in base fluid form boundary films, typically 2 to 6 nm thick in lubricated contacts. These films appears to be partially viscous and partially solid-like in that a proportion of the film, usually 1 to 2 nm is retained for long periods in the stationary contact. In some cases, these boundary lubricating films are quite thick, up to 20 nm, indicating some degree of multilayer formation. This thick film-forming behaviour is, however, difficult to obtain repeatably and may be highly sensitive to the cleanliness of the rubbing surfaces.

An Experimental study of Film Thickness in the Mixed Lubrication Regime.

Gao Guangteng and H.A. Spikes

Proceedings 23rd Leeds-Lyon Symposium on Tribology, to be published, (1996).

This paper describes an experimental study of the influence of surface roughness on elastohydrodynamic film thickness in a steel ball on glass flat contact under nominally pure rolling conditions. Steel balls with a range of isotropic roughnesses have been employed and measurements have focused on the mixed lubrication regime where the film thickness is comparable to or below the composite surface roughness. It has been found that full film lubrication is only realised when the nominal lambda ratio (λ) has a value of 2 or higher. Below this value, the film thickness decreases, first gradually and then rapidly, as the nominal smooth surface lambda ratio decreases. The mixed regime, where both roughness and entrainment velocity influence film separation, appears to span a large range in terms of the lambda ratio, from $\lambda = 2$ to $\lambda = 0.1$. The mean separation between rough surfaces in static contacts has been measured over a range of loads and the problem of the precise definition of lubricant film thickness in rough surface conditions is discussed.

Friction and Wear Reduction by Boundary Film-forming Viscosity Index Improvers.

Selda Günsel, Matthew Smeeth and Hugh Spikes

SAE Technical Paper Series No. 962037, Subjects in Engine Oil Rheology and Tribology (SP - 1209) 1996.

Recent work by the authors has indicated that some types of viscosity index improver polymers can form thick boundary films in lubricated contacts. These films appear to result from the adsorption of molecules of polymer on metal surfaces to produce layers, about 20 nm thick, having higher polymer concentration and thus higher viscosity than the bulk solution. In the current paper it is shown that these VII boundary films are able to separate rubbing surfaces in both rolling and sliding contacts and that they make a significant contribution towards reducing friction and wear at temperatures up to at least 140°C. The mechanism by which these polymers reduce friction and wear is elucidated.

Fractionation of liquid lubricants at solid surfaces.

Gao Guangteng, Hugh Spikes
32. Wear, 200, pp.336345,(1996).

The film-forming properties of lubricant base fluid mixtures in elastohydrodynamic contacts have been studied using ultrathin film interferometry. It has been shown that in binary mixtures where one of the components is more polar than the other, the EHD film thickness formed in the very thin film (10 nm region) is controlled by the viscosity of the polar component rather than the viscosity of the blend. This means that a mixture of a highly viscous ester in less viscous hydrocarbon gives thicker than predicted lubricant films in the sub 20 nm region and vice versa. This phenomenon can be ascribed to the fractionation of the lubricant mixtures close to the surface caused by lubricant molecule/surface van der Waals forces.

Friction behaviour of ZDDP Films in the Mixed, Boundary/EHD Regime.

Giuseppe Tripaldi and Antonio Vettor

SAE Technical Paper Series No. 962036, Subjects in Engine Oil Rheology and Tribology (SP - 1209) 1996.

Recent work in the literature has suggested that the poor performance in the ASTM Sequence VI fuel efficiency test may result from an inappropriate balance of ZDDP antiwear agents. This paper describes a study of the friction behaviour of ZDDPs. Two recently-developed techniques have been employed to chart the variation of film thickness and friction of ZDDP-containing oils from the EHD through to the boundary lubrication regimes. It is shown that some secondary ZDDP additives give significantly higher friction coefficient in the mixed EHD/boundary regime at temperatures above 80 °C. This behaviour is very similar to that seen using formulated ASTM Sequence VI reference oils. Film thickness measurements show that the onset of high friction seen with the ZDDPs correlates with the formation of a solid-like reaction film in the lubricated contact.

Prediction of the influence of lubricant formulations on Fuel Economy, from Laboratory bench test.

Charles Bovington and Hugh Spikes

34. Proceedings of the International Tribology Conference Yokohama 1995.

This paper shows how a combination of bench tests, measuring relevant lubricant properties, allows the prediction of the influence of oil formation on gasoline engine fuel economy under different operating conditions and in different engines. Correlations with performance Seq VI and Seq VIA engine tests are demonstrated.

The Control of Friction by Molecular Fractionation of Base Fluid Mixtures at Metal Surfaces.

Gao Guangteng and Hugh Spikes

STLE preprint No.97-AM-4E-1, Presented at the 52nd Annual meeting In Kansas City, Missouri 1997.

The elastohydrodynamic film forming and friction properties of ester/hydrocarbon lubricant base fluid mixtures have been measured down to the very thin film regime. The film thickness results show that the near-surface viscosity, and thus elastohydrodynamic (EHD) film formation in the thin film region, is dominated by the rheological properties of the ester even when this has only low bulk concentration. This suggests that the ester in a blend, being the more polar component, concentrates close to the rubbing surfaces. The friction measurements show that this fractionation of ester close to the surface has a direct influence on the friction coefficient in the mixed lubrications regime. When a lubricant is blended from a higher viscosity ester and a lower viscosity hydrocarbon, the resultant enhancement of viscosity close to the surfaces, and thus of the EHD film thickness, produces a transition from boundary to EHD lubrication at lower speeds than would otherwise be the case. The converse is seen when a lower viscosity ester is blended in a higher viscosity hydrocarbon. Mixing appears to have little effect on the thick film EHD traction properties. The findings have implications for the design of energy-efficient liquid lubricants.