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Elastohydrodynamic Performance of Unexcited Electro-Rheological Fluids.

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ABSTRACT

Exploratory test results are presented for a series of mixtures of unexcited electro-rheological (ER) fluids under elastohydrodynamic lubrication (ehl) conditions. These were obtained from direct observation of film formation in an optical interferometric apparatus. Results are presented as photographs of the fluid film and plots of film thickness versus speed for a range of ER fluid solid fractions. Adequate film formation is limited by the tendency of the solid particles to evade the contact region. At very low contact speeds particles enter the ehl contact and generate a fluid film. At higher speeds the particulates do not become entrained in the contact; the film formation is then determined by the viscosity of the base fluid.

1. Introduction

ER fluids promise their greatest potential in fast, flexibly operated machines where inertial loading is high. In such operating regimes the fluid must fulfil a number of functions. It must minimise friction at the contact points to reduce heat generation and power loss. It must prevent excess wear to achieve an extended machine service life. And it should carry away any generated heat from the interface sites. The fluid must therefore perform adequately as a lubricant. Depending on the nature of the machinery this lubricity may be required over the boundary, hydrodynamic, and elastohydrodynamic lubricating regimes.

In earlier work[1] a pin-on-disk machine was used to study the lubricating properties of unexcited ER fluids in the boundary regime. The chemical reactivity of the base fluid was considered to be most important in the reduction of friction and wear. The chemically active base fluid (polychlorinated biphenyl) showed lower wear rates than the relatively non-polar base fluid (silicone oil). The active components in the former are believed to be physically or chemically absorbed onto the component surfaces providing a thin 'boundary' film. The wear behaviour in the presence of a suspended solid phase showed anomalous behaviour. The chemically active base with suspended particles showed a higher wear rate than the base fluid alone. The non-polar fluid showed similar wear rates both with and without particulates (although the particulates were noted to reduce friction coefficients). The particles appear therefore to be able to act as either suspended abrasives or solid lubricants. In all cases wear rates were found to be significantly higher than those for a mineral oil (of comparable viscosity).

The film formation in the hydrodynamic regime has also been investigated[2]. The test procedure involved pressure measurements in a Rayleigh step bearing at constant film thickness (higher viscosity fluids generate greater pressures and therefore have the best load carrying capacity). The behaviour of an ER fluid, and ER base fluid was compared to a mineral oil (the viscosity of which was chosen to be in between that of the base fluid and the mixture). The pressures developed were found to be in proportion to their viscosities. It was the viscosity of the particle/fluid mixture that was found to be significant in determining the pressure generation (and hence lubricity) of an ER fluid. These findings were then used in later work[3,4] to predict film formation in unexcited and excited hydrodynamic applications.

The purpose of the present work programme was to examine the performance of an ER fluid in the elastohydrodynamic lubricating regime. The study is limited to an investigation of the basic parameters controlling film formation.

2. Test Method

2.1 Apparatus

In order to study the generation of an elastohydrodynamic lubricant film, it is instructive to replace one of the contacting elements by glass. The motion of the suspended particles and the generation of a separating film can then be directly observed. The apparatus used for these tests is shown in figure 1(a).

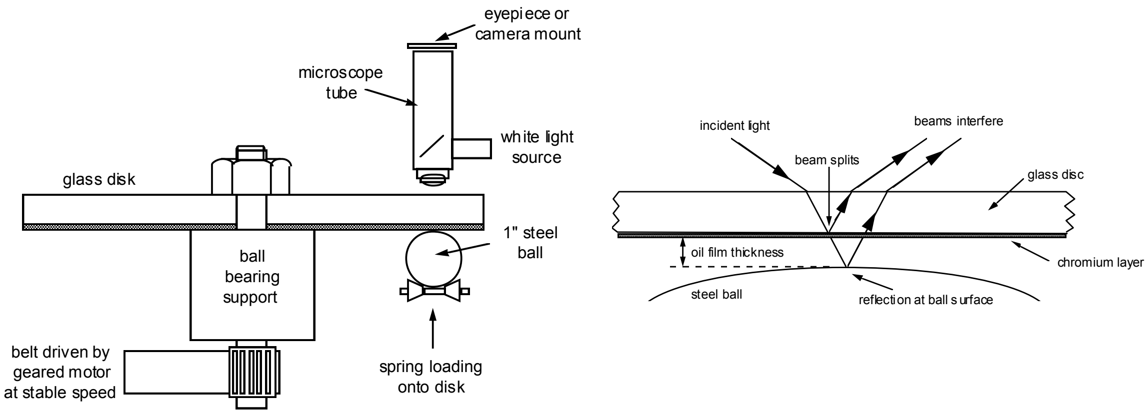

Figure 1. Schematic diagram of (a) the optical interferometric apparatus, (b) interference of an incident and reflected light.

A steel ball is sprung loaded onto the underside of a glass disk. The spring force is maintained constant throughout the test. The load is such that a peak contact pressure is 0.5 GPa and the radius of the contact area is 180 μm. The disk is rotated at constant speed driving the ball. White light is shone through a beam splitter onto the contact. Figure 1(b) shows the mechanism whereby the light rays reflected back at the disk underside and the ball surface interfere to generate a fringe pattern (similar to Newton's rings). This fringe pattern is observed from above through a microscope. The quality of the image is improved by the addition of a thin chromium coating as shown in figure 1(b). The colour of the fringe may then be related to the thickness of the lubricant film. Figure 2 diagramatically shows a typical fringe pattern generated by a mineral oil. The central region is at a greater separation compared to the surrounding 'horseshoe'.

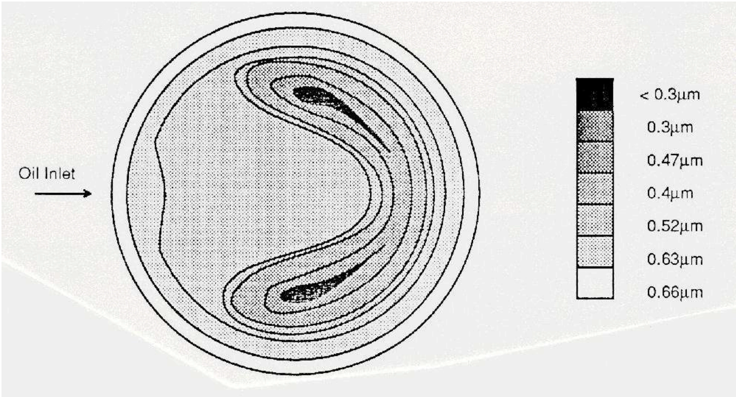

Figure 2. Diagrammatic map of a typical elastohydrodynamic fluid film generated by a mineral oil.

2.2 Test Fluids

The following fluids were used in the experiments. Table 1 summarises the properties of these test fluids relevant to this study.

(i) Electrorheological fluid consisting of a polydimethyl siloxane base oil (silicone oil) with a water free suspension of 6 μm mean sized polyurethane particles. Used in solid particle fractions of 30, 50, and 60%.

(ii) Electrorheological fluid consisting of 5 μm mean sized lithium polymethacrylate (lipol) particles in a dielectric base fluid.

(iii) The silicone and dielectric base fluids alone.

(iv) A standard mineral oil (Shell Tellus 68), with a similar viscosity to the ER fluid mixtures, for comparative purposes.

Base test fluid	Solid particle content	Viscosity, mPas at 22.5°C	Pressure viscosity coefficient, GPa-1
Silicone oil	30%	-	-
Silicone oil	50%	54	-
Silicone oil	60%	188	-
Silicone oil	0%	5	12
Dielectric fluid	30%	187	-
Dielectric fluid	0%	40	58
Shell Tellus 68	-	160	22

Table 1. Properties of the test fluids used in experimentation.

2.3 Test Details

The test fluid was fed onto the glass disk using a constant flow syringe so as to become entrained into the ball on disk contact. The temperature was maintained constant throughout the test (at 22.5°C). A video camera, with a shuttering speed of 1/4000th of a second, and recording at 25 frames per second, was used to record and freeze the moving images.

The fringe order is converted to an optical path difference and then to a fluid film thickness (by dividing by the refractive index). The lowest film thickness measurable by this method is 0.13 μm (corresponding to first order yellow fringe). Measurements are then limited to thicknesses corresponding to successive fringes (first order red, blue, green, then second order yellow and so on). In practice it is convenient to gradually increase the speed and record the point at which the central fringe changes colour. In this way the variation of fluid film thickness with speed can be investigated. Further details of this optical technique for measuring film thickness can be found in the text by Gohar[5].

For the test fluids two sets of tests were performed;

(i) Film generation with speed of rotation. The film thickness was monitored as rolling speeds were increased from zero to 50 mm/s.

(ii) Film generation with time. It was noted that fluid films were not generated immediately on start-up. For each fluid, therefore, film build at low speed up was monitored with time.

All tests were carried out at room temperature. ER fluid film measurements (because of the irrepeatability of the particle entry process) were carried out four times.

3. Results

3.1 ER Fluid Base Oils and Mineral Oil Film Generation

The silicone base oil produced no measurable fluid film in the speed range used[†]. The more viscous dielectric base oil generated a measurable film at around 150 mm/s. The mineral oil produced a measurable film at a speed of 70 mm/s. Both fluid films were stable with time, responded immediately to speed alteration and showed a thickness increase with speed increase. Figure 3(f) and (h) shows the test measurements.

Hamrock and Dowson[6] give a relation for the thickness[‡] of an elastohydrodynamic lubricant film, h_c generated by a Newtonian fluid;

$$\frac{h_c}{R} = 2.69\left(\frac{U\eta}{2E^*R}\right)^{0.67}\left(2\alpha E^*\right)^{0.53}\left(\frac{W}{2E^*R^2}\right)^{-0.067}\left(1-0.61\mathrm{e}^{-0.73k}\right)$$

Where R is the ball radius, W the applied load, U is the mean speed of the surfaces, k is the ellipticity parameter (in this case k=1.03), α the pressure viscosity coefficient, η is the viscosity of the fluid at the inlet temperature, and E^* is the reduced modulus, given by;

$$E^* = \left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right]^{-1}$$

Where E_1 and ν_1 are the modulus and Poisson's ratio of surface 1. Figures 3(i), (g), and (j) show the fluid film thickness predictions for the mineral oil and the two base fluids using this relation. Agreement between test data and prediction for the mineral and dielectric base fluid is good. The prediction for the silicone base fluid shows film thickness below the measurable limit.

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† It is possible that at higher speed a film would have been generated. However operating the apparatus at low film thickness and high speed tends to result in costly wear damage to the disk.

‡ This value corresponds to the film thickness in the central plateau region (see figure 2) and is usually taken as being representative of the average thickness of lubricant film.

3.2 Preliminary Observations on ER Fluid Film Generation

Fluid films were only produced by the silicone based mixtures at low speeds. Video of the contact showed the bulk of the suspended particles being swept around the contact sides. A mass of particles appeared trapped in the inlet region from which some passed into the contact (the particle entry being dominated by contact speed). These became plastically flattened out and produced regions of separating film. The film formation was apparently controlled by this particle entry process. Ball motion appeared slightly jerky as discrete masses of particles entered the contact.

The photograph included as figure 4(a) shows the fluid film. The film is typically patchy, with thicker regions corresponding to a mass of particles. Frequently a central strip of greater separation is observed (corresponding to the region where most entrained particles pass).

Some of the glass disks had some fine surface scratches present after testing with ER fluids. It is not clear whether this surface damage was caused by the particles themselves, some foreign contaminant, or from direct contact between the ball and disk when no film is present.

3.3 Film Generation with Speed

As the speed was increased fewer particles become entrained into the contact and the film thickness falls. At speeds of around 30 - 50 mm/s particles were unable to enter the contact and no measurable film was formed. Figure 3 (a), (b), and (c) show the plot of film variation with speed for three particle concentrations.

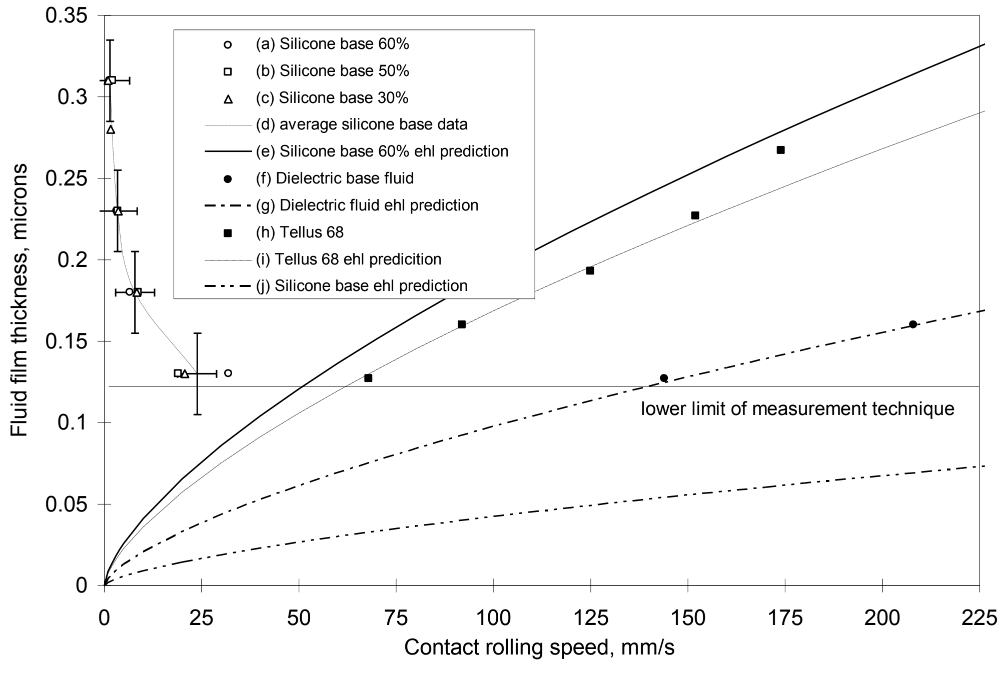
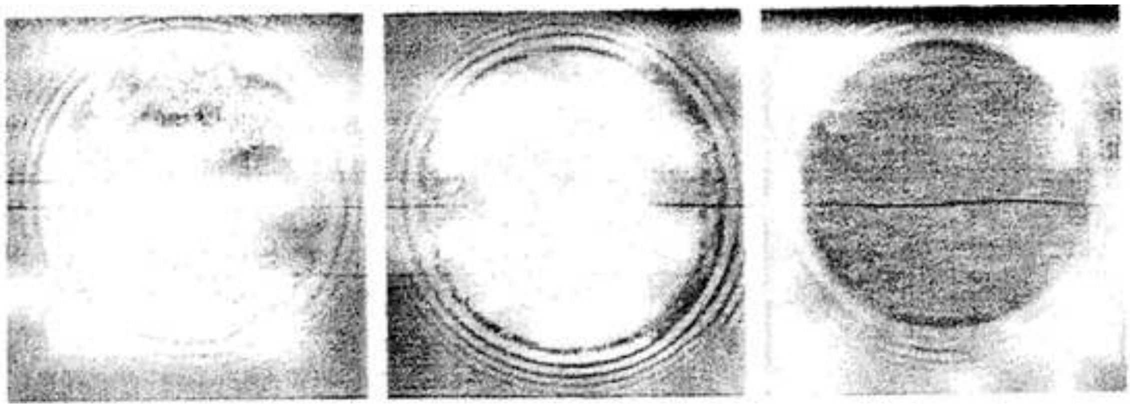


Figure 3. Plot of film thickness against rolling speed. Test data for: three silicone based ER fluid mixtures, a dielctric base fluid, and Shell Tellus mineral oil. Hamrock and Dowson theoretical predictions for: mineral oil, dielectric base fluid alone, silicone base oil, and a 60% mixture ER fluid.

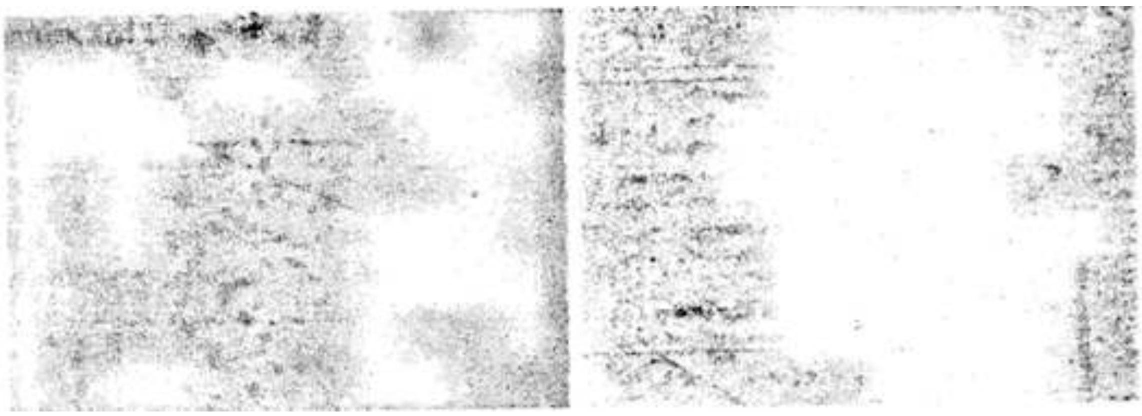
Each data point is the average of four measurements, the scatter is demonstrated by the error bars. The horizontal line represents the lower limit of the measuring technique (the thickness corresponding to the formation of the first light interference fringe). In figure 3 the theoretical predictions of the Hamrock and Dowson equation are also displayed. The mineral oil and dielectric fluid alone shows good agreement with test data. The predictions for the silicone based ER fluid, shown as curve (e), are calculated assuming the fluid is Newtonian with a viscosity equivalent to that of the fluid mixture. Clearly for ER fluids this assumption is not appropriate. Figure 4 shows a sequence of photographs of the film formation behaviour at increasing rolling speed.



(a) (b) (c)

Figure 4 - Photographs of the fluid film generated by 60% silicone based ER fluid mixture. The sequence shows the effect of the increase in speed (a) 1.7 mm/s, (b) 15 mm/s, and (c) 27 mm/s.

After testing, the glass disk was careful removed (without disturbing the adhered fluid) and examined under an optical microscope. Figure 5 shows the tracks where the ball has passed at (a) high and (b) low rolling speed.



(a) (b)

Figure 5. Tracks on the disk left by the passage of the ball rolling at; (a) high speed - 50 mm/s; and (b) low speed - 3 mm/s.

At low speed the contact has a concentrating effect. Particles are entrained into the contact and assist in the generation of a film. A track of fluid with a higher particle concentration than the bulk is left on the surface. At higher speeds these particles are swept to the sides of the contact. This leaves a depleted region of fluid on the rolling track surface.

It is likely that at still higher speeds the ER silicone base fluid alone will start to generate a measurable film; and the curves 3(a), (b), and (c) will tend to curve 3(j). However, this could not be verified since operating the apparatus at high speed with low film thickness causes costly surface damage to the coated glass disk.

3.4 The Effect of Particle Concentration

Fluids of 30%, 50%, and 60% solid content were tested in the above manner. For these fluids, particle concentration seems to have no substantial effect on film formation within the scatter in the results (see curves a, b and c on figure 3). These three fluid mixtures are of greatly differing viscosity (60% is some three times more viscous than 50%). This has little effect on the film thickness; again we see that it is the entry behaviour of the particles, and not the mixture viscosity, that dominates film behaviour.

Video photography shows a build up of particles in the inlet region which then pass into the contact. The concentration in this area would therefore be of most relevance to the entry process. This ‘inlet region concentration’ may not be particularly dependent on the ‘bulk particle concentration’. However, it is likely that at lower bulk concentrations, the entry of particles (and film formation) will show a greater dependency on concentration.

3.5 Film Generation with Time

The mineral oil and dielectric base oil immediately developed a fluid film on start-up which subsequently remained stable with time. The silicone base oil negligible film condition also did not alter with time. However the silicone based ER fluids did not generate fluid film immediately. Figure 6 shows the variation of film thickness with time for a 60% mixture ER fluid at a rolling speed of 3 mm/s.

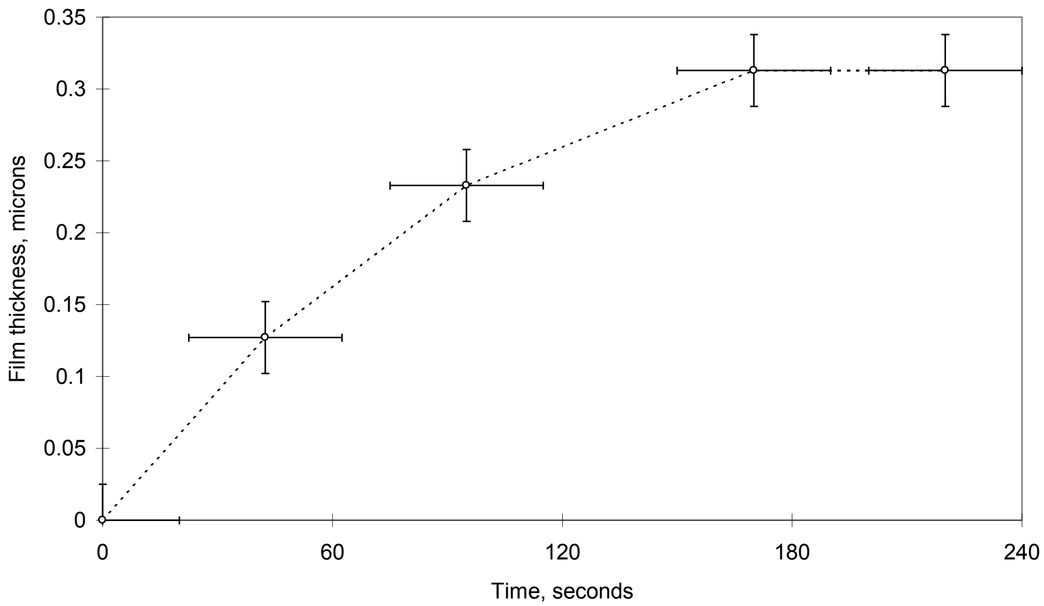


Figure 6. Variation of film thickness with time for a silicone base 60% mixture ER fluid at a rolling speed of 3 mm/s.

Some three minutes was required before a film was generated (this corresponds to several complete revolutions of the ball). It appeared that during this time solid particles were adhering to the ball and disk surface. A few revolutions were required before sufficient particles were adhered and/or entrained into the contact. The film formation therefore seems also to be partly governed by the ability of the solid particles to adhere to the rolling elements. Examination of the rolling tracks did not suggest firmly bonded particles; rather particles weakly adhered or electrostatically attracted to the surfaces.

4. Discussion

The limit of ER fluid machinery is frequently determined by thermal considerations (heat generation and removal) resulting in melt, expansion, or breakdown of continuum. The presence of increasingly rapid accelerations and high inertia has resulted in flow mode designs requiring high system pressures (fulfilling the need to keep the parasitic mass of hydraulic components low). Under these conditions of high temperature, load, and speed, the service life of the system is likely to be governed by failure of the lubricated conjunctions.

Fluid film formation is dependent on the entry of solid particles into the loaded conjunction. In turn this entry process is dependent on fluid forces acting on particles in the contact inlet region. At higher speed these drag forces increase and particles are more likely to be swept around the contact sides. Thus slow speed operation allows particle entry whilst higher speed reduces it. Complimentary research[7] into the entry process for other particle sizes and materials has also the importance of film thickness and particle size. The results presented in this paper represent the case relevant to ER lubricity.

The continuum assumption, which appears to hold for hydrodynamic lubrication processes[2], is clearly not appropriate in the elastohydrodynamic case. The separation of moving components is of the same order as the particle size (in contrast to that in hydrodynamic pad or journal bearings).

These results show the difficulty in achieving adequate lubricating films at realistic contact speeds (typically a rolling bearing might operate at speeds of 0-5 m/s). Lubricating films should ideally be thicker than the combined surface roughness of the contacting elements (typically 0.1 - 1 μm for a ground surface) to minimise surface contact and hence friction and wear. Thus to achieve adequate elastohydrodynamic lubrication with an ER fluid a viscous base is required. This raises a dilemma. The contribution of this base viscosity to the overall ER fluid mixture viscosity would, at high speeds, result in excessive heating and power loss by viscous shearing.

If such a condition cannot be tolerated then components which would usually operate under ehl (counterformal contacts such as bearings, gears, or cams) will experience a boundary lubrication regime. It is then the ‘surface activity’ of the base oil which will be important in the control of friction and wear[1].

5. Conclusion

The generation of elastohydrodynamic films by the ER fluids tested is controlled by the viscosity of the base oil and the entry of particulates into the loaded conjunction. At realistic operating speeds particle entry is restricted and a viscous base oil is required to generate a sufficient separating film.

With the present generation of fluids the average particle sizes are an order of magnitude greater than typical concentrated contact film thickness using good lubricants. The continuum assumption for these ER fluid mixtures is therefore not valid under elastohydrodynamic conditions. However, at low speeds some particles do pass through the contact and assist in film formation. However, there is also evidence that compaction of these particles in the contact zone may cause surface damage.

Based on the results of this study, the following are broad recommendations for machine operation and fluid design to optimise elastohydrodynamic lubricity:

(i) Base oil viscosity should be maximised, within the constraints of fluid stability and viscous heating effects.

(ii) Low operating speeds and periods of start-up under low load, would be beneficial in the formation of 'particle assisted' separating films.

(iii) Where a high viscosity cannot be tolerated a surfactant base should be used to maximise boundary lubricating properties.

(iv) Fluids with much lower particle sizes, may fulfil the continuum assumption, and perform improved elastohydrodynamic lubrication.

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