

Influence of dumbbell base oil blends on micropitting

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ABSTRACT

Micropitting is a type of surface fatigue that occurs in rolling-sliding contacts. It results from stress fluctuations caused by surface asperity interactions. Both the number and severity of asperity interactions increase at low lambda ratios, so it is becoming a significant challenge to develop low viscosity lubricants for gears and rolling bearings that mitigate micropitting effectively. In this paper, the influence on micropitting of dumbbell blends of PAOs and PIBs with an equivalent kinematic viscosity at test temperature is studied. The result shows that appropriate blends of PAOs and PIBs are able to provide thick oil film thicknesses and reduce micropitting while maintaining low viscosity. The insights here can help with the design of lubricants that are effective in controlling micropitting.

1. Introduction

Micropitting is a type of surface fatigue damage that occurs in high pressure, lubricated rolling-sliding contacts operating under thin lubricant film conditions. In such conditions, surface asperity interactions lead to stress fluctuations at the asperity scale. These result in the initiation of numerous surface cracks that then propagate and interact to cause fragments of material to detach from the surface, leading, in some cases, to high rates of material loss known as *micropitting wear*. Micropitting wear is becoming one of the most important failure modes in gears and rolling bearings because of increases in the power density of mechanical systems and the introduction of low viscosity lubricants, both of which lead to a greater number of more severe asperity interactions [1]. Despite this, the underlying mechanisms of micropitting are poorly understood and there are currently no universally accepted design criteria. Some of the factors recognised to affect micropitting include specific film thickness [1,2], contact pressure [3,4], surface roughness [5–9], sliding magnitude and direction [2,4], steel hardness [8,10,11] and lubricant antiwear [7,9] and friction behaviour [6, 12–14]. Among these, the specific film thickness, commonly defined via the lambda ratio, i.e. the ratio of lubricant film thickness to composite surface roughness, is a significantly influential parameter in micropitting [1].

Decreasing lambda ratio raises the number and severity of asperity interactions, so that it might be expected that decreasing lambda will also increase micropitting. However, in practice, this simple relationship

between lambda and micropitting does not hold when mild adhesive or abrasive wear is present. Morales-Espejel et al. [1,5] showed that in the presence of mild wear, micropitting may reach a maximum value as lambda decreases, after which any further decrease in lambda value leads to reduced micropitting. This trend is a direct result of the continuous competition between micropitting and mild wear. The key aspect is that while low lambda combined with minimal surface wear promotes accumulation of asperity contact cycles and consequently increases micropitting, the occurrence of significant rates of mild wear reduces surface roughness and thus the number and severity of asperity stress cycles, as well as continually removing small, surface-initiated cracks.

One way for lubricants to control the balance between micropitting and mild wear in low lambda conditions is to control the ability of antiwear additives to form tribofilms. Previously, the authors showed that the rapid formation of antiwear tribofilms early in operation prevented adequate running-in of the initially rough surfaces [7]. This resulted in high asperity stresses throughout subsequent operation, causing increased micropitting. By contrast, a lack of effective antiwear tribofilm enabled running-in, and thus reduced micropitting damage, but eventually led to component failure due to excessive wear.

Recently, it has become a significant challenge to design lubricants to protect gears and bearings from both micropitting and mild wear because of the trend to use very low-viscosity oils to reduce hydrodynamic friction and thus increase mechanical efficiency. Generally, transmission component manufacturers impose upper limits to

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kinematic viscosity (KV) at a certain temperature as a main requirement of lubricants for use. As KV is reduced, so generally is the elastohydrodynamic (EHD) lubricant film thickness and thus the lambda ratio. One challenge for lubricant designers is thus to reduce kinematic viscosity (KV) while still maintaining a thick lubricant film. EHD film thickness depends on the effective viscosity of the lubricant in the pressurised contact inlet and thus on both a lubricant's dynamic viscosity and its pressure viscosity coefficient [15]. LaFountain et al. [16] showed that pressure viscosity coefficient (alpha value) depends on the molecular size of polyalphaolefin base oils (PAOs) and that it varies approximately linearly with log (dynamic viscosity), both for neat PAOs and blends of PAOs of different viscosities. Since EHD film thickness increases with alpha, PAO blends with high alpha values might thus reduce micropitting. Polyisobutenes (PIBs) have considerably higher alpha values than PAOs due to their bulky molecular structures [17], so these are likely to increase lambda ratio and hence mitigate micropitting. Unfortunately, it is also well-reported that PIBs give high friction coefficients in EHD contacts [18], and it has been shown that high friction can promote micropitting by increasing tensile and shear stresses around contacting asperities [12]. Clearly, the prediction of the effect of PIB blends on micropitting is not simple and easy.

One possible approach is to use dumbbell blends of PAOs and PIBs. Dumbbell blends are mixtures of pairs of base fluids having very different viscosities, and using these it might be possible to obtain the “best of both worlds”; i.e. the low EHD friction coefficient of the lower viscosity component and the high alpha value of the higher viscosity component. Methods for predicting the high pressure viscosity of lubricant blends have been developed. Hayashi et al. [19] showed that for many blends the pressure viscosity varied linearly with log(kinematic viscosity) for two-component blends while Hata et al. [20] developed a model for predicting the viscosity of polymer blends in base oils at high pressures.

Understanding the pressure and shear dependence of viscosity is important to understand the mechanisms of film forming and friction in concentrated contacts. The rheology of mixtures of polymer blends have been well studied [19–23]. Bair et al. [21] studied that shear-dependent viscosities have been measured and were fitted to a generalized Newtonian model with the effective shear modulus specified by an empirical power-law shifting rule. Compared with olefin copolymer (OCP) and polymethacrylate (PMA), the use of PAO 40 as a thickener delayed shear-thinning to very high stress. Based on the shear thinning behaviour of PAO4-PAO100 and PAO4-PAO600 blends, the Grunberg–Nissan mixing rule [24], with effective mole fractions, provides an good mixing rule for the temperature and pressure-dependent low-shear viscosity [22]. These previous studies found that blending of base oils of nearly equal proportions causes a broadening of the transition to power-law behaviour. When the concentration of the higher viscosity component is small, there are two transitions in the power-law exponent. The viscosity mixing rule for PAO is independent of pressure while for PIB it is not.

As well as their piezoviscous response, base blends with high molecular weight components are also likely to experience shear thinning at the high shear stress conditions present within EHD contact inlets and this will affect their effective viscosity and thus film thickness [25,26]. Thus, estimation of high pressure viscosity of the mixture of PAO and PIB, especially the one with high molecular weight, is still a challenge. In addition to effects of blending on EHD film thickness there is limited evidence that some dumbbell blends of PAOs may show beneficial EHD friction properties [16]. Therefore, it is of practical and as well as theoretical interest to understand the influence of dumbbell blending of PAOs and PIBs on EHD film thickness, friction, micropitting and mild wear. However, there has been very limited previous work on the tribological behaviour of dumbbell blends, and apparently none on micropitting.

In view of this, this paper aims to clarify the effect of dumbbell blends of PAOs and PIBs on micropitting. First, the effect of dumbbell

blends of PAOs and PIBs with different molecular weights on micropitting was measured, varying the proportions of the two blend components to give a set KV at the test temperature of 100 °C. Second, the EHD oil film thickness and friction properties of the test blends were investigated to understand the mechanism by which they might affect micropitting. Thirdly, polymer shear thinning in the contact was studied to help interpret the film thickness behavior of the dumbbell blends. The results obtained provide practical insight into the formulation of lubricants with anti-fatigue performance and some understanding of the relevant mechanisms by which lubricant additives mitigate micropitting.

2. Test methodology

2.1. Experimental equipment

All micropitting tests were conducted using a Micropitting Rig (MPR, PCS Instruments, London) [9], schematically illustrated in Fig. 1. The rig is based on a triple contact design whereby a central roller specimen is in contact with three counterface discs as shown in the photograph of the inside chamber of MPR (Fig. 2). This gives three roller contact cycles per roller revolution and thus facilitates study of fatigue processes such as micropitting. The three counterface discs are located 120° apart which results in equal reaction force at each of the three roller–disc contacts. The roller and set of counterface discs are driven by separate motors. Test specimens are lubricated using a temperature-controlled dip lubrication system, with the bottom two counterface discs partially submerged, so that they drag oil into all three contacts during operation. Oil temperature is measured using a thermocouple positioned within the test chamber and controlled via a heating/cooling system. Load is applied to the roller specimen through the top disc via a motorized loading arm.

2.2. Test specimens

Details of the geometry and properties of the test specimens used are shown in Fig. 3. The test specimens employed in this study were a 12 mm diameter test roller and 54.15 mm diameter cylindrical counterface discs. The disc-roller contact is formed transverse to rotation over a 1 mm wide contact track on the roller, resulting in a truncated line contact. All specimens were made of case-carburized 16MnCr5 gear steel. The test roller case depth was approximately 0.9 mm and the measured hardnesses of the test roller and the counterface discs were 670 ± 20 HV and 750 ± 20 HV, respectively. Harder discs were employed to ensure that the surface of the counterface discs remained largely unchanged over the test duration and that the micropitting damage was preferentially generated on the test roller. The surface

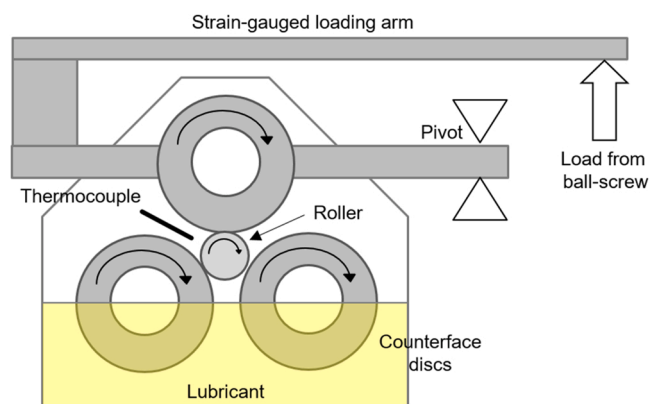


Fig. 1. A schematic of the micropitting test rig including the loading mechanism.

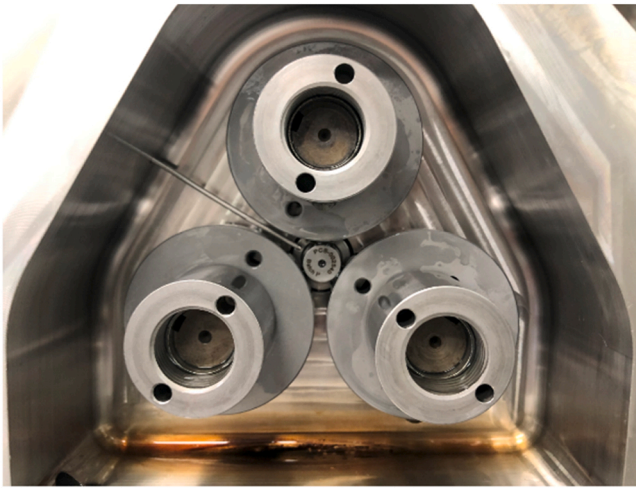


Fig. 2. Inside of MPR test chamber showing the central roller and the three counterface discs.

finish of the specimens was carefully controlled to minimize the variation between tests. All rollers and discs were circumferentially ground so that the roughness lay was oriented in the rolling direction on all specimens. All surface roughness values were measured using a stylus profilometer. The measured surface roughnesses of both the test roller and counterface disc were $Ra = 0.125 \pm 0.02 \mu\text{m}$ and were averages of four measurements for each specimen taken in the direction transverse to rolling direction. It should be noted that minor variations of the roller roughness were largely irrelevant since the roller was softer than the discs, so its initial surface topography was very quickly modified through running-in and later by micropitting. By contrast, the roughness of the harder counterface discs is of major significance since it persists during the test. This means that any significant roughness variation from specimen to specimen would affect the relative rates of micropitting.

2.3. Test conditions

Test conditions were chosen to be representative of steel gear applications as well as to ensure that micropitting was produced in preference to excessive mild wear. If mild wear occurs it is difficult to study micropitting quantitatively since there are competing damage mechanisms. Also excessive mild wear, particularly of the harder counterface, inhibits crack initiation and propagation [7]. Table 1 shows the test conditions employed in the MPR tests to generate micropitting. In all tests, maximum Hertzian pressure, entrainment speed, slide-roll-ratio (SRR, see Table 1 for definition), oil temperature, and test cycles were the same. MPR tests were carried out for 18 million cycles on the rollers (a test time of 20.4 h). SRR was held at a relatively small value of -5% to promote micropitting with little mild wear, and also to minimize frictional heating [4]. It was calculated that frictional heat increased contact inlet temperature from 100°C to ca. 106°C in all tests [4].

2.4. Test lubricants

Table 2 lists the viscometric properties of the six polyalphaolefin (PAO) and five polyisobutene (PIB) base fluids used in this study. For the PAOs, as is conventional the number after PAO corresponds the approximate KV at 100°C , i.e. PAO4 has $4.1 \text{ mm}^2/\text{s}$ of KV at 100°C . Molecular weight (MWt) was measured using gel permeation chromatography. As expected, viscosity index increases with MWt and thus viscosity for each class of base oil and is greater for PAOs than PIBs of equivalent MWt.

Table 3 (a) and (b) show the base oil ratios of 13 test blends; (a) six blends of pairs of PAOs and (b) seven PIB blends, six of PIB with PAO and one blend of two PIBs. All blends were formulated to a KV close to $7.0 \text{ mm}^2/\text{s}$ at 100°C and thus a dynamic viscosity (DV) of ca. 5.5 cP at 100°C . High viscosity PAOs and PIBs were blended with mainly PAO4 while PAO2 was employed to increase the ratio of PAO40, PAO300, HV35 and HV1900 in dumbbell blends. To limit mild wear, a SP anti-wear additive combination based on phosphate and thiophosphate was included in all test lubricants at a concentration of $0.12 \text{ wt\% P}$ and $2.2 \text{ wt\% S}$. These additives are commonly employed in axle oils at such a

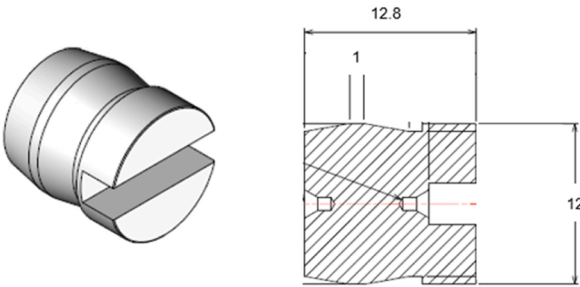
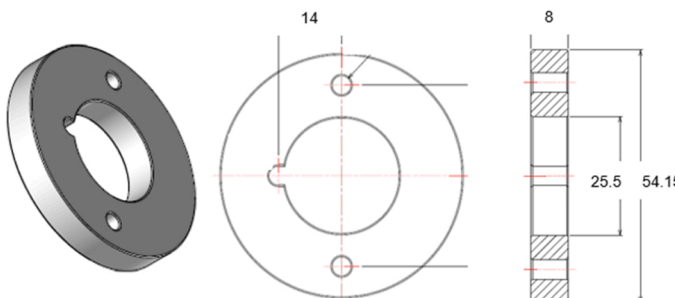
	Geometry	Others
Roller		Material: 16MnCr5 Measured hardness: $670 \pm 20 \text{ HV}$ Surface roughness: $Ra=0.125 \pm 0.02 \mu\text{m}$
Counterface disc		Material: 16MnCr5 Measured hardness: $750 \pm 20 \text{ HV}$ Surface roughness: $Ra=0.125 \pm 0.02 \mu\text{m}$

Fig. 3. The geometry and property of MPR specimens of a chamfered roller and a cylindrical disc (not to scale). Dimensions shown are in mm.

Table 1

MPR test conditions.

Maximum Hertzian pressure	2.0 GPa (550 N)
Entrainment speed	3.15 m/s
Slide-roll-ratio (SRR)	-5% (roller surface speed U_{roller} is slower than disc surface speed, U_{disc})
$2 * (U_{roller} - U_{disc}) / (U_{roller} + U_{disc})$	
Bulk oil temperature	100 °C (Contact inlet temperature: ca. 106 °C)
Test cycles	18 million (test time 20.4 hrs)

Table 2

Property of base oils.

Base oil	Density, g/cm ³ 15 °C	KV, mm ² /s		VI	Approximate Mwt
		40 °C	100 °C		
PAO2	0.79	5.6	1.8	N/A	400
PAO4	0.82	18.6	4.1	126	700
PAO10	0.84	63.9	9.7	134	1300
PAO40	0.85	396.5	39.9	151	3400
PAO100	0.85	1231	98.7	167	6000
PAO300	0.85	3386	305	241	14,500
LV7	0.83	11.6	2.7	49	400
LV50	0.85	108	9.8	57	840
HV35	0.88	2373	87.4	95	1500
HV300	0.90	26,370	592.8	155	4000
HV1900	0.91	160,000	3710	257	9700

concentration to lubricate gears and bearings.

2.5. Micropitting test procedure

Prior to each micropitting test, fresh roller and disc specimens were cleaned in toluene. The specimens were then mounted in the MPR, the oil bath filled with the lubricant and a rolling-sliding test of 18 million cycles started. After the test, the roller and the discs were rinsed in toluene in an ultrasonic bath for 10 min to remove supernatant oil prior to surface measurements. Micrographs of surface cracks and micropitting on the roller were obtained using an optical microscope. The averaged percentage of micropitted area on the roller wear track was quantified from the optical micrographs at 10 positions in the wear track around the circumference of the roller using Image J (Wayne Rasband, National Institute of Health). This image processing software allows the area of micropits and cracks, which have different optical contrast from wear tracks without such surface damage, to be quantified. Surface roughness values of the discs after the tests were measured using a stylus

Table 3

Test oil formulations (a) PAO blends and (b) PIB blend. DV is dynamic viscosity. All blends include a SP additive combination.

(a) Oil code	Formulation (Base oil + SP additive)						DV, cP	KV, mm ² /s		VI
	PAO2	PAO4	PAO10	PAO40	PAO100	PAO300	100°C	40°C	100°C	
PAO4 + PAO10		31	69				5.5	38.8	6.9	136
PAO4 + PAO40		70		30			5.5	37.1	7.0	151
PAO2 + PAO40	45			55			5.5	35.1	7.1	171
PAO4 + PAO100		80			20		5.5	36.0	7.0	158
PAO4 + PAO300		86				14	5.5	34.2	6.9	169
PAO2 + PAO300	67					33	5.5	28.8	7.0	220
(b) Oil code	Formulation (Base oil + SP additive)						DV, cP	KV, mm ² /s		VI
	PAO2	PAO4	LV7	LV50	HV35	HV300	100°C	40°C	100°C	
LV7 + LV50			16	84			5.6	58.4	7.0	65
PAO4 + LV50		19		81			5.5	54.3	7.0	82
PAO4 + HV35		72			28		5.6	40.9	7.0	132
PAO2 + HV35	49				51		5.6	41.8	7.1	145
PAO4 + HV300		82				18	5.5	38.8	6.9	137
PAO4 + HV1900		89					5.6	37.3	7.1	155
PAO2 + HV1900	77						5.5	31.5	7.0	196

profilometer. The quoted roughness values are averages of measurements from all three discs. For each disc, four different profiles were measured transverse to rolling direction. All tests shown in this paper were repeated twice.

2.6. EHD oil film thickness

The EHD film-forming properties of the test oils were measured using an ultrathin film measurement system (EHD2, PCS Instruments), both to measure EHD film thickness and thereby to estimate effective pressure viscosity index, i.e. alpha value. This measurement system employs optical interferometry to measure lubricant film thickness in a pure rolling contact. In this type of film thickness measurement, a steel ball/glass disc tribopair is most often employed to measure EHD film thickness, but this gives a relatively low contact pressure since, because of the low elastic modulus of glass, the reduced elastic modulus of the steel/glass combination is only 58 GPa as compared to that of steel/steel of 115 GPa. To ensure high contact pressure similar to the MPR tests, a WC ball/sapphire disc tribopair was employed [27]. This combination has a reduced elastic modulus of 280 GPa so that 45 N applied load gives a maximum contact pressure 2.0 GPa, the same as that in the microptting tests. At this high contact pressure contact, film thickness was measured over a range of entrainment speeds in nominally pure rolling.

2.7. ETM friction

An extreme-traction machine (ETM, PCS Instruments) was employed to obtain Stribeck curves (curves of friction coefficient *versus* entrainment speed at fixed slide-roll ratio) at a maximum contact pressure 2.0 GPa. An ETM rather than the more widely used MTM was used since the latter cannot reach the required contact pressure with steel test specimens. Test conditions are listed in Table 4. In the ETM a steel ball is loaded against the flat surface of a steel disc immersed in lubricant. The ball and the disc are driven by separate electric motors at user-specified rolling/sliding conditions. A 19.05-mm-diameter AISI 52100 steel ball and a 46 mm diameter AISI 52100 disc were employed and were

Table 4

ETM test conditions.

Mode	Stribeck
Maximum Hertzian pressure	2.0 GPa (290 N)
Entrainment speed	3–0.01 m/s
Slide-roll-ratio (SRR)	-5% (a ball is slower than discs)
$2 * (U_{roller} - U_{disc}) / (U_{roller} + U_{disc})$	
Bulk oil temperature	100 °C

supplied by PCS Instruments. Both specimens had smooth surfaces, less than 10 nm Ra.

2.8. USV

The high shear rate viscosity of the test oils was estimated using an Ultra Shear Viscometer (USV, PCS Instruments). The USV is based on a concentric cylinder geometry with a very small gap of typically between 1 and 1.5 μm . To avoid a significant temperature rise at high shear rates, a motor accelerates a flywheel to high speed and then a clutch system engages to transmit the rotational energy to the inner cylinder (rotor) for just a few revolutions at a set shear rate. In the USV, a series of engagements is generally made, one to obtain the temperature offset and then three consecutive engagements for measurement. A torque sensor is fitted to the outer concentric cylinder (stator), and the average measurements of the last three engagements are used to determine a viscosity value. The test temperature was 100 °C. A new test oil was used by flushing the previously used sample 10 times with fresh test oil. Sheared viscosity was measured in two ways.

1. to estimate temporary shear thinning, the test oils were measured once (4 cycles) in separate tests at shear rates of 10^6 and 10^7 s^{-1} . Before each measurement, the test chamber was cleaned by a fresh oil.
2. to study permanent shear thinning, the test oils were measured 10 times in succession (40 cycles) without an oil flushing between each measurement. The shear rate was 10^7 s^{-1} . Note that one measurement shears the test oils 4 times and gives an averaged sheared viscosity.

3. Micropitting results

3.1. Effect of PAO blends on micropitting

In this section the performance of the blends of low viscosity and high viscosity PAOs are described. Four blends are based on PAO4 blended with PAO10, PAO40, PAO100 and PAO300 respectively, while two are PAO2 blended with relatively high proportions of PAO40 and PAO300. Fig. 4 shows representative optical micrographs of the rubbed track on the rollers at two different magnifications at the end of tests with these PAO blends, as well as the measured percentage of micropitted area on the roller wear track. The variations listed are the standard deviation of 10 measurements. The directions of friction and contact motion are also shown.

Micropitting occurred on the rollers tested in all six blends. PAO4 + PAO10 and PAO4 + PAO100 gave 59% pitted area ratio. Compared to this, while PAO4 + PAO40 reduced micropitting to 49%, PAO4 + PAO300 slightly increased the pitted area ratio to 67%. The larger amount of PAO40 in PAO2 + PAO40 than in PAO4 + PAO40 slightly mitigated micropitting, with the pitted area ratio reduced from 49% to 45%. Compared to PAO4 + PAO300, the larger amount of PAO300 in PAO2 + PAO300 gave an equivalent micropitted area of 65%. On some rollers a blueish colour was observed and this is likely to be tribofilm from the SP additive.

From the magnified micrographs in Fig. 4, it can be seen that the surfaces contain a high density of uniformly spaced, V-shaped cracks and small pits in all cases. These cracks are oriented transverse to the rolling direction with length up to 50 μm . In some cases, adjacent cracks have coalesced or overlapped one other. This damage morphology was consistent around the whole circumference of the specimens and covered the entire width of the running track. It should be noted that in this study the test duration was insufficient to produce a significant depth of wear so that the initial stage of micropitting, in which the micro-cracks develop eventually to cover the surface, was being studied.

Metallographic sections of test rollers were prepared by cutting through the centre of the running tracks along the direction of rolling,

followed by polishing. Fig. 5 shows representative optical micrographs of such roller sections obtained from PAO4 + PAO10, PAO4 + PAO40 and PAO4 + PAO300 tests. The direction of friction and surface motion with respect to the contact is also shown. In all cases, cracks grow into the subsurface in the direction opposite to the direction of the applied friction force. It is evident that cracks generally form a shallow angle with the surface and have a length of less than 100 μm . Cracks initially extend into the material, to eventually forming a micropit with a depth of approximately 10 μm . The general appearance of micropitting described here was very similar across all lubricants employed in this study, and has been observed previously for surface-initiated rolling contact fatigue cracks [28].

It is well known that both the roughness of the counterface discs and the friction coefficient influence the magnitude of stress experienced by the roller surface and thus the latter's micropitting [7,12]. Fig. 6 shows averaged counterface disc roughness after the tests. Error bars indicate the standard deviation from 9 measurements. In all cases, the disc roughness reduced after the 18 million cycle tests from Ra 0.1 μm to Ra 0.08–0.09 μm . While PAO4 + PAO40 and PAO2 + PAO40 gave slightly higher final disc roughness than the others, no significant differences were observed between blends. Fig. 7 shows the evolution of friction coefficient in the tests. All lubricants gave a stable and equivalent friction coefficient during the tests of between 0.085 and 0.09.

3.2. Effect of PIB blends on micropitting

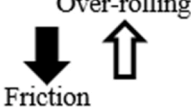
Fig. 8 shows representative optical micrographs of the wear tracks on the rollers at two different magnifications for the seven tested PIB dumbbell blends, as well as the measured percentages of micropitted area on the roller wear tracks. PAO4 + HV300 gave a similar extent of micropitting to PAO4 + PAO10, providing 59% of pitted area ratio, while PAO4 + HV1900 slightly increased micropitting area to 65%. By contrast, LV7 + LV50 and PAO4 + LV50 very significantly reduced micropitting to 5% and 8% of pitted area ratio respectively. PAO4 + HV35 also provided a relatively low level of micropitting, with 26% of pitted area ratio. The larger amount of HV35 in PAO2 + HV35 than PAO4 + HV35 resulted in a lower pitted area ratio of 15% as opposed to 26% in the latter. By contrast, the larger amount of HV1900 in PAO2 + HV1900 gave similar micropitting damage of 63% pitted area ratio to that of PAO4 + HV1900.

From the magnified micrographs in Fig. 8, the surfaces all contained a high density of uniformly spaced V-shaped cracks and small pits, similar to the PAO blend micrographs shown in Fig. 4.

Fig. 9 shows measured disc roughness after the tests. Error bars indicate standard deviations of 9 measurements. Disc roughness from tests with LV7 + LV50, PAO4 + LV50, PAO4 + HV35 and PAO2 + HV35 were only slightly decreased to Ra 0.09 μm . Compared to these, PAO4 + HV300, PAO4 + HV1900 and PAO2 + HV1900 gave lower disc roughnesses, between 0.083 and 0.085 μm .

Fig. 10 shows the evolution of friction coefficient in the tests. While all lubricants reached a stable friction coefficient during the tests, unlike the PAO blends the various PIB blends showed different friction values. LV7 + LV50, PAO4 + LV50, PAO4 + HV35 and PAO2 + HV35 gave a relatively high friction coefficient, between 0.093 and 0.102 at the end of the tests. It is noteworthy that PAO2 + HV35 gave a slightly higher friction coefficient of 0.097 than the 0.093 of PAO4 + HV35, which contained less PIB. By contrast, the friction coefficients of PAO4 + HV300, PAO4 + HV1900 and PAO2 + HV1900 were stable at 0.088 which is equivalent to that of PAO4 + PAO10.

Since all the blends tested had the same dynamic viscosity at the test temperature, and also broadly similar chemical compositions, it is evident that the variations in micropitting noted above must originate from some other characteristics of the blends studied. Based on previous studies of micropitting, the two most likely candidates are the EHD film thickness and the friction [1,6,12]. These are described and discussed in the next two sections.

Over-rolling

 Friction

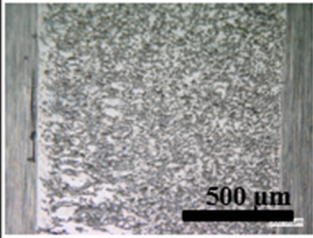
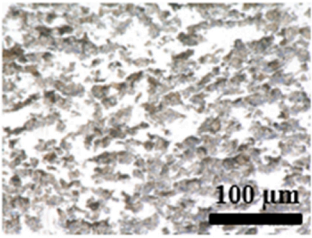
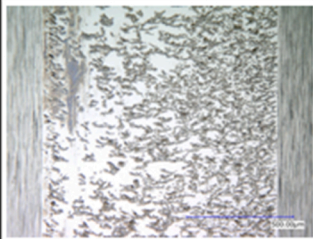
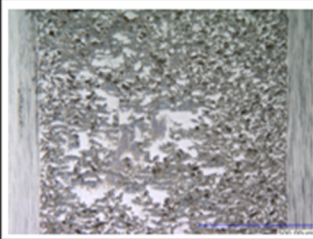
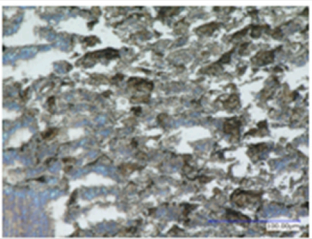
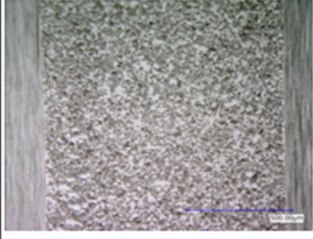
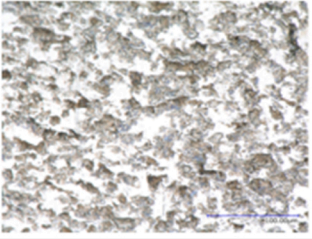
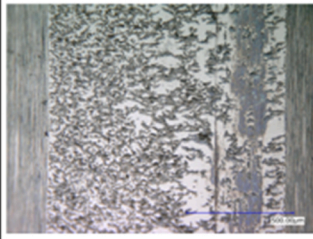
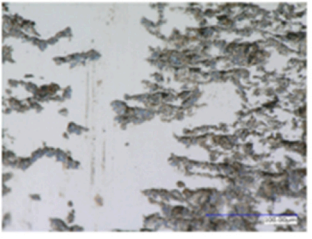
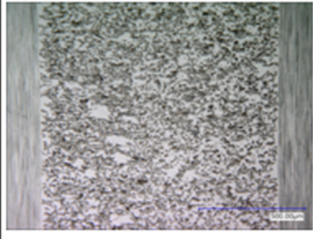
	Micrograph of rollers (x250)	Micrograph of rollers (x1000)	Pitted area ratio, %
PAO4+ PAO10			59 ± 5
PAO4+ PAO40			49 ± 4
PAO4+ PAO100			59 ± 4
PAO4+ PAO300			67 ± 2
PAO2+ PAO40			45 ± 3
PAO2+ PAO300			65 ± 4

Fig. 4. Typical optical micrographs of wear tracks on rollers from tests conducted with different PAO dumbbell blends as well as measured percentage of micropitted area. (Note: the scale bar included in the top images of the figure applies to all images).

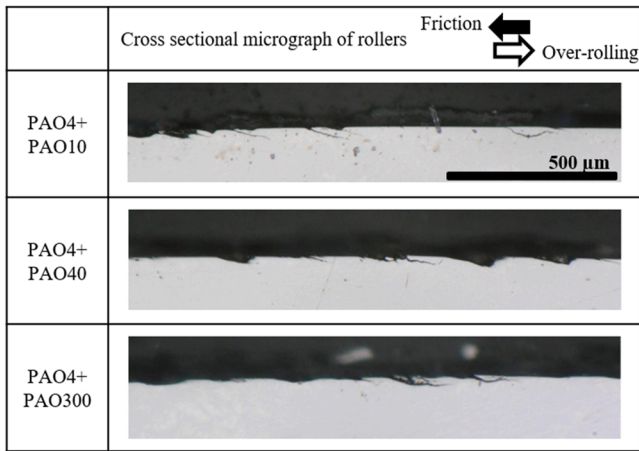


Fig. 5. Typical examples of optical micrographs of the rollers lubricated by PAO dumbbell blends and sectioned in rolling direction, showing typical morphology of micropits. (Note: the scale bar included in the top images of the figure applies to all images).

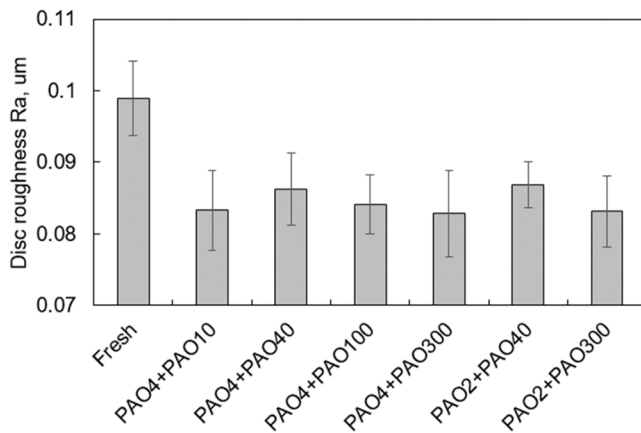


Fig. 6. Measured disc roughness after the MPR tests conducted with PAO dumbbell blends. Error bar indicates standard deviation from nine measurements.

4. EHD film thickness

An influential parameter on micropitting is well known to be the ratio of EHD film thickness to composite surface roughness, the lambda ratio [1], so, EHD oil film thicknesses were measured as described in Section 2.5.

Fig. 11 shows the EHD oil film thickness *versus* entrainment speed behaviour of (a) PAO/PAO blends and (b) PIB blends measured using a sapphire disc-WC ball tribopair at a maximum contact pressure of 2.0 GPa. All oils showed linear $\log(\text{film thickness})$ *versus* $\log(\text{speed})$ response, with a slope of approximately 0.7, in accord with EHD theory. No anomalous film thickness behaviour was seen at low speeds, but this is as expected since the film thickness was always more than 10 nm at lowest entrainment speed of 200 mm/s.

Despite all blends having very similar dynamic viscosities at 100 °C, it can be seen that their oil film thickness behaviour varied. PAO4 +PAO40 gave a slightly thicker oil film of 102 nm than the 94 nm seen with PAO4 +PAO10. Compared to this, the larger amount of PAO40 in PAO2 +PAO40 increased oil film thickness to 108 nm at 3 m/s. On the other hand, the increased proportion of PAO300 in PAO2 +PAO300 gave a slightly lower oil film thickness of 86 nm at 3 m/s compared to the 91 nm of PAO4 +PAO300.

The PIB blends show significant differences in oil film thickness. LV5 +LV70 and PAO4 +LV50 gave much thicker films than the others; 141.0 nm and 128.0 nm respectively at 3 m/s. The larger amount of HV35 in PAO2 +HV35 increased film thickness from 106 nm to 116 nm at 3 m/s compared to PAO4 +HV35. By contrast, the increase of HV1900 ratio in PAO2 +HV1900 did not notably thicken oil film thickness compared to PAO4 +HV1900.

Fig. 12 plots the measured EHD film thickness at an entrainment speed of 3 m/s *versus* micropitted area for all fluids and shows that micropitting area increases as EHD oil film thickness at 3 m/s is reduced.

5. EHD and boundary friction

Another factor that has been reported to influence micropitting is friction [12]. Figs. 7 and 10 showed the measured friction coefficients during micropitting tests. Friction values were quite similar for the various PAO blends but were considerably higher for some of the PIB blends. To explore the impact of friction further, Stribeck curves showing how friction coefficient varies with entrainment speed and thus EHD film thickness were measured for all test blends using the ETM. These are shown in Fig. 13 for (a) PAO blends and (b) PIB blends.

The PAO blends all showed very similar behaviour across the entrainment speed range, with low friction coefficient of 0.025–0.029 at

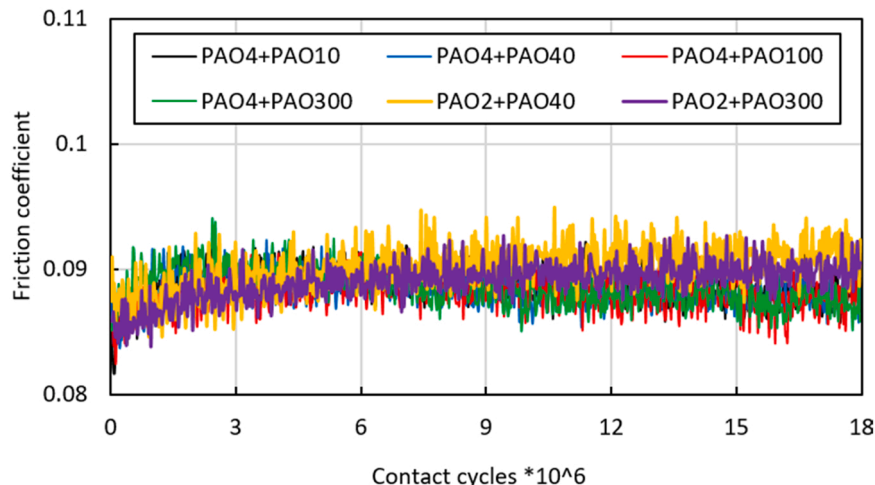


Fig. 7. Friction coefficient development in the MPR tests conducted with PAO dumbbell blends.

Over-rolling
 Friction

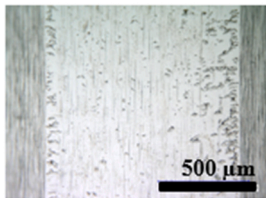
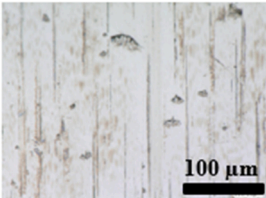
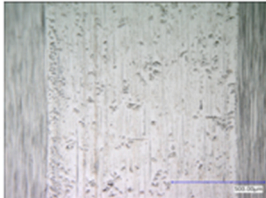
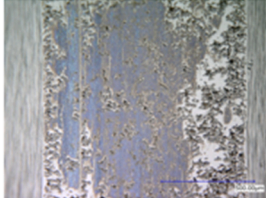
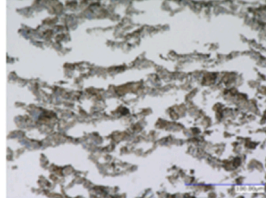
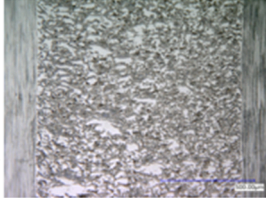
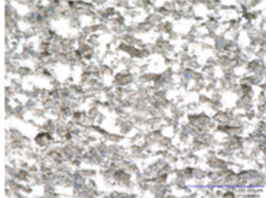
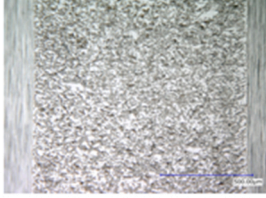
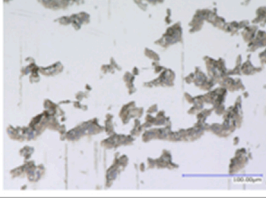
	Micrograph of rollers (x250)	Micrograph of rollers (x1000)	Pitted area ratio, %
LV7+ LV50			5 ± 1
PAO4+ LV50			8 ± 1
PAO4+ HV35			26 ± 6
PAO4+ HV300			55 ± 2
PAO4+ HV1900			65 ± 3
PAO2+ HV35			15 ± 2
PAO2+ HV1900			63 ± 5

Fig. 8. Typical examples of optical micrographs of wear tracks on rollers from tests conducted with the different PIB blends as well as measured percentage of micropitted area (Note: the scale bar included in the right images of the figure applies to all images).

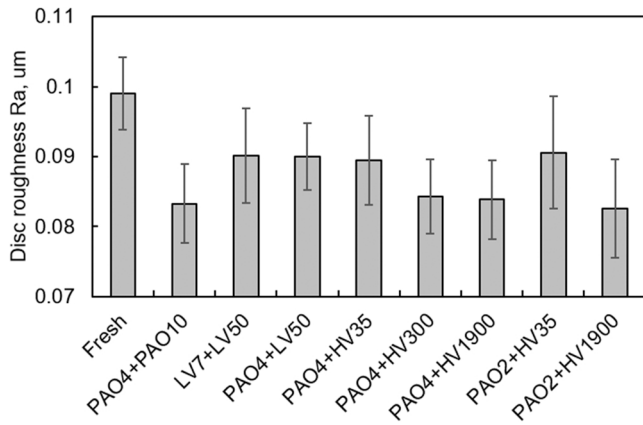


Fig. 9. Measured disc roughness after the tests conducted with PIB dumbbell blends. Error bars indicate standard deviation of nine measurements.

high entrainment speed (corresponding to full EHD film conditions) to *ca.* 0.0875 at the lowest entrainment speed studied. The estimated EHD film thickness at lowest speed was *ca.* 3 nm, suggesting a lambda ratio of *ca.* 0.1 and thus mixed/boundary lubrication. The PIB blends showed much more varied friction, especially at high entrainment speeds and this reflects very different EHD friction (traction) properties. PIBs are well known for giving high EHD friction while PAOs have low EHD friction, so these differences reflect variations in the balance between the two. As expected, the blend of PIB with PIB gives the highest friction while the PAO/PAO blend gives the lowest. As entrainment speed is reduced, friction increases due to the onset of mixed lubrication. However, the blends retain the same order, with the PIB/PIB blend having the highest friction throughout. It is noteworthy that although the friction coefficient was different in the ETM tests from the micropitting tests, due largely to the very different specimen roughnesses, the same trend of friction variation between fluids was seen in both the MPR tests and these ETM ones.

Fig. 14 plots three types of measured friction coefficient against micropitted area for all the test blends. Fig. 14 (a) shows MPR friction coefficient at 18 M cycles in the micropitting tests, (b) shows EHD friction using ETM measurements at an entrainment speed of 3 m/s, and (c) shows mixed/boundary friction at the lowest ETM entrainment speed of 10 mm/s. All show that micropitting area increases as friction reduces. This is quite contrary to micropitting studies that have investigated the effect of friction [6,12–14] and this suggests that in the current work friction itself does not directly influence micropitting. In this study

EHD film thickness and thus lambda ratio appears to be the dominant factor.

It should be noted that there is a well-known and general correlation between EHD film thickness and EHD friction, with fluids that give thick films having higher EHD friction coefficients [29]. This is very clearly seen by comparing Figs. 12 and 14.

6. Discussion

The results presented here show that the PAO and PIB dumbbell blends significantly influence micropitting even when they have equivalent dynamic viscosity at the test temperature. In this section the relevant mechanism is discussed.

Generally, lubricants can affect micropitting *via* the following three factors. Each of these is discussed below.

- i) Tribofilm formation [7,9]
- ii) Friction coefficient [6,12]
- iii) Oil film thickness [1,2]

6.1. Tribofilm formation

In this study, tribofilms formed by the test oils are not likely to be dominant in determining the magnitude of micropitting since all test oils contain the same SP-type additives. It is well known that polarity of base oil influences tribofilm development [30], and the PIBs will generally have higher polarity than the PAOs, so the various blends might form different thickness tribofilms. However it was found that test oils with the same aniline point, an index of polarity of lubricants [31], gave quite different magnitudes of micropitting. Thus the aniline points of PAO4 +HV35, PAO4 +HV300 and PAO4 +HV1900 were all 123 °C, but these oils gave 26%, 55% and 65% of pitted area respectively, as shown in Fig. 8.

6.2. Friction

As described in the Section 5, it was found that micropitting area increases as friction reduces. This is quite contrary to micropitting studies that have investigated the effect of friction directly using friction modifier additives [6,12] and this suggests that in the current work friction itself does not directly influence micropitting. This is probably because previous work to study the impact of friction on micropitting has been based on varying boundary friction, which is most likely to control the magnitude of asperity stresses. However, the differences in

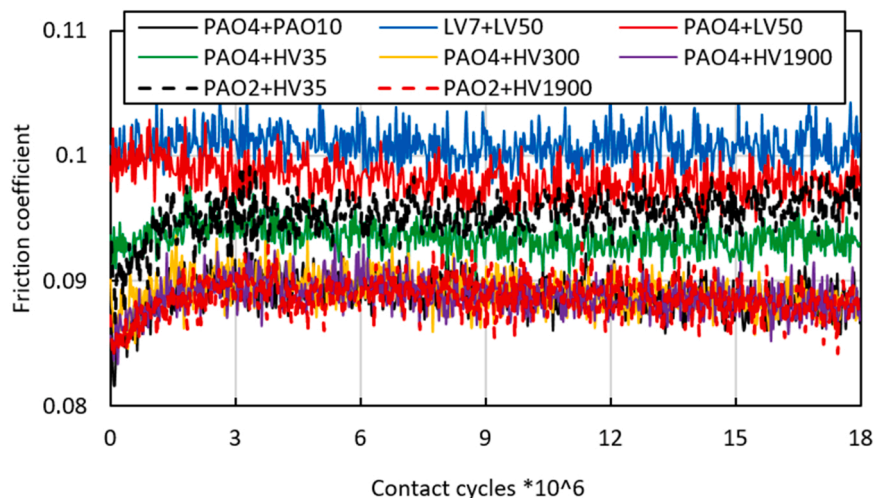


Fig. 10. Friction development in tests conducted with PIB dumbbell blends.

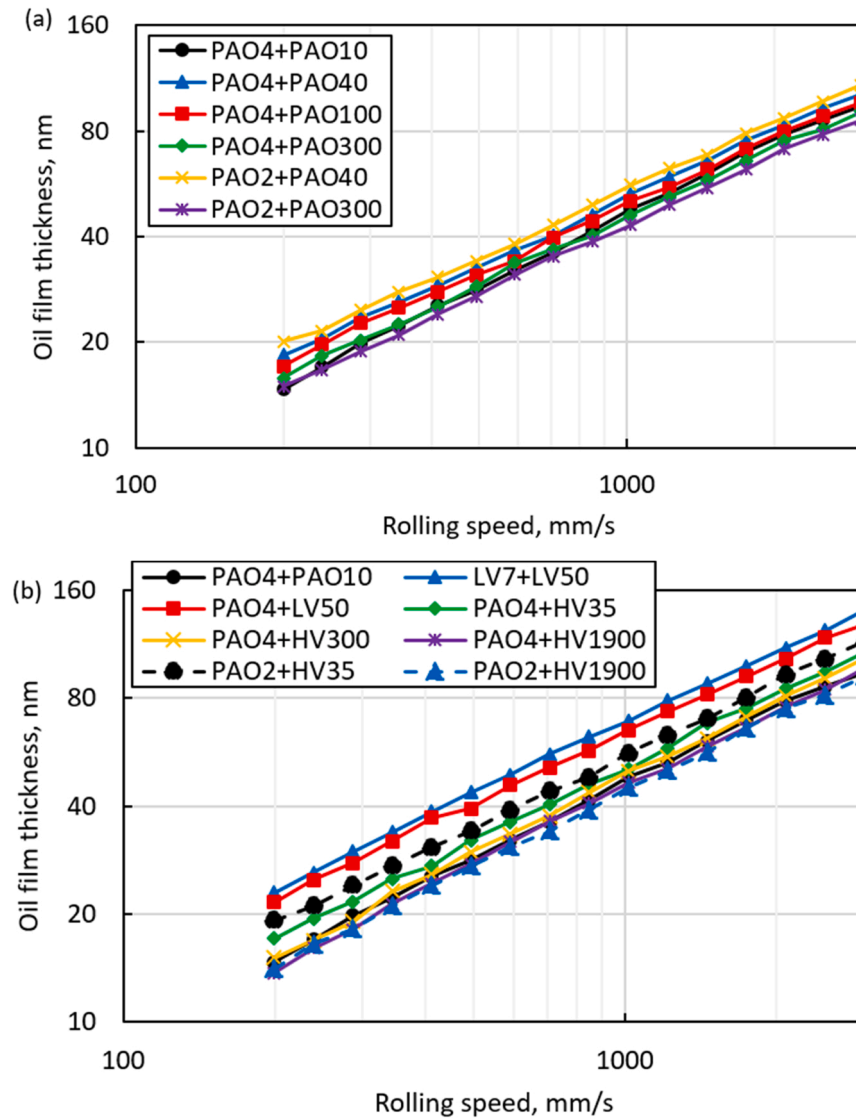


Fig. 11. EHD oil film thickness of (a) PAO and (b) PIB blends using sapphire disc-WC ball at 24 N and 100 °C in pure rolling.

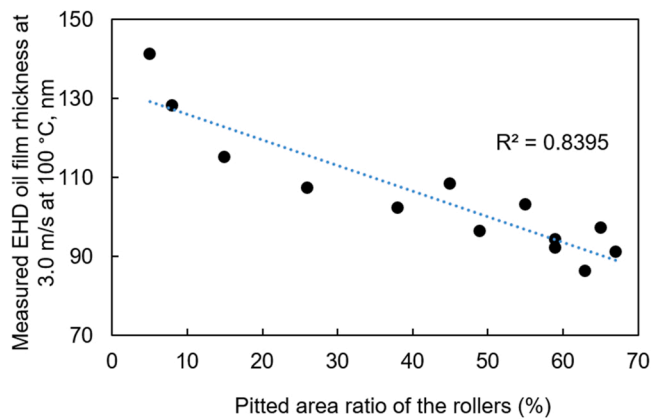


Fig. 12. The relationship between micropitted area ratio and measured EHD film thickness at entrainment speed 3 m/s.

friction measured in the current study reflect primarily differences in EHD friction. This may influence overall contact shear stress but not predominantly asperity stresses and the boundary friction that will influence asperity stress is likely to be very similar for all the test oils since the same SP additive was used throughout.

6.3. Oil film thickness

The correlation shown in Fig. 12 between EHD film thickness measured by interferometry for the various blends and their micropitting performance suggests that film thickness and thus lambda ratio is the most likely influential factor of the dumbbell blends on micropitting. It is thus of interest to estimate the EHD film thickness and thus lambda ratio in the MPR tests from the film thickness measurements made using interferometry. From EHL theory, at a fixed load, elastic modulus, contact geometry and entrainment speed, central EHD film thickness depends on the dynamic viscosity, η and pressure viscosity coefficient, α (alpha value) for point contact (as present in the optical film thickness measurements) according to [32];

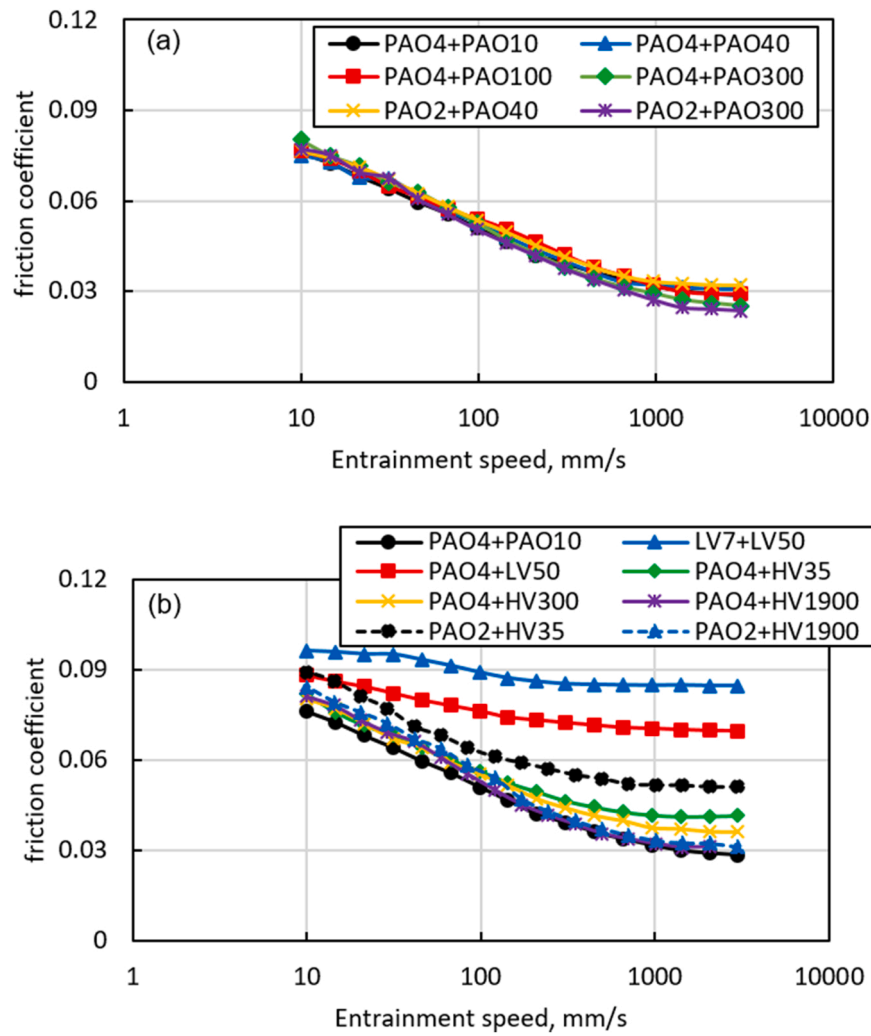


Fig. 13. Stribeck curves measured at 100 °C during low speed rolling/sliding ETM tests using (a) PAO blends and (b) PIB blends.

$$h_c \propto \eta^{0.67} \alpha^{0.53} \quad (1)$$

Eq. 1 is predicated on the assumption that the fluid does not exhibit any shear thinning in the contact inlet, so that its effective viscosity in this region originates only from its low shear rate viscosity at atmospheric pressure and its pressure viscosity coefficient. However, it is well-known that the EHD film thicknesses formed by solutions of medium to high MWt polymers in lubricating oils are generally thinner than those predicted from EHD theory based on the low shear rate viscosities of the polymer solutions [33–35]. This is usually ascribed to shear thinning of polymer solutions in the high shear stress conditions in the inlet of the EHD contact. Such shear thinning results primarily from the very high shear rates in this region that occur due to recirculation even in pure rolling conditions. It has been suggested that this shear rate reaches about $1.5U/h_c$ where h_c is the central EHD film thickness [36]. The impact of this high shear rate on shear thinning is compounded by the fact that the pressure in the contact inlet increases the lubricant viscosity so the shear stress, which is the product of the shear rate and the inlet viscosity becomes quite large. The resulting inlet shear thinning, which is quite likely to occur with high viscosity PAOs and PIBs, complicates the calculation of pressure viscosity coefficient using Eq. 1 since the competing impacts of pressure-induced viscosity increase and shear rate-induced viscosity decrease on film thickness cannot easily be separated. However, it has been suggested that the problem can be addressed by using the dynamic viscosity measured at high shear rate in Eq. 1, typically measured at 10^6 or 10^7 s⁻¹, rather than the low shear

rate viscosity [37]. Based on this, a concentric cylinder high shear rate viscometer (USV) was used to measure the viscosity of the test oils at shear rates of 10^6 or 10^7 s⁻¹ at 100 °C in this work.

6.3.1. Shear thinning

Shear thinning of the test oils was studied using a USV. Two types of shear thinning commonly occur for polymer solutions. Permanent shear thinning results from the thermomechanical scission of the polymer chains at the high shear stresses present in lubricated contacts and leads to a permanent reduction in viscosity of the lubricant [38]. By comparison, temporary shear thinning is generally believed to result from conformational changes, such as partial alignment of the polymer molecules in solution under shear. This type of shear thinning is recovered fully after cessation of shear [39].

Although most lubricant base oils are generally considered not to shear-thin under normal hydrodynamic conditions, they certainly do so at the very large shear stresses present within high pressure EHD contacts [40]. It is also possible that the high MWt PAOs and PIBs used in this study may show some shear thinning in the moderately high pressures, but very high shear rate conditions present in EHD contact inlets. As an initial test for any permanent shear thinning of the blends, their KV_s at 100 °C at the end of MPR tests were measured as shown in Fig. 15. Only the blends using PAO300 and HV1900 showed a reduction of KV after the MPR tests. The blends with higher proportions of PAO300 and HV1900 in PAO2 gave greater reductions of KV than PAO4 + PAO300 and PAO4 + HV1900, which contained lower proportions of the high

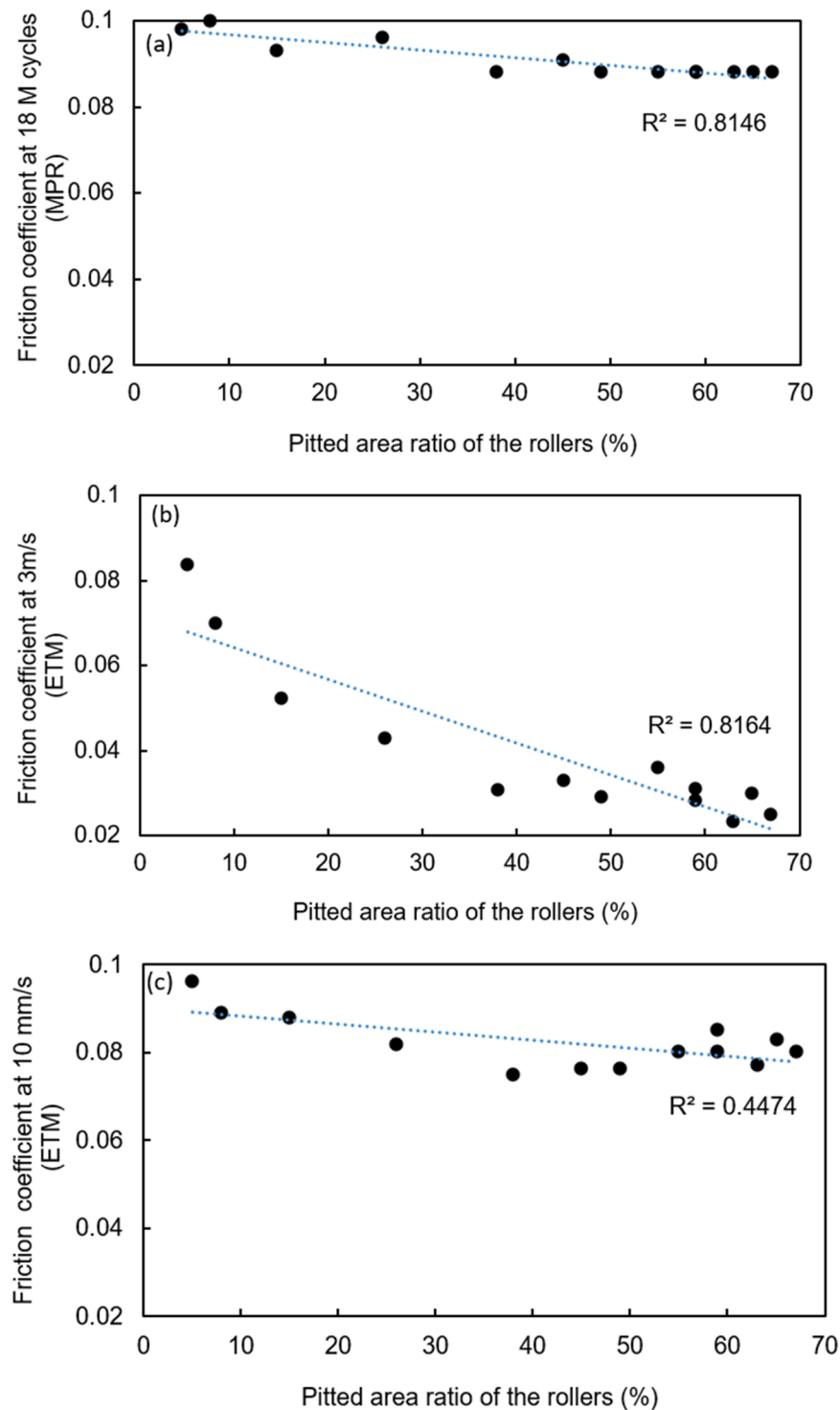


Fig. 14. The relationship between micropitted area ratio and (a) the measured MPR friction coefficient at the end of the test, (b) ETM friction coefficient at 3 m/s and (c) ETM friction coefficient at 10 mm/s.

viscosity components. However, it should be noted that actual amount of KV100 reduction after MPR tests is less than 1% and thus will not have a significant effect on EHD film thickness.

To assess the temporary shear thinning behaviour of the blends, dynamic viscosities were measured in the USV at 10^6 and 10^7 s^{-1} and compared with the values measured at low shear rate. Fig. 16 shows how much lower the viscosities were at high shear rate. All blends experienced some temporary sheared at 10^6 and 10^7 s^{-1} . The blends with the highest molecular PAO and PIB, i.e. PAO300 and HV1900 shear thinned

the most, with a more than 5% reduction in viscosity. Such a response is most likely to reduce EHD oil film thickness.

To make sure that this reduction in viscosity was due to temporary rather than permanent shear thinning, high shear rate viscosities were measured over 10 repeat measurement cycles, as proposed by Marx et al. [41,42] and described in Section 2.7. If permanent shear thinning were occurring, this should result in a progressive reduction in viscosity from cycle to cycle. Such reductions were not observed, so it can be concluded that the highest MWt base oils used in this study were subject to

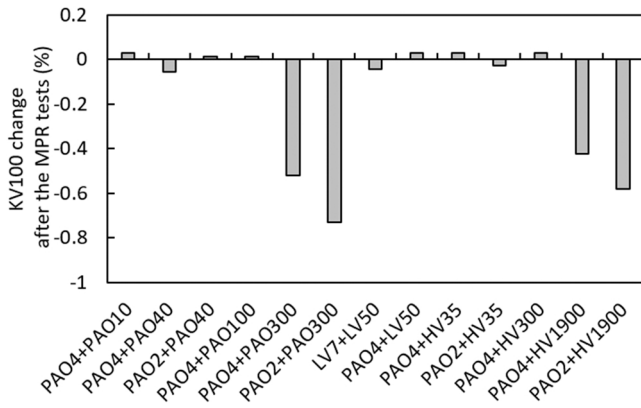


Fig. 15. Kinematic viscosity change at 100 °C of the test lubricants after the MPR tests.

temporary shear thinning but not permanent shear thinning in the USV.

6.3.2. Estimation of effective pressure viscosity coefficient, α

From the USV shear thinning measurements shown in Fig. 16 together with the point contact EHD film thickness measurements, Eq. 1 was used as described by Foord et al. [43] to estimate the α value of each blend. This method compares its measured EHD film thickness of a blend with that of a reference oil of known α value and dynamic viscosity at the same contact load, geometry, material combination and entrainment speed [43]. From Eq. 1 this gives

$$\frac{h_{cB}}{h_{cR}} = \left(\frac{\eta_B}{\eta_R} \right)^{0.67} \left(\frac{\alpha_B}{\alpha_R} \right)^{0.53} \quad (2)$$

where the suffix B refers to the test blend and R to the reference oil. The latter was a white mineral oil having dynamic viscosity $\eta_R = 7.1$ cP and $\alpha_R = 14.8$ GPa⁻¹ at 100 °C.

To allow for the impact of inlet shear thinning on film thickness, the measured dynamic viscosity of each test oil at a shear rate of 10^7 s⁻¹ at 100 °C was used as η_B in Eq. 2. Table 5 lists the measured EHD film thicknesses of all blends at an entrainment speed of 0.5 m/s and measured dynamic viscosities of the test oils at shear rate of 10^7 s⁻¹ at 100 °C. An entrainment speed of 0.5 m/s was used rather than a higher value to achieve an inlet shear rate as close to 10^7 s⁻¹ as possible, this

being the maximum attainable USV shear rate. Also shown in Table 5 are the resulting calculated α values, α_B , and, from these, the initial lambda ratios of the MPR tests at 100 °C. Lambda ratio was defined as the ratio of minimum EHD film thickness to composite root mean square surface roughness and the minimum EHD film thickness was calculated from the Dowson and Toyoda's equation for line contact with the appropriate high shear rate viscosity and α value [44]. It can be seen that the initial lambda ratios are in the range 0.21–0.36.

Fig. 17 plots (a) α value at 100 °C and (b) lambda ratios at 100 °C of micropitting test versus micropitted area for all fluids. It is evident that micropitted area reduces as α value and thus lambda ratio increases.

It should be noted that this calculation does not taken into account a possible scale effect noted by Krupka et al. [23]. They found that for fluids that shear thinned, contacts with a smaller reduced radius gave thinner films than predicted from Eq. 1 compared to those with larger reduced radius. The reduced radii in optical film thickness tests was 9.5 mm, while that in MPR tests was 5 mm. It is also important to note that for the MPR tests, the maximum shear stress in the inlet is calculated to be ca. 450 kPa for pure rolling with a Newtonian liquid. This is roughly 8 times higher than the one obtained from USV measurement. Thus, the approach to estimate α and lambda values in this study

Table 5

EHD film thickness at 0.5 m/s, high shear rate viscosity (USV), effective pressure viscosity coefficient and lambda ratio of all blends. All measured and estimated values are at 100 °C.

	EHD film thickness at 0.5 m/s (nm)	Dynamic viscosity at 10^7 /s	Alpha value (GPa ⁻¹)	Lambda of MPR tests
PAO4 + PAO10	30.5	5.4	8.7	0.23
PAO4 + PAO40	35.0	5.3	11.7	0.27
PAO2 + PAO40	37.0	5.3	12.8	0.28
PAO4 + PAO100	33.5	5.1	11.1	0.25
PAO4 + PAO300	31.0	4.9	9.9	0.23
PAO2 + PAO300	29.0	4.7	9.3	0.21
LV7 + LV50	45.5	5.5	18.5	0.36
PAO4 + LV50	425	5.4	16.9	0.33
PAO4 + HV35	35.0	5.4	11.1	0.28
PAO2 + HV35	38.0	5.4	13.5	0.31
PAO4 + HV300	315	5.1	10.0	0.22
PAO4 + HV1900	29.5	4.9	9.0	0.21
PAO2 + HV1900	29.0	4.7	9.3	0.21

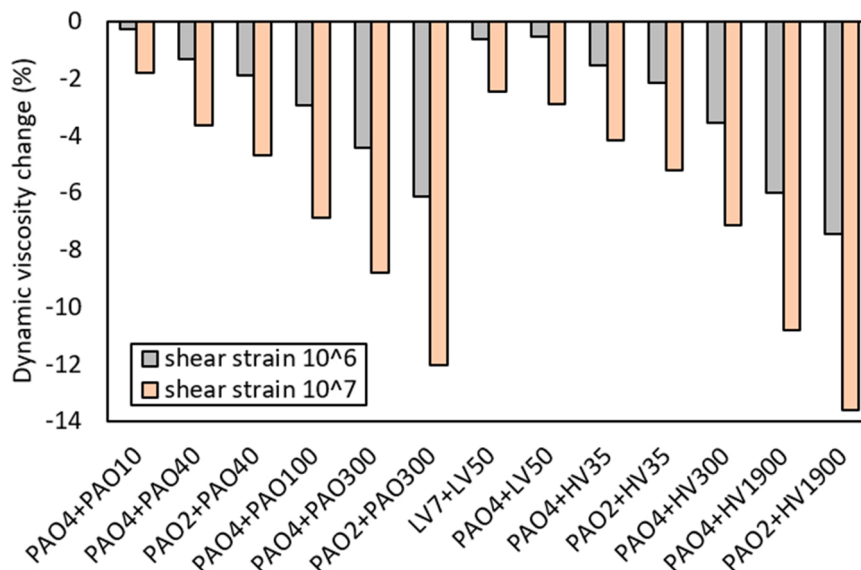


Fig. 16. Difference between dynamic viscosity at 10^6 s⁻¹ and 10^7 s⁻¹ and that at low shear rate.

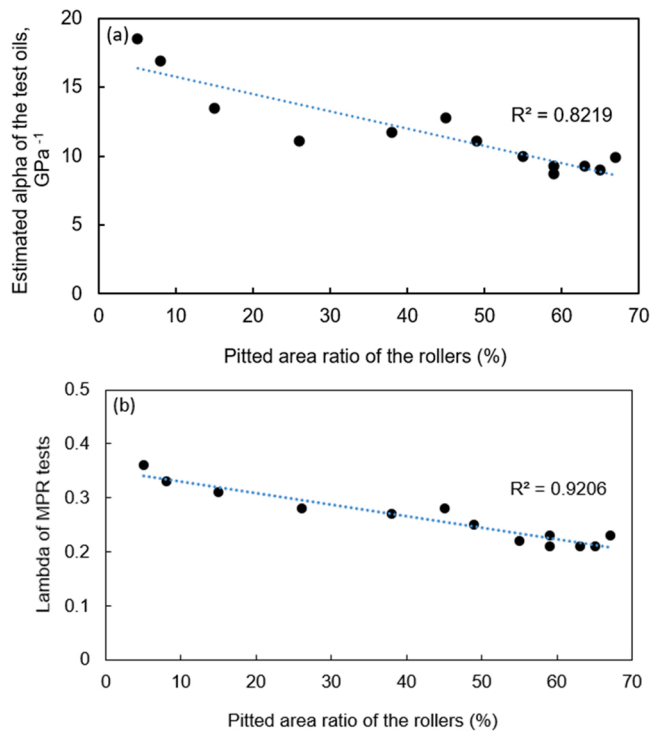


Fig. 17. The relationship between micropitted area ratio and (a) estimated alpha at 100 °C and (b) lambda at the end of micropitting test.

does not fully simulate the condition in the MPR study.

It is of interest to consider why some dumbbell blends are beneficial. LaFountain et al. [16] studied the viscometric properties of blends of low and high viscosity PAOs. Fig. 18 shows how dynamic viscosity and alpha value vary with composition of the blend (data taken from Table 2 in [16]). The plots show that while dynamic viscosity of the blends varies logarithmically with composition, alpha value varies close to linearly. Thus, the benefit of a dumbbell blend might be that a relatively large proportion of high alpha component having high viscosity can be used without strongly impacting on the blend viscosity. Therefore, compared with using a single base oil, addition of some high viscosity base oil may contribute to the high alpha to the dumbbell blend oil but not increase its viscosity overly. However, the high viscosity base oil must not have too high MWt and thus be too viscous, or inlet shear thinning may cancel out the benefit of having a high alpha value.

7. Conclusions

This study has used MPR with custom dumbbell oil blends of PAOs and PIB to investigate the latter's effects on micropitting. The main findings can be summarised as follows:

1. The type of dumbbell blends, especially with PIB blends, significantly influences micropitting despite their having equivalent dynamic viscosity at the test temperature.
2. Micropitting area increases as friction reduces in this study. This is quite contrary to micropitting studies that have investigated the effect of friction directly and this suggests that in the current work friction itself does not directly influence micropitting at the given EHL condition, probably because the dominant friction is EHD rather than boundary.
3. The micropitting area increase as EHD film thickness and thus lambda ratio reduces.
4. Since all blends have the equivalent dynamic viscosity at the test temperature, their variation in film thickness may originate from

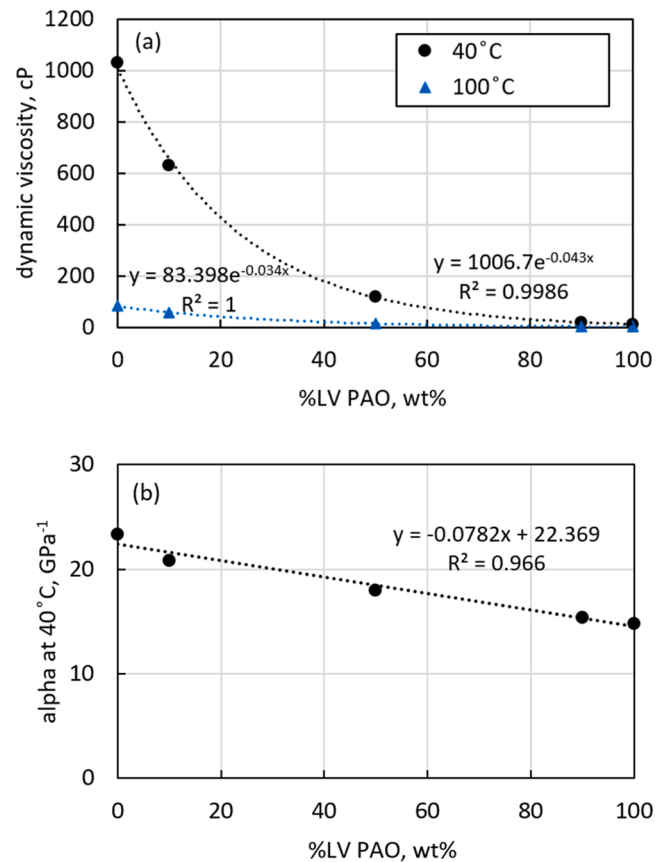


Fig. 18. The relationship between the ratio of low viscosity PAO and (a) dynamic viscosity and (b) alpha [16].

either or both of variation in effective pressure viscosity coefficient (alpha value) and inlet shear thinning.

5. High molecular base oils such as PAO300 and HV1900 showed significant temporary shear thinning at 10^7 s^{-1} , representative of EHD inlet shear rate condition.
6. When this inlet shear thinning is taken into account, there remains a significant variation of alpha value between the blends. This alpha value correlates with micropitting area via its impact on EHD film thickness.

Statement of originality

Manuscript "Influence of Dumbbell Base Oil Blends on Micropitting" by M. Ueda, J. Wong, and H. Spikes submitted for publication in Tribology International. We confirm that this article has not been published previously; is not under consideration elsewhere; has the full consent of all authors; and that, if accepted, will not be published elsewhere in the same form, in English or in any other language, without the written consent of the Publisher.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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