Mechanical Properties and Wear Resistance of Industrial Bearing Liners in Concentrated Boundary-Lubricated Sliding

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Abstract

The friction and wear behavior were studied for three materials typically found in industrial bearing applications: a Sn-based Babbitt, polytetrafluoroethylene (PTFE) and a polyether ether ketone (PEEK) composite. Test conditions were unidirectional sliding with a ball-on-disc geometry where the counter surface material was a 440C stainless steel ball (6.35 mm dia.). The tests were also in the presence of a lubricant, ISO46 oil, with the sample and contact submerged throughout the test. The relative effects of load and sliding velocities on the wear rates were assessed by means of regression analysis. Connections between wear and the materials mechanical properties, which were measured by instrumented indentation, were also made. The ranking of wear performance of the materials correlated best to the ratio of $H/(E^*)^{0.447}$, where H is the test material's hardness and E* is the reduced modulus for the contact. The power applied to the reduced modulus is that used in previous studies to estimate the oil film thickness for an isoviscous, elastic lubrication regime.

Keywords: Lubricated wear, hydrodynamic bearings, mechanical properties, materials selection.

Introduction

Hydrodynamic bearings are ubiquitous in industrial machinery. Their operation relies on the build-up of pressure in a thin layer of lubricant that separates two sliding surfaces by a few tens or hundreds of micrometers, thus reducing wear to practically negligible rates. In practice, however, such ideal conditions are not always maintained. During start-ups and shut-downs, the combination of low velocities and high loads render the oil film unable to fully separate the runner or journal surfaces from that of the bearing, and the onset of wear inevitably ensues. The longevity of hydrodynamic bearings partly depends on their ability to resist wear in such transient operation conditions.

Sn-based alloys commonly known as Babbitt or white metals are the traditional choice of material to line a hydrodynamic bearing. Patented in the 19th century, Babbitt linings are known for their low hardness, tailored to avoid excessive wear during contact with the more sensitive journal or runner steel surfaces. Babbitt is also known for being able to embed hard contaminant particles that are occasionally found in the oil, preventing continuation of abrasive degradation [1]. A low hardness, however, does not bode well for the lifetime of Babbitt linings and the low melting point of white metals also limits their use to temperatures lower than 100 °C.

The replacement of Babbitt linings by polymer-based materials is becoming widespread due to a perceived improvement in performance. One such example refers to the utilization of PTFE-lined thrust bearings in hydroelectric power plants which, according to an early report [2], can withstand higher loads and service temperatures, and exempted operators from using oil jacking systems during start-ups, a common practice to avoid premature wear in babbitt bearings. Also, the improved load carrying capacity of polymer-lined bearings, derived from their compliant nature, helped to create a concave interface that favoured the retention of lubricant and resulting in hydrodynamic performances (oil film pressure and thickness), nearly indistinguishable from those of Babbitt [3–5].

On the other hand, it was soon observed that some PTFE-faced pads experienced important surface wear, that may be higher than that of Babbitt, as shown by Glavatskih et al. [6 - 7], which suggests that the development of composite pad liners should be considered. However, reports on the oil-lubricated wear of PTFE composites are not very extensive. Early studies by Shen et al. evaluates different fillers for PTFE including metallic powders [8] as well as fibers or whiskers [9]. The authors ranked the composites in terms of their wear rates in a paraffin-lubricated block on (steel) ring tests, identifying Ni powder and glass fibers as the most promising PTFE fillers. Graphite also seems to be a good reinforcing agent. As reported by Polycarpou et al. [10], unless the oil lubricant is contaminated by hard Si-particles, the wear rates of graphite-reinforced PTFE cylindrical pins sliding against tool steel disks was unmeasurable. As shown in [11], reinforcing PEEK with glass fibers reduced the neat polymer's boundary-lubricated wear rates, largely outperforming carbon steel plates tested in the same conditions.

While the reports [8-11] are encouraging, they are mostly concerned with the development of material formulations, and the varying range of test conditions complicate comparison. As a result, bearing users considering replacement of babbitt by composite liners are faced with an extensive list of commercially available candidates. Except for practical reasons such as cost and ease of manufacturing, at the present time, there are no means to rank the performance of lining materials based on their properties. The present work assesses tribological and mechanical properties of bearing materials by means of lubricated ball-on-disc and instrumented indentation tests. Through this work, a simple parameter from indentation testing is proposed as a means to initially rank the candidate lining materials in terms of their wear resistance.

Methodology

Wear Testing

Discs (Ø = 29 mm, thickness = 3 mm) were machined from as-cast Babbitt bars (McMaster Carr), and plates of commercially pure PTFE (Ensinger Plastics), as well as a composite based on PEEK (70 wt.%) having carbon fibers, graphite and PTFE, each added in weight fractions of 10% (TECAPEEK Black, Ensinger Plastics). The surface roughness of the Babbitt, PTFE and PEEK composite discs were determined by optical profilometry (Zygo) with results of arithmetic mean heights (Sa) of 0.29 ± 0.02 µm, 0.27 ± 0.03 µm and 0.57 ± 0.04 µm, respectively. The average wear rates and corresponding standard deviations were calculated based on the areas of the wear track grooves measured along five different positions. Material accumulated at the track edges were not considered in the calculations.

The wear tests were performed in a tribometer (TRB3 Anton Paar) having a rotating stage contained in a cup that was filled with a controlled volume of 20 mL of ISO 46 oil with a standard dynamic viscosity of 46 centistokes or 0.0396 Pa×s. This volume of oil was sufficient to keep the contact submerged for all of the test conditions presented here. A 440 C stainless steel ball (McMaster Carr) with Ø = 6.35 mm was used as counter surface. A total sliding distance of 50 m was the same for each test while, other test parameters were varied as follows: normal loads of 5N, 10N and 15N, and linear velocities of 0.01 m/s, 0.03 m/s and

0.05 m/s, totalling 9 tests for each material (no replicates). The test parameters were selected to emulate, in a laboratory setting, the transient service conditions where a full separation of the bearing lining and bearing runner/journal does not occur (mixed or boundary lubrication regime). It should be mentioned that the chosen contact loading conditions exceed what is typically found in journal or thrust bearings. However, they were found suitable to characterize the wear rates of the test materials in a reasonable amount of testing time. Additionally, transient thermoelastic distortions caused, for example, by fast start-ups [12] may reduce the idealized contact area between static/running surfaces to a value much lower than originally designed, creating a more concentrated load configuration which may resemble the test conditions explored in this work.

Mechanical Properties

Instrumented indentation (MHT3 Anton Paar) tests were done with a diamond Vickers pyramidal tip. Hardness and elastic moduli were calculated by the Oliver and Pharr method [13]. As polymeric materials exhibit viscoelastic behavior, it is important to evaluate whether the indentation test parameters affect the measurement results. Therefore, the samples were loaded following a quadratic time t function, i.e. the indenter load P obeys the relationship $P = kt^2$ where k is a constant. Six equally spaced maximum loads ranging from 250 mN – 1500 mN were used. The loading/unloading times were varied between 2s, 10s and 50s, totalling 18 indentations for each material. The Poisson's ratios (ν) were selected based on published data. For Babbitt, $\nu = 0.3$ [14], for PTFE $\nu = 0.45$ [15] and for the PEEK composite $\nu = 0.4$ [16].

Results

Friction and Wear Rates

Friction coefficient measurements as a function of cycle are plotted for selected tests for the three materials in Figure 1. The PEEK composite showed a short running-in phase that proceeded to an eventual steady-state stable friction. PTFE displayed a similar behavior, though some COF instabilities were observed especially for low sliding distances. In the case of Babbitt, the running-in process and progression to a steady-state was less obvious. Friction initially dropped and was followed by a rise to a peak COF value. For some tests this was followed by a mostly stable friction, but in other tests conditions the friction continued to vary significantly through the end of the test. The unstable friction for Babbitt and PTFE is likely due to the high wear rates and third body flows that can lead to friction instabilities [17]. As an example, there was an obvious formation of a Sn-rich deposit on the steel ball identified by electron microscopy and EDX analysis (Figure 2). No such layers were observed on the steel balls slid against the polymeric materials. It may be argued that the babbitt debris adhere more strongly to the steel ball.

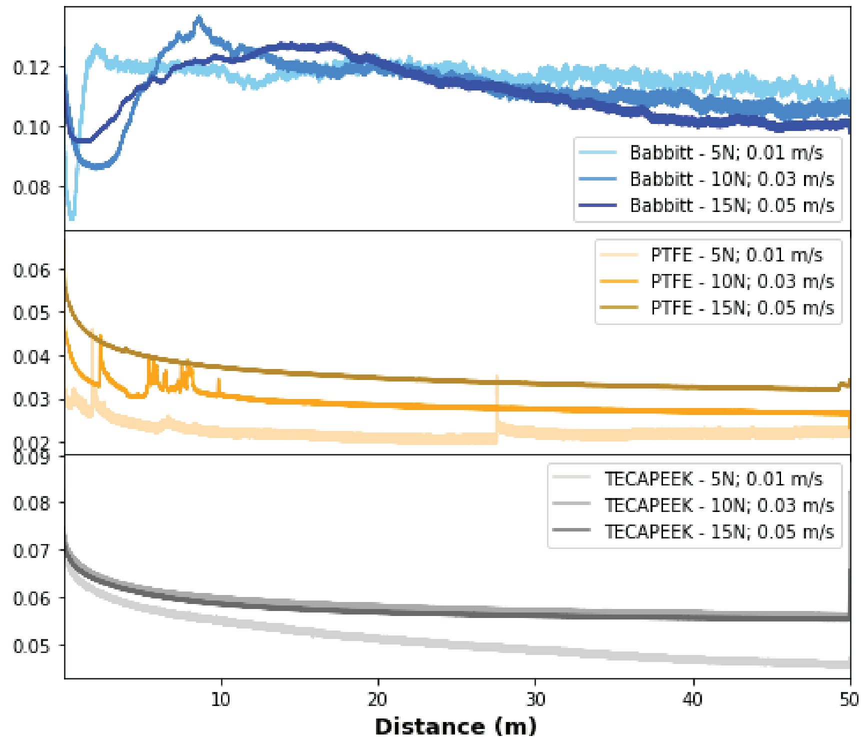
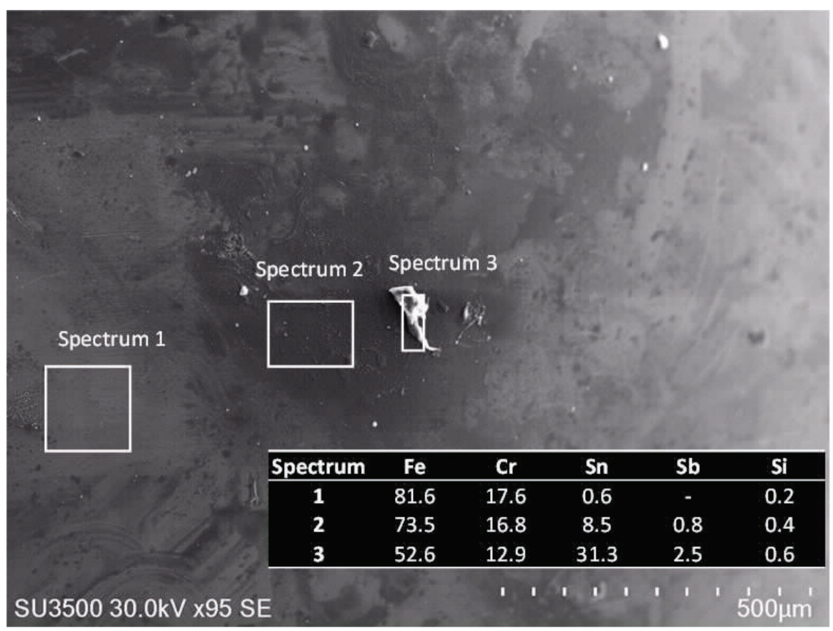


Figure 1 – Evolution of the coefficient of friction with sliding distance.



Spectrum	Fe	Cr	Sn	Sb	Si
1	81.6	17.6	0.6	-	0.2
2	73.5	16.8	8.5	0.8	0.4
3	52.6	12.9	31.3	2.5	0.6

Figure 2 – Sn-rich debris adhered to the 440C stainless steel ball surface.

As summarized in Table 1, the effects of load and sliding velocity on the measured COFs were different for each material. For Babbitt, the COF increases with higher test loads. For example, when the load is increased from 5N to 15N at a constant speed of 0.05 m/s, the COF increases by 24%. This is likely due to an increase in the contact area between the steel ball and the disc. On the other hand, at a constant load of 5N, when the sliding speed is increased from 0.01 m/s to 0.05 m/s the COF measured at the end of the test duration (distance = 50 m) decreases by 26%. This effect may derive from a lubrication effect at the contact interface. It is worth mentioning that Pukasiewicz et al. reported a COF=0.07 for Babbitt in similar oil-lubricated conditions [18]. In comparison, the PEEK composite response to the test parameters is inverted. At a constant load, the COF values may increase by more than 50% due to an increase in the sliding velocity. On the other hand, at a constant sliding velocity, if the test load is increased the COF can be reduced by as much as 15%. For the case of PTFE, increasing either the test load or sliding velocities caused the COF values to rise, possibly due to a thermal softening effect at the contact interface.

Table 1 – Summary results of the tribological behavior of bearing materials. The last COF measured values are reported. The errors associated to the specific wear rates correspond to one standard deviation.

Load (N)	Velocity (cm/s)	Coefficient of Friction			Specific Wear Rates (x 10^{-6} $mm^3N^{-1}m^{-1}$)		
		Babbitt	**PTFE**	**PEEK Composite**	**Babbitt**	**PTFE**	**PEEK Composite**
5	1	0.108	0.022	0.046	58 ± 3	61 ± 3	-
	3	0.096	0.028	0.063	89 ± 7	164 ± 7	-
	5	0.080	0.033	0.068	99 ± 2	248 ± 22	-
10	1	0.118	0.024	0.045	112 ± 14	131 ± 2	3.7 ± 0.5
	3	0.106	0.025	0.056	128 ± 7	377 ± 7	4.8 ± 0.7
	5	0.110	0.031	0.061	178 ± 10	569 ± 64	7.4 ± 1
15	1	0.120	0.025	0.039	184 ± 15	219 ± 6	2.3 ± 0.2
	3	0.099	0.030	0.054	213 ± 7	495 ± 2	6.2 ± 0.6
	5	0.099	0.034	0.061	300 ± 7	790 ± 8	8.5 ± 0.6

In terms of specific wear rates (SWR), the PEEK composite shows a superior performance, as expected [6, 7]. At 5N, the wear rates of the composite could not be measured. For higher loads, the SWRs of the composite are about two orders of magnitude lower compared to the other two materials. Despite their different physical properties, the SWRs of Babbitt and PTFE are remarkably similar at low sliding velocities.

The use of SWRs to compare a group of materials' resistances to wear implies the assumption that load and sliding distances have equal influence on the total volume of worn material. However, the data in Table 1 shows that the measured wear rates for each material are a function of the test parameters, rendering interpretation of the results unclear. To address this issue, a least-squares regression analysis of each material's wear rates (W_R, $mm^3.m^{-1}$) was performed. Good agreement was found between the data and an empirical equation having the form $W_R = A\boldsymbol{L}^{\alpha}\boldsymbol{v}^{\beta}$, where A is numerical coefficient, L and v are load and velocity, respectively given in N and m/s, each associated with their exponents α and β.

As illustrated in Figure 3, the proposed empirical model has very good agreement with the wear rates of Babbitt and PTFE. The agreement with the PEEK composite data is not as strong, probably due to the larger uncertainties in the wear rate measurements for this material. The load exerts a nearly quadratic influence on the wear rates of Babbitt and PTFE, much more relevant than the velocity exponents β, lower than unity for both materials. It is worth mentioning that the β exponent of PTFE is about 3 times higher than that of Babbitt. This correlates well with the observed SWRs of PTFE (Table 1), which are close to those of Babbitt at 0.01 m/s tests, but quickly rises to 2.5 – 3 times those of Babbitt at 0.05 m/s. As for the PEEK composite, both exponents are closer to unity. The different sensitivities each material displayed to the test parameters are further elaborated in the discussion section.

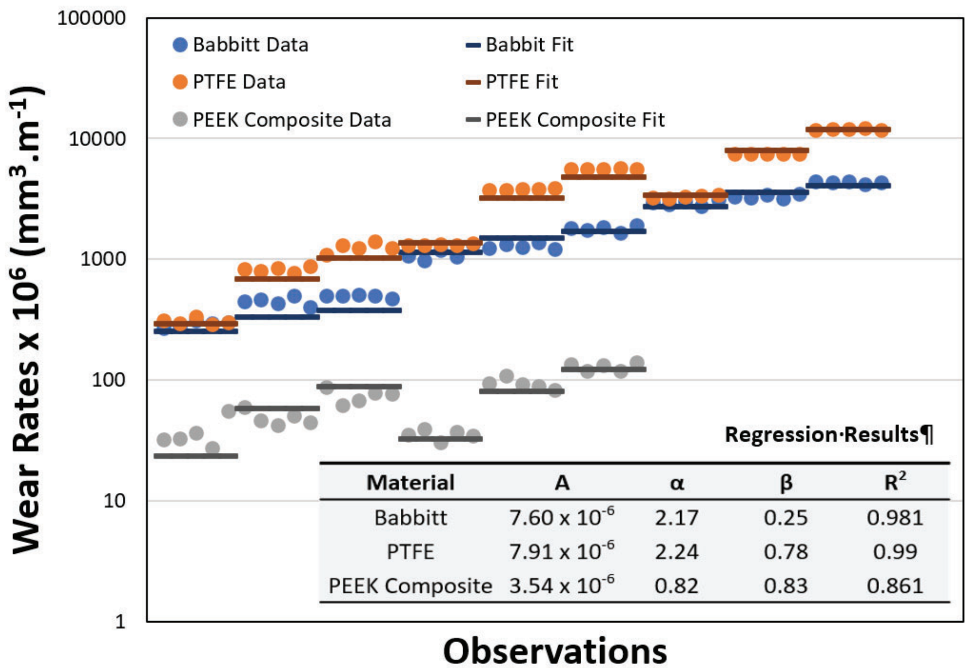


Figure 3 – Wear rate measurement observations. Good fit between an empirical equation and data is illustrated.

Mechanical Properties

The indentation response of the investigated materials is illustrated in Figure 4 and the measurement results summarized in Table 3. The mechanical behavior of Babbitt is characterized by relatively high elastic modulus E and hardness H. A distinctive feature of the polymeric materials is their high viscoelastic recovery ability, which can be measured by the ratio of elastic work τ_e to the total work of indentation τ_T. Despite having the lowest E, PTFE recovered a considerable amount of elastic strain. However, with its low hardness, the fluoropolymer sustained high levels of plastic deformation, as indicated by its residual indentation depth h_p. The PEEK composite combines a hardness superior to that of Babbitt while displaying a greater viscoelastic recovery τ_e/τ_T than PTFE.

It is worth mentioning that despite the changes in the maximum indentation loads or loading/unloading times, the uncertainty of the average properties summarized in Table 3 are not very relevant. It may be stated that under the chosen indentation test conditions, the measured properties and ranking metrics are not significantly affected by viscoelastic/plastic effects.

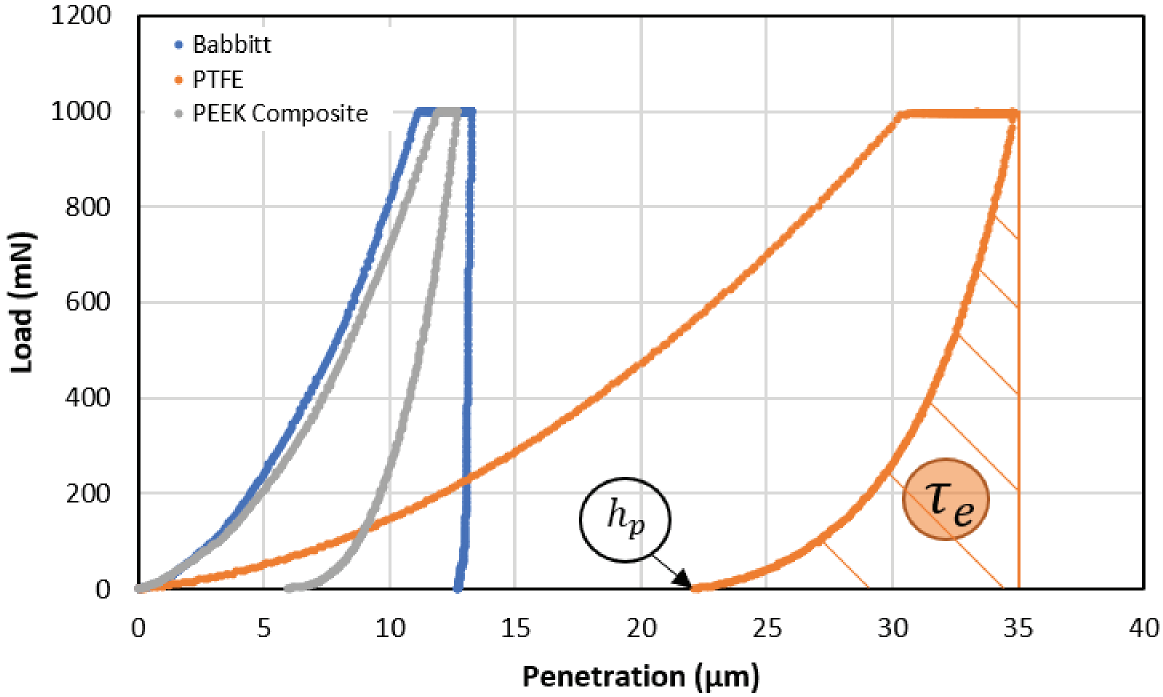


Figure 4 – Mechanical behavior of bearing materials as measured by instrumented indentation.

Table 2 – Mechanical properties and wear resistance ranking numbers of bearing materials. H/E ratios are dimentionless.

Material	H (MPa)	E (GPa)	H/E x 10^3	τ_e/τ_T (%)	H/($E^{*0.447}$) x 10^3	H/($E^{0.4}$) x 10^3
Babbitt	248 ± 4	75 ± 3	3.4 ± 0.1	2.1 ± 0.1	40 ± 1	44 ± 1
PTFE	42.0 ± 0.4	1.08 ± 0.03	39.2 ± 1.2	23 ± 1	39 ± 1	41 ± 1
PEEK Composite	283 ± 1	5.5 ± 0.1	51.5 ± 1.6	35 ± 1	128 ± 4	143 ± 5

Discussion

The good adequacy between the wear rates predicted by the empirical equation $W_R = A\boldsymbol{L}^{\alpha}\boldsymbol{v}^{\beta}$ and the measured wear rates is encouraging. Like the well-known PV factor, strong changes in the equation's constants may indicate a change of wear mechanisms or the crossing of a material threshold (PV limit). However, the contributions of load and velocity to the response of a tribosystem need to be evaluated separately.

To interpret the effect of load on the measured wear rates, a parallel with contact mechanics can be made. In an indentation test, the load P can be related to the *elastic* penetration depth h by $P \propto h^m$ where m is a constant which values 2 for a conical indenter and 1.5 for a sphere [19]. If an equivalency between the wear rates and the indentation depth is assumed, then the relationship $W_R \propto P^{1/m=\alpha_e}$ would be expected in an elastic contact, with $\alpha_e = 1/m = 0.667$ for a spherical sliding indenter. Therefore, the more the load exponent α deviates to values higher than α_e, the higher is the volume of material stressed beyond its yield thresholds. As the PEEK composite load exponent $\alpha = 0.82$ is only 23% higher than α_e, one may argue that an increase in the test load causes a relatively small increase in the volume of material undergoing permanent plastic damage. In contrast the load exponents of Babbitt and PTFE were approximately $\alpha \cong 2$ indicating that an increase in load causes a relatively large increase in the volume of material plastic flow. Close examination of the wear tracks illustrated in Figure 5 reveals extensive material displacement to the track edges. Regardless of the test conditions, the volume of Babbitt accumulated at the wear track edges is about the same as that of the wear groove. In the case of PTFE, the displaced volume is about 30% of the groove volume.

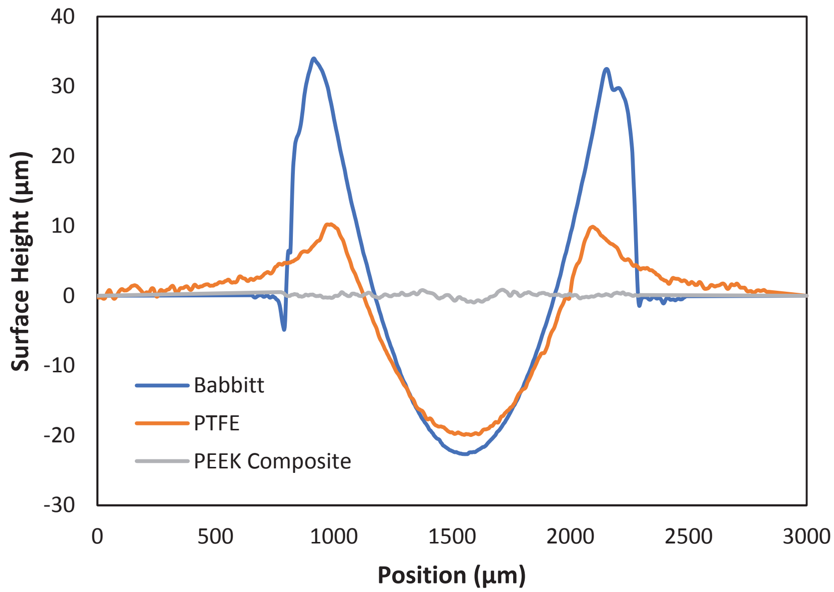


Figure 5 –Section view of the wear tracks of Babbitt and PTFE after the wear test done with 15N and 0.01 m/s.

Given the large contributions of plastic flow to the wear rates of Babbitt and PTFE, one may argue that a steady-sate wear regime was not achieve during the tests. On the other hand, a transition from boundary to hydrodynamic regime happens in a time span of a few seconds [20], meaning that knowledge of early wear rates may be relevant. In industrial bearings, typical oil film thicknesses are of the order of a few tens of microns, which compares well with the measured wear groove depths in Figure 5. Future work may help identifying changes in the wear rates with increasing sliding distances.

The wear rate sensitivities to the sliding velocities may be related to frictional heating and associated local changes in mechanical properties. As the thermal conductivity of Babbitt (25 – 50 $W.m^{-1}.K^{-1}$ [5]) is about one order of magnitude higher than that of PTFE (0.2 $W.m^{-1}.K^{-1}$) and the PEEK composite (0.8 $W.m^{-1}.K^{-1}$), it dissipates heat more rapidly, thus experiencing less softening than both polymers.

Many approaches to correlate mechanical properties and wear performance are presented in the literature [13–15], most of which are established for dry sliding or abrasive wear conditions. For example, it was shown [22] that the yield pressure (or resistance to plastic deformation) in a rigid-ball on elastic/plastic plate is proportional to H^2/E^3. The H/E ratio is commonly used to characterize the elastic strain to failure of thin films and coatings [23]. For polymeric materials, Brostow et al. [24] ranked the sliding wear resistance in terms of their viscoelastic recovery ability, i.e. the ratio between the residual and total penetration depths measured in a scratch test. In this work, the elastic to total work of indentation τ_e/τ_T ratio was used to characterize such ability with excellent correlation between the values reported for PTFE in Table 3 and in [24].

One may notice in Table 3 that the H/E ratio ranks the PTFE closer to the PEEK composite rather than Babbitt, which does not reflect the measured wear rates. A similar effect is observed by comparing the τ_e/τ_T ratios of the investigated materials. Neither ranking metric considers the potential contributions of lubrication to the material's performance.

In reference to [25], N. Marx et. al [26] presents equations to determine the central oil-film thickness (here designated t_c) in various lubrication regimes as function of dimensionless load, velocity and elasticity parameters. It may be shown that, for the isoviscous-elastic lubrication regime (i.e. changes in the oil viscosity due to pressure are disregarded), the dimensional t_c may be calculated (in meters) by the equation $t_c = 5.08 \cdot L^{-\frac{16}{75}} E^{*^{-\frac{67}{150}}} R'^{\frac{23}{30}} (v\eta)^{\frac{33}{50}}$, where L is the contact load, v sliding velocity, E^* the reduced modulus, η the dynamic viscosity, and R' the reduced contact radius. Using the mechanical properties reported in the methodology section, in Table 3, and assuming that the stainless steel ball has $E = 210\ GPa$ and $\nu = 0.3$, the t_c has been calculated for some of the contact conditions used in the present work. A hypothetical material having $E = 30\ GPa$ and $\nu = 0.45$ has also been included in the analysis. The results illustrated in Figure 6 show, that $t_c \propto E^{-0.4}$.

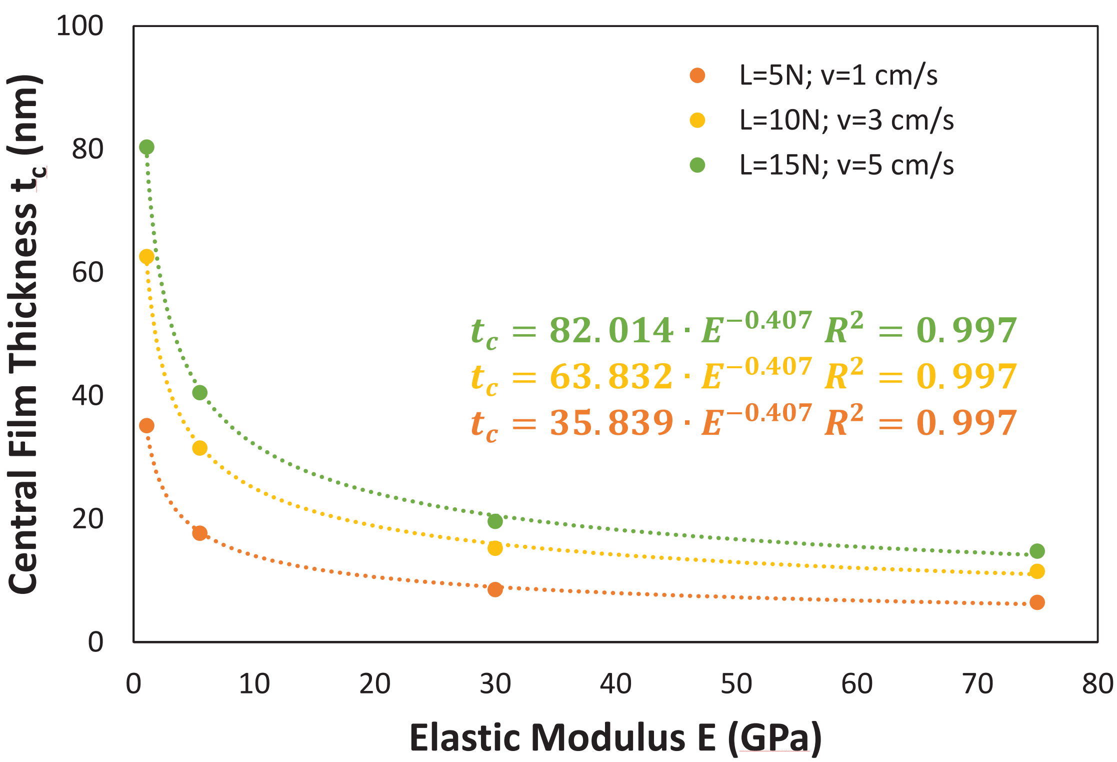


Figure 6 - Relationship between the central oil-film thickness and the elastic modulus E of a plate in isoviscous elastic lubricated contact with a stainless steel ball.

A new wear resistance ranking number may now be introduced, which uses hardness H to account for the resistance to the damage caused by sliding wear and the reduced modulus $E^{*^{-\frac{67}{150} \sim -0.447}}$ to account for the material's compliance, creating an interface capable of entrapping a relatively large lubricant volume (when compared to a rigid material), which attenuates wear. As shown in Table 3, the H/($E^{*0.447}$) ratio ranks Babbitt and PTFE closely, and the composite ranks three times better than the two previous. From the perspective of a bearing lining materials selector, the ratio H/$E^{0.4}$ is more straightforward and, as shown in Table 3, also accurately ranks the wear resistance of materials with a wide range of mechanical behaviors.

Though it may be inaccurate to assume a perfect EHL lubrication regime in the test conditions explored in this work, the good agreement between the H/($E^{*0.447}$) ratio and the measured wear rates provides evidence that the oil film has an important role on the tribological behavior of oil-submerged ball-on-plate unidirectional sliding contacts. Future work combining the measurement of wear rates with precise oil-film thickness measurements such as reported in [18,19] may result in better ranking criteria.

The results of this work show that a relatively simple test methodology allows one to predict important tribological information of materials in boundary or partial lubrication conditions. Future work on the wear behavior of lining materials in more relevant service conditions may confirm the validity of the relationships between mechanical and tribological properties of materials found in this case study.

Conclusions

The tribological and mechanical properties of relevant bearing materials were investigated in boundary lubricated conditions. The variation of the wear rates with the test conditions suggest an important contribution of a partial dynamic lubrication effect to the tribological behavior of oil-submerged ball-on-plate unidirectional sliding contacts.

It was shown that the empirical equation $W_R = A\boldsymbol{L}^{\alpha}\boldsymbol{v}^{\beta}$ can be used to predict the bearing materials' wear rates. While comparable with the well-known PV factor, the equation allows one to assess the contributions of load and velocity separately.

Finally, it was shown that numbers derived solely from mechanical properties cannot adequately rank the materials performance in boundary-lubricated wear. Referring to the EHL lubrication theory, the number $E^{*-0.447}$ was proposed as a quantity that measures a material's ability to entrap lubricant at the contact interface and an adapted $H/E^{*0.447}$ ratio was introduced as a better wear resistance ranking number for the investigated test conditions.

Acknowledgments

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