# Friction and Wear of Some Selected Polymeric Materials for Conformal Tribopairs Under Boundary Lubrication Conditions

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## Abstract

This work is aimed at investigating the friction and wear performance of different polymeric materials having potential for hydraulic system components under lubricated sliding conditions against a steel counter face. A pin-on-disc test configuration was used for the experimental study. The different polymeric materials selected for these studies were commercial polyimides (PI), polyether ether ketone (PEEK) and flouropolymers, some of them were bulk materials whereas others were coatings applied on cast iron substrate. The tribological characteristics of the polymers were compared with a reference grey cast iron. The frictional characteristics were evaluated in both static and dynamic conditions. The results have shown that by using polymeric materials it is possible to reduce breakaway friction by an order of magnitude compared to grey cast iron. However, the breakaway friction increased significantly after the wear tests. The polymeric materials having lowest breakaway friction have shown the highest wear with the exception of the PEEK-PTFE coating which showed low wear. PI with graphite fillers also showed low wear but it resulted in relatively high friction. The carbon fibre reinforced materials resulted in unstable friction as well as higher wear compared to the PI materials with graphite fillers.

KEYWORDS: polymers, friction, wear

## 1. Introduction

Break away friction is an important parameter in many industrial lubricated applications like journal bearings and hydraulic motor components. Under steady state conditions, the operation of moving machine components is in full film lubrication or at least in mixed lubrication regime. However, during start up and at low speeds, the machine components operate in boundary lubrication regime where there is risk of high wear and friction. PTFE and other polymers have been widely used materials to reduce break away friction. The drawback with polymers in general and PTFE in particular is their low strength and poor wear resistance. With the use of fillers, the strength and wear resistance of polymeric materials can be significantly improved.

There are many different polymers on the market like polyimide (PI). polyetheretherketone (PEEK) and polytetraflouroethylen (PTFE). The polymeric materials are often reinforced with fillers and used in the form of composites. Usages of these fibres increase the load carrying capacity and wear resistance of the polymeric materials. Fibre reinforcement is often used in conjunction with solid lubricant particles like MoS2, graphite or PTFE to improve the frictional properties of the composite material. Fibres can be distributed randomly in the matrix or oriented in the mould fill direction. The effect of fibre orientation on wear was studied by Cirino /1/, who reported that fibres parallel to the sliding gave lower wear compared to fibres in the normal direction. In some instances fibres can abrade the counter surface. However, in some cases this abrading effect can be beneficial because of the polishing effect on the counter surface. Newly developed composites also make use of nano particles as fillers which have the interesting feature of a large interfacial area. These nano particles based composites have been reviewed by Friedrich /2/. PTFE with its low friction has been the most important polymeric material for tribological applications. The low friction is governed by the formation of a thin and oriented transfer film on to the counter face during initial sliding. An important parameter in the formation of an effective transfer film is the surface roughness of the counter surface. Too smooth a surface can hinder formation of transfer film and a very rough surface may lead to high wear of the polymer due to abrading action of the hard counter surface asperities. So there often exists an optimum roughness of the counter surface for desirable tribological performance of polymeric materials.

Due to their self lubricating properties, polymers have mostly been used in applications where the use of lubricating fluids is undesirable such as pharmaceutical and food industries. Owing to this, most of the tribological research on polymers has been carried out in dry conditions and only a very few studies under lubricated conditions have been reported.

In lubricated conditions, some studies have shown higher wear of polymers vis a vis in dry conditions /3/ owing to degradation of their mechanical properties due to absorption

of fluid into the polymer and also the limited transfer film formation in presence of a lubricant. On the contrary, some researchers have shown lower friction and wear of polymers in oil lubricated conditions compared to those in dry conditions. Dickens and co-workers /4/ made a thorough study of wear and friction of PPO, PTFE and PEEK at different loads, speeds and fluid viscosities. They found out that friction and wear were always higher in dry conditions even at speeds as low as 1 mm/s. At the highest tested speed of 1m/s, wear was 3-4 orders of magnitude lower in lubricated conditions and this was attributed to hydrodynamic effects. Zhang /5/ reported that friction of a sintered bronze bearing with PTFE reduced by 2-3 orders of magnitude and the pv limit was also enhanced with an order of magnitude in lubricated conditions. In an earlier study, Sethuramiah et al have reported a decrease in wear by  $1 \sim 2$  order of magnitude of pure PTFE under lubricated conditions compared to that in dry sliding /6/. They further opined that in case of PTFE wear is inversely dependent on hydrodynamic effects. Choudhary /7/ discussed the filler enrichment on surface during both dry and lubricated sliding of polymer composites and reported that the filler enriched layer may have a positive effect on lubricated wear.

Recently, research on PTFE based composites as replacement for babbitt material in hydro generator thrust bearings have also been carried out /8/. The breakaway friction of polymers has been studied /9/, /10/ with a view to reduce the breakaway friction of hydrodynamic journal bearings and to replace the conventional babbitt material. A soft polymer layer can be beneficial not only for starting friction but also for the operation in full film regime due to the compliant property of polymers. The hydrodynamic pressure can be reduced and the oil film thickness can be increased, Kuznetsov et al. /11/. However, the oil film temperature can increase due to lower heat transfer coefficient of polymers compared to metals.

Thin thermoset polymer coatings are interesting because of the ease in applying a polymer layer to a substrate. Some studies have been conducted on air refrigerant compressors in which the use of PEEK/PTFE and PEEK/MoS2 resulted in low friction and wear under marginal lubrication conditions /12/. Demas and co-workers /13/ studied polymeric PTFE-based coatings and found that the coatings were comparable to a DLC coating regarding their friction and wear performance. At high loads, the polymer coatings were worn, but the wear particles worked as a third-body lubricant and were beneficial in the scuffing performance.

The understanding of friction and wear characteristics of polymer under lubricated conditions is therefore vital as most high performance hydraulic and mechanical systems involve the use of hydraulic or lubricating fluids. Conventional materials like cast iron are known to have a stable boundary friction coefficient and an important question is the stability of the breakaway friction of polymers during a wear process if the cast iron was to be replaced by polymeric materials. Thus the aim of this work is to investigate the lubricated friction and wear characteristics of different commercially available polymeric materials (both in bulk and coating forms) and compare them with those of a conventional cast iron material. The idea is to ascertain whether the polymers can be a good choice for conformal tribopairs such as a journal bearing which usually operate in hydrodynamic lubrication regime with some hydrostatic lift and also occasionally under boundary lubrication conditions.

## 2. Experimental

In this work, eight different commercial polymer materials and one reference cast iron were chosen for tribological studies. Their salient properties have been summarized in **Table 1**. Five of these are bulk materials and four of them were used as coatings applied on a hard substrate of cast iron or steel. Tribological studies under lubricated conditions were carried out by using a pin on disc machine.

Material	Base material	Fillers	Compr. strenght [MPa]
A (bulk)	Cast iron	Graphite flakes	840
B (bulk)	PFA	Long CF	302/80
C (bulk)	PI	Graphite	170
D (bulk)	PI	Graphite	145
E (bulk)	PI	Short CF	163
F (coating)	PEEK	PFA	118
G (coating)	PEEK	PTFE	118
H (coating)	Flouropolymer		
I (coating)	PTFE	Sintered bronze	250

#### Table 1: Properties of tested materials

The test configuration for the pin-on-disc test can be seen from **Figure 1**. The upper specimens for the pin-on-disc tests were discs with diameter 4 mm and height 3 mm. The test specimen edges were rounded off with a radius of 0,2 mm in order to avoid edge effects. This also reduced the effective diameter of the contact surface to 3,6 mm, and the corresponding area was 10 mm<sup>2</sup>. Specimens A-E was polished with a #400 grit

polishing paper as the final finishing operation. The resulting surface roughness and flatness can be seen from **Table 2**. Despite the same polishing procedure, the resulting roughness is quite different. Smoothest surface is obtained with cast iron closely followed by C and D. Both B and E are composite materials with fibre reinforcements and the presence of these fibres result in a rougher surface despite the usage of the polishing procedure as those for the other polymers. The polishing process resulted in a convex shape. Specimens F and G were sand blasted before applying the coating in order to ensure good adhesion but it also resulted in higher surface roughness values. Specimen H was turned before the coating process and the coating process resulted in a rough surface with cavities and low flatness. The polymer coatings F, G and H were spray coated and cured. Specimen I was produced from a plain bearing with diameter 40 mm. It was flattened out before forming it into the shape of an upper specimen. The cross sections of the four polymer coatings are shown in **Figure 2**. The lower specimen was a disc made of hardened 100Cr6 bearing steel with a hardness of ~ 800HV and roughness S<sub>k</sub> ~ 0,1 and it is considerably smoother than the upper specimens.

Material	S <sub>k</sub> b. test [mm]	S <sub>k</sub> a. test [mm]	Flatness b. test [mm]
A	1,4±0,1	0,4±0,1	4-10 convex
В	5,8±2,6	2,7±0,7	4-6 convex
С	2,0±0,5	1,1±0,2	3-4 convex
D	2,1±0,5	1,6±0,2	3-4 convex
Е	3,2±1,2	2,1±1,2	3-5 convex
F	6,4±1,3	1,4±0,2	8-10
G	3,8±0,5	1,6±0,4	4-6
Н	6,5±5,6	3,6±1,6	20-30
I	6,1±2,6	3,3±0,9	14-20

 Table 2: Surface characteristics of tested specimens



**Figure 1:** Schematic of the pin-on-disc test configuration with pin (1), specimen holder (2), upper specimen (3) and lower specimen (4)

The hydraulic oil ISOVG 32 (mineral oil) containing anti wear additives was used as a lubricant in all the tribological tests.



Figure 2: Cross sections of the polymer coatings, designations according to Table 1

The conformal test used in this work has no converging gap which means that hydrodynamic effects are negligible. The speed 0,1 m/s was intended to ensure operation in boundary lubrication regime. This was confirmed by tests at speeds varying from 0,05 to 0,2 m/s where the friction was only marginally different. The fact that static and dynamic friction values are very close for all tested materials also indicates that operating lubrication regime was boundary lubrication.

## 3. Test configurations and procedure

The design of the pin-on-disc test configuration is shown in Figure 1. A half sphere was used as holder for the upper specimen to ensure an even loading of the specimen against the rotating disc. In this way, the friction force between upper and lower specimen will not tilt the upper specimen. All tests were repeated five times, but because of technical problems with the test rig, friction measurements were not correct in the first two test rounds. Therefore, only the results from the three last test rounds are presented here. To further ensure uniform loading, the coated samples were made 2 mm thick for the two last test rounds, which enabled the use of a flexible 1 mm polymer disc to be mounted on top of the specimen. The even loading could also be verified after the test when the specimens were examined. The contact area was 10 mm<sup>2</sup> which means a maximum contact pressure of 100 MPa at 1000N load.

Both the static and dynamic friction measurements using pin-on-disc test machine were done. For static friction measurements, a torque wrench was used to apply and gradually increase the tangential force on the specimen until sliding occurred. The torque was increased slowly during 10-20 s and a typical result from a static friction test is illustrated in **Figure 3**. Typically, 4-5 break away tests were performed, then one minute standing still under load to see any effect of oil squeezing out of the contact. After that, another 8 to 15 break away tests were performed, the number of tests depending on the consistency of the obtained friction values. An average of the five highest values was taken from each test to be used in the comparison between the tested materials.



Figure 3: Typical appearance of a breakaway test in pin-on-disc

In the dynamic tests, the lubricant was circulated and poured on top of the rotating disc. No heating device was used so the operating temperature was dependent on the frictional heat generation and the ambient temperature. The bulk oil temperature at the end of the tests varied from 32-37°C depending on the friction heat input. An incremental loading sequence was used in which the load was increased in steps of 100 N to 1000N in 10 minutes. The sliding speed was 0,1 m/s in all the tests.

The rotation started when the load had reached 100N. Duration of the test at 1000N was 2h.

All tests included a static test, a 2h dynamic test and another static test after the completion of the dynamic test.

All upper specimens were weighed before and after test in order to estimate the wear. The procedure before weighing was ultrasonic cleaning in ethanol and 15 minutes in an oven at 60°C to evaporate any absorbed fluid. The weight measurements were repeated four times for each sample to get reliable results. The test specimen surfaces were also analyzed before and after test with an optical profiler (Wyko NT1100). Two magnifications were used, 10X and 2,5X analyzing surface area of of 0,6 x 0,46 mm and 2,5 x 1,9 mm respectively. 10X magnification was used for calculating the  $S_k$  values in Table 2 and 2,5X was used to obtain the flatness values.

#### 4. Results

#### 4.1 Friction results

A dynamic friction curve for the cast iron, material A is shown in **Figure 4** as an example of a typical dynamic friction curve obtained from three test repetitions. Friction values were obtained from the curve at three different time intervals. The first value was taken at 100N immediately after the start of rotation. The second value was at the end of the incremental loading when load reached 1000N. The third value was taken after 2h wear test at 1000N.



Figure 4: Friction curve from the 2h dynamic test in pin-on-disc for the cast iron specimens

The comparison of coefficients of friction of the nine different materials is shown in **Figure 5**. The friction coefficients are presented in relation to the static friction coefficient for material A before wear test. There are five values of coefficients of

friction for each material. These are: the static coefficient of friction before the test; the dynamic coefficient of friction at 100 N immediately after the start of rotation; the dynamic coefficient of friction at the end of the incremental loading when load reached 1000N; dynamic coefficient of friction after 2h wear test at 1000N; and the static coefficient of friction after the 2 hour wear test. The values are mean values and the error bars are the standard deviation of the three repetitions for these tests.

The frictional behaviour of materials A, C and D are quite similar as the static friction is equal to or slightly lower after the test compared to that before test. Also the dynamic friction at 1000N is stable or slightly decreased during the test. Material E showed an increase in friction during the dynamic test and the static friction is also higher after the test. Material B and I have low friction before test but friction increased throughout the test. The PEEK based materials, F and G, have higher dynamic friction than static friction but the friction during the 2h wear test remained stable or decreased.





#### 4.2 Wear results

The analysis of wear and its quantification for different materials was done by means of a 3D optical surface profiler, an optical microscope and gravimetric measurements. In **Figure 6**, the 3D surface profiles of the upper pin specimens before and after the tests are shown for four materials. The roughness marks from the production process can

still be seen on surfaces of all material test specimens except B, I and E. This means that wear of most material test specimens is small and is confined to the surface asperities. Materials C and D specimens behave in a similar manner and only polishing of asperities and some deeper scratches in the sliding direction have been seen. Materials F and G specimens also behave in the same way. The rough surface from the blasting process appears to have smoothened out and a plateau surfaces with deep valleys have been formed. Material E specimen shows higher wear and only traces of the original surface on some of the specimens can be seen.



Figure 6: Images with 3D optical profiler for four of the tested materials. Direction of sliding is indicated with an arrow

The optical microscopic images in **Figure 7** reveal the presence of some scratches on the mating disc surface but it has almost remained unaffected by the wear test. However, in case of material F the mating disc has been abraded in all the five repeat tests either due to the abrading nature of the fillers or the embedded particles from the sand blasting process. These optical microscope images also show that the alignment of test specimen during the pin on disc tests was good and the load was uniformly distributed within the contact. However, in case of A and H, the test specimens were

not sufficiently flat to result in uniform loading. The carbon fibres are clearly visible on the surfaces of material B and E test specimens. On many of the polymer materials, for example C, D, E and G, deep single scratches have developed in the direction of sliding.



Figure 7: Microscope images for all tested materials

The quantification of wear of polymeric materials from gravimetric measurements poses certain difficulties, see **Figure 8**. Polymers C and D have gained weight during the tests despite the fact that the wear is low as observed by the optical surface profiler images. It seems that C and D both absorb fluid. Besides these i.e., C and D, the weight loss measurements and results from optical surface profiler and optical microscopic examination indicate similar behaviour. Polymer B and E have shown the highest wear of the bulk materials and A the lowest. Material I has shown the highest wear of all materials, both from gravimetric measurements and optical surface profiler analysis. The wear of the polymer coatings is low as seen from weight loss measurements.



Figure 8: Weight loss for all tested materials

## 5. Discussion

All polymeric materials studied in this work except C have the potential to reduce the starting friction in a hydrodynamic journal bearing. Materials B, G and I appear to be most promising from the viewpoint of low starting friction for short duration operation in boundary lubrication regime such as that encountered during starting and stopping.

The reason for the increased static friction after the test for B, G and I is probably that PTFE or other low friction fillers are worn away and the base matrix, like bronze, PEEK and carbon fibers, determine the resulting friction after the wear test. Materials C and D can be robust in a journal bearing with low wear but the starting friction would be similar or only marginally lower than that of a cast iron bearing.

One advantage with a thin polymer coating compared to a bulk polymer material is the better heat transfer. Even though the thermal conductivity of the polymer is the same, the thin layer will increase the heat transfer due to the higher thermal conductivity of the substrate material. The temperature on top of the upper specimen was measured in some of the tests. A comparison of tests F and C shows similar friction coefficient during the test and the temperature in the bulk oil was the same i.e., 35°C after the tests. On the back of the upper specimen C, the temperature was also 35°C but on the back of specimen F, the temperature was 41°C, indicating better heat dissipation. Another advantage with a polymer layer is that it will distribute the load more evenly and lower the maximum operating pressure, Kuznetsov /10/. This is also apparent from this test series. With a thin soft coating on cast iron substrate, like material F, the load

is evenly distributed on the whole disc as compared to that with the cast iron specimen, A, which resulted in concentrated loading in the middle of the specimen despite a convex form of only a couple of microns.

The ability to form a hydrodynamic oil film is governed by the surface roughness and conformity of the interacting surfaces. Therefore, it is important that a sliding bearing material is easy to manufacture to a smooth surface. One indicator of this is the surface roughness values in Table 2 for the bulk polymers with the same surface preparation process. Materials C and D seem to be better than B and E in this respect. Also, the surface roughness and form that develops during the running-in process is crucial for the function in a journal bearing. For optimal hydrodynamic performance, the surface needs to be smooth but any form errors also need to be flattened out easily. Surface roughness and form can be produced to some extent but very smooth surface and exact form is difficult and expensive to produce. Some of the polymer coatings also need a blasted surface for good adhesion which will roughen the surface. It is also important to remember that the surface roughness in the loaded condition can be quite different from the unloaded case since polymer materials have low Youngs modulus.

Some of the materials, for example the PEEK based materials have higher dynamic friction than static friction. This phenomenon has also been experienced when performing the breakaway tests in which the start of the movement could not be sensed as a jerk. Instead, the torque increased after start of the movement. This may be explained by the composite structure of the materials.

The material B has quite different properties in flow direction compared to those in a direction perpendicular to flow. In this test, the specimens were, of practical reasons, produced with flow direction perpendicular to the sliding direction. The performance may have been better with flow direction parallel to sliding direction as indicated in /1/.

The surface finish of the counter surface was very smooth in these tests, which have been reported to give high friction in dry sliding due to limited transfer film formation. However, in a lubricated contact, the transfer film formation is not as important as in dry sliding. Also, a smooth surface finish on the counter surface will facilitate full film lubrication in a journal bearing application.

The deeper scratches seen occasionally on the polymer specimens are difficult to explain. These are not likely a result of 2-body abrasion but possibly caused by some extraneous particles or other hard constituents in the composite materials.

## 6. Conclusions

The tribological characteristics of eight different commercial polymer materials under lubricated sliding conditions have been studied and compared with those of reference cast iron. The main findings of this work have been summarized as follows:

The PTFE based materials have very low static friction coefficient, up to one order of magnitude lower than the reference cast iron at 100 MPa contact pressure but after 2h wear test the static friction has increased to about 50% of the reference friction of the cast iron.

PI based materials with graphite fillers are wear resistant with stable friction and may be suitable for journal bearings that continuously operate in boundary lubrication and they can be machined to a smooth surface roughness. But the breakaway friction is equal to or only up to 20% lower than that with the reference cast iron.

The friction in carbon fiber reinforced materials tends to increase as the sliding progresses and their wear is also higher as compared to those of other bulk polymers.

The friction of polymer coatings tends to decrease and their wear is also low as seen from the two hours of sliding wear test.

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