Effect of Shaft Roughness and Pressure on Friction of Polymer Bearings in Water

Arash Golchin^{1)*}, Tan Dat Nguyen³⁾, Patrick De Baets³⁾, Braham Prakash¹⁾ and Sergei Glavatskih^{2), 3)}

¹⁾ Division of Machine Elements, Department of Engineering Sciences and Mathematics, Luleå University of Technology, 97187 Luleå, Sweden

²⁾ Division of Machine Design, School of Industrial Engineering and Management, Royal Institute of Technology, Stockholm, Sweden

³⁾ Department of Mechanical Construction and Production, Ghent University, Gent, Belgium

*Corresponding author: aragol@ltu.se

1. Introduction

It is well known that the combined surface roughness of shaft and bearing surfaces play an important role in determining the lubrication regime of sliding bearings. This role becomes even more crucial in water lubricated bearings due to the much larger roughness to film thickness ratios in comparison to the oil lubricated bearings.

Earlier simulations show the beneficial influence of reduced combined surface roughness on hydrodynamic lubrication of journal bearings [1]. Using a smoother shaft could potentially allow for applying higher loads and increased load bearing capacity while maintaining fluid film lubrication under certain operating condition. However, this not only affects the bearing performance in the hydrodynamic lubrication regime, but it can also influence the tribological performance of the system during start-up and stop when a mechanical contact between shaft and bearing surfaces is inevitable.

In dry sliding contacts, Mofidi and Prakash [2] showed that a reduced friction can be obtained with elastomers in sliding against a rougher counter surface. Zsidai et al. found similar behavior with some thermoplastic polymers under low loads [3]. In another study Quaglini et al. showed that an increased counter surface roughness influenced the material's frictional behavior depending on the polymers' elastic modulus [4] such that an increased counter surface roughness led to increased friction for soft polymers and decreased friction for polymers with high elastic modulus. Some other studies suggest the existence of an optimal surface roughness for minimal friction of different polymers [3, 5].

The influence of contact pressure on tribological behavior of polymers has been extensively studied earlier in order to evaluate the limiting PV values for various polymeric materials in dry sliding conditions. However, in lubricated contacts frictional response of polymers differs from that in dry contacts due to the effects arising from the presence of lubricant. Despite the practical significance of the latter, very little work has been accomplished in regards to the effect of counter surface roughness or contact pressure on friction of polymers in lubricated conditions [6, 7].

This study is therefore aimed to study the influence of counter surface roughness and operating conditions on

frictional behavior of selected polymers in a water lubricated journal bearing configuration.

2. Experimental Work

Tribological studies were carried out using four different unfilled thermoplastic polymers namely polytetrafluoroethylene (PTFE), polyether ether ketone (PEEK), polyethylene terephthalate (PET) and ultra-high molecular weight polyethylene (UHMWPE). The experiments were carried out using a small-scale journal bearing test rig. The detailed description of the test rig can be found in [8]. Plain polymer bearings were machined from polymer rods and press-fitted into stainless steel bushings. The test shafts were machined from Inconel 625 rods and polished to the desired surface roughness using various grades of SiC sand paper (#800P-#4000P).

Each bearing was run-in at sliding speed of 0.06 m/s (40 rpm) for four hours. Dynamic friction curves were obtained with variation in speed for each material and shaft roughness combinations at different time intervals during running-in.

The experimental conditions for obtaining dynamic friction curves during running-in are shown in Table 1. Following the running-in of the bearings, breakaway and dynamic friction maps were obtained for each material, shaft roughness and pressure combination. This was achieved through intermittent motion of the shaft (start-stop cycles) at the lowest practical rotational speed of the tribo-meter. A full description of the test conditions for the intermittent tests is provided in Table 2. At least three repetitions were carried out for each test combination throughout this study and the results were averaged from these test runs.

Table 1 Experimental condition for running-in tests

Radial Load	141 N
Specific Bearing Pressure	0.3 MPa
Rotational Speed	40 - 690 rpm
Sliding Speed	0.06-1.08 m/s
Time Intervals	10, 55, 115, 175, 235 min
Test Duration	4 h
Bearing Materials	PTFE, PEEK, PET, UHMWPE
Shaft Ra Roughness	0.02, 0.1, 0.2, 0.4 μm
Lubricant	Distilled Water
Lubricant Temperature	R.T. (23 °C)

Table 2: Experimental conditions for intermittent tests for obtaining friction maps

Load	141, 224, 336, 449, 562, 679 N
Specific Bearing Pressure	0.3, 0.5, 0.75, 1, 1.25, 1.5 MPa
Rotational Speed	40 - 690 (rpm)
Sliding Speed	0.06-1.08 m/s
Bearing Materials	PTFE, PEEK, PET, UHMWPE
Shaft Ra Roughness	0.02, 0.1, 0.2, 0.4 μm
No. of Cycles	100
Cycle Duration	12 Sec
Test Duration	20 min
Lubricant	Distilled Water
Lubricant Temperature	R.T. ($\sim 23^\circ\text{C}$)

3. Results

3.1. Friction evolution during running-in

Figure 1 shows the dynamic friction behavior of the materials versus sliding speed at different stages of running-in using shafts with Ra surface roughness of 0.02 μm and 0.4 μm .

Figure 1: Dynamic friction behavior of tested materials at different time stages of the running-in process (specific bearing pressure= 0.3 MPa, test duration=4 h, shaft Ra roughness=0.02 and 0.4 μm)

In general, all the materials showed a trend of decreasing friction coefficient during the running-in period and this trend was consistent with shafts of different surface roughness values.

While many polymers are generally regarded as chemically resistant, their interaction with metallic counter-parts in a tribological system cannot be neglected. Frictional heat and pressure at asperity-asperity contact can enhance the conditions for chemical reaction between polymers and metal counter-faces in water.

In earlier studies on tribo-chemical reaction of PTFE with metal counter-faces [9, 10], formation of metal fluorides were detected using XPS when PTFE was rubbed against aluminum, stainless steel and nickel counter-parts. Deposition of the reaction products and formation of such tribo-films on metal surfaces can influence the wettability and surface free energy of the metal surfaces and thus may alter the lubricating and frictional behavior of the surfaces.

To investigate the latter, screening tests were carried out to examine the possible changes in wettability of Inconel counter-faces when sliding against the polymeric materials. Figure 2 shows the results of water contact angle measurements for unworn and worn Inconel plates and polymer materials.

The results show a significant reduction in hydrophobicity of Inconel surfaces when sliding against the polymers in water. This suggests formation of a reaction layer on Inconel surfaces rather than deposition of a physical polymer transfer layer. Formation of a reaction layer on the Inconel counter-face could have partially contributed to the reduction of friction during running-in. However the significant differences in the

Figure 2: Water contact angles of unworn Inconel, unworn polymer and worn Inconel surfaces on the wear track

Figure 3: Average Ra roughness of bearing surfaces before and after sliding against shafts with different roughness values

magnitude of friction reduction when using shafts of different surface roughness suggest that the dominant mechanism for the trend is not only the result of formation of a reaction layer and possible changes in surface free energy of Inconel counter-faces.

It is well known that one of the major surface characteristics which can affect the tribological behavior of tribo-pairs is topography of the contacting surfaces. Roughness measurements of polymer surfaces in the contact region of the bearings before and after the tests showed a considerable reduction in the surface roughness of PEEK, PTFE and PET. Figure 3 shows the average Ra roughness of the polymer bearings before and after sliding against shafts of different surface roughness values. It can be seen that no significant change in roughness characteristics of UHMWPE could be observed due to its relatively high wear resistance. The reduction in friction during running-in period is mainly attributed to the smoothing of the polymer surfaces at the contact region of the bearings.

A considerably larger reduction in friction during running-in was obtained when experiments were carried out using the smoothest shaft ($R_a=0.02\mu\text{m}$) compared to the case with the roughest shaft ($R_a=0.4\mu\text{m}$). PEEK, PTFE and PET exhibited a lower initial friction followed by 50-75% reduction in friction during running-in when using the smoothest shaft. A marginal reduction in friction during running-in (approx. 10%) was obtained when the experiments were carried out with the roughest shaft.

After the running-in period, frictional behavior of the materials obtained with smooth and rough shafts was significantly different. Figure 4 shows the average dynamic friction curves obtained for each material after four hours of running-in using shafts of different surface roughness. UHMWPE bearings provided almost unchanged friction with variation in sliding speed or shaft surface roughness.

However, it was a different case for the remainder of the materials; a decreased shaft roughness not only reduced friction at high sliding speeds but also led to a

Figure 4: Dynamic friction behavior of materials after 4h running-in (specific bearing pressure=0.3 MPa)

considerable reduction in friction in the boundary/mixed lubrication regime, simultaneously shifting the friction curves down and to the left. As shown in Figure 4, a considerable reduction in friction was obtained by reducing the shaft surface roughness from $0.4\mu\text{m}$ to $0.1\mu\text{m}$; however, a further reduction in friction by using a smoother shaft ($R_a=0.02\mu\text{m}$) was marginal and less significant.

3.2. Friction Maps

Breakaway and dynamic friction maps were obtained for all materials after the four hour running in period.

Figure 5 shows the results of average breakaway and dynamic friction coefficients of different polymeric materials obtained with variation in specific bearing pressure and shaft surface roughness. The friction trends observed for different materials are described as follows:

PEEK. At the lowest specific bearing pressure, PEEK exhibited a trend of decreasing friction with decreasing shaft surface roughness. The reduced combined surface roughness increases film parameter and enhances lubrication of the surfaces when using a smoother shaft. However, with an increase in load, a considerably

Figure 5: Average dynamic and breakaway friction after four hours of running-in versus specific bearing pressure and shaft surface roughness

higher friction was obtained; while no consistent trend or a significant change in dynamic friction could be observed with further variations in pressure or shaft surface roughness. At breakaway, PEEK exhibited a different frictional response to variations in shaft roughness and contact pressure with a trend of decreasing friction with increasing shaft roughness and bearing pressure.

UHMWPE. UHMWPE showed similar trends in dynamic and breakaway friction maps. Variations in shaft roughness led to marginal changes in friction while a trend of decreasing friction with increasing pressure could be observed with more pronounced effects occurring at breakaway compared to dynamic friction.

PTFE. PTFE exhibited a reduction in friction with reduced shaft surface roughness. More pronounced effects of pressure on friction were observed with high shaft roughness values; however, in general a trend of decreasing friction was found with increasing pressure for PTFE.

PET. The dynamic friction map of PET is not included in Figure 5 due to the large scatter in the results. However, in accordance with the breakaway friction found for PEEK, PTFE and UHMWPE, a trend of decreasing friction coefficient could be observed with increasing pressure for PET.

In general, a trend of decreasing friction was obtained with increasing contact pressure for all materials while frictional response to variations in shaft surface roughness varied from one material to another.

A trend of increasing friction was observed with increasing shaft roughness for PTFE whereas an opposite trend was obtained with PEEK at breakaway. No significant dependence of friction on shaft roughness was found with UHMWPE or PET. The various trends observed in friction of the polymers with variations in shaft roughness may be explained by the contribution of adhesive and deformation components of friction for each material considering their vast differences in elastic modulus and surface free energy. These results indicate that although using a shaft of reduced surface roughness can favorably decrease the dynamic friction of polymer bearings; it may adversely affect the materials' breakaway friction and thereby increase the torque required for machine start-up; a critical issue in some applications such as pumped storage hydropower plants.

4. Conclusions

The major findings of this work can be summarized as follows:

1. In general, all the materials showed a trend of decreasing friction coefficient during the running-in period and this trend was consistent for the shafts of different surface roughness.
2. For PEEK, PTFE and PET, a lower initial friction followed by 50-75% reduction in friction was

observed during running-in with the smoothest shaft. A higher initial friction and marginal reduction in friction during running-in (~10%) was observed with the roughest shaft.

3. Contact angle measurements revealed a significant increase in wettability of Inconel counter faces. This suggests formation of a reaction layer on worn Inconel surfaces when sliding against the polymers.
4. The friction maps showed a trend of decreasing friction with increasing pressure; however the materials' frictional response to changes in counter surface roughness were varied.
5. A trend of increasing friction was observed with increasing shaft roughness for PTFE whereas an opposite trend was observed for PEEK at breakaway. No significant dependence of friction on shaft roughness was found for UHMWPE and PET.
6. A shaft of lower surface roughness may be beneficial for low dynamic friction of polymers in all lubrication regimes; however, it can adversely affect frictional response at breakaway.

5. References

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