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Wear and Friction Behaviour of Additive Manufactured PEEK under Non-conformal Contact

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Abstract. Tribological properties of laser sintered polyether- ether-ketone (EOS PEEK HP3) were investigated using a rolling-sliding test rig. This investigation aimed to study the wear and friction failure mechanism of EOS PEEK HP3. The main objectives included to conduct wear and friction tests under non-conformal contact, to monitor surface temperature, to carry out surface characterization with microscopy. With this rolling-sliding test rig, tests were carried out on an EOS PEEK HP3 specimen running against a steel disc unlubricated, with various slip-ratios under a contact pressure of 56 MPa, 48 MPa and 39 MPa respectively. Both wear and friction were measured. The results have shown that both friction and wear were increased with an increase of either slip-ratios or the contact pressures, exacerbated by high surface temperatures. It has also been observed that both friction and wear failures were associated with the degradation of the non-conformal contact surfaces due to crystallinity changes that correlated well with working conditions. Using microscopy it was found that such failures as pitting, fatigue and surface cracking were affected by the surfaces in contact, including the degree of melting of the surface. Based on the observation on the contact surfaces, the failure mechanisms of EOS PEEK HP3 include surface melting and contact fatigue failures with the high slip-ratio and the high contact pressure conditions. The findings of this investigation have the potential to help to design & develop additive manufacturing PEEK products. Typically, these results can be used in a design process for a more effective polymeric gear system.

1. Introduction

High-temperature selective-laser-sintered PEEK is attractive in aerospace, automotive, mechanical engineering & energy industries, such as bearing and gears because it is a typical high-temperature resistant semi-crystalline polymer and has many good mechanical properties resistance to chemical and radiation damages, lower coefficient of friction and light weight [1-4]. Mechanical properties of high-temperature selective-laser-sintered PEEK have been reported widely [2-4] but not its wear and friction behaviors under a non-conformal contact. This has limited the potential of this new type of materials in design of gears and bearings. Rolling-sliding test rig can be employed to explore the wear performance of two polymer discs, such as extruded PEEK, as a simple means for analysing the performance of polymeric gear teeth [1-4]. A further exploration is needed to identify and manage the properties of wear and friction of this type of material.

This paper reports fundamental wear and friction behaviors of laser sintered PEEK. Tests were carried out on a laser sintered PEEK (EOS PEEK HP3) specimen running against a steel disc unlubricated, with slip-ratios of 3.9%, 14.29%, and 28.29%, and loads of 220 N, 330 N, and 460 N, (giving the contact pressure of 39 MPa, 48 MPa and56 MPa respectively). For a laser sintered PEEK gear tooth, these slip-ratios provided a snap-shot of the critical wear and frictional behaviour of the pitch point, important for performance, but was not well understood. These results suggest that laser sintered PEEK can be engineered to produce high-performance polymer gears.

2. Experimental

All laser sintered PEEK discs were machined by EOS and Victrex plc. The initial surface roughness before testing was approximately 3.354 µm. A typical dimension of a disc is shown in Figure 1.

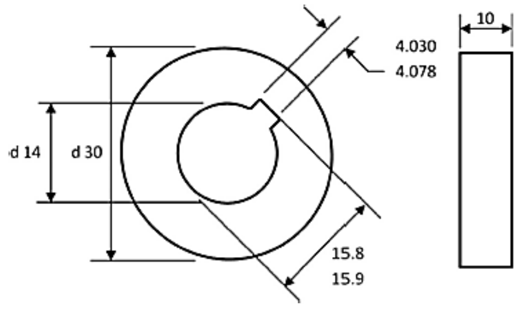

Figure 1. Typical dimension of a PEEK disc in mm [6].

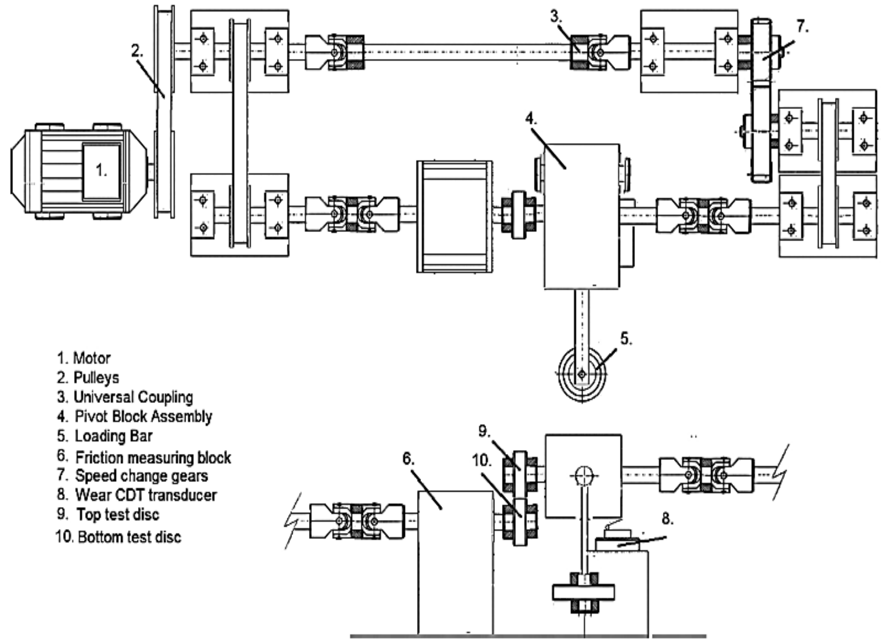

Figure 2. Schematic of the rolling-sliding test rig [6].

Figure 2 shows a rolling-sliding test rig which was employed to investigate both wear and friction properties of the EOS PEEK HP3 under unlubricated conditions. This test rig at the University of Hertfordshire provides a simplified technique for determination of the dynamic response of the polymeric gears to better understand their performance from the first contact point to around the pitch contact point [1,6]. As shown in Figure 2, two cylindrical discs of equal diameters (items 9 and 10 in the figure) fixed on spindles passing through friction measuring blocks (item 6 in the figure) and a pivoted block for applying a load (item 5 in the figure). This twin-disc test rig can be used to simulate the contact features found in gears [5]. A Fluke Ti25 infrared camera was employed to measure the body temperature of the disc materials, the optical microscopy was used to characterise the wear surfaces of the discs, and the sample crystallinity was investigated with a differential scanning calorimetry (DSC).

3. Results and discussion

Table 1 shows the testing conditions when an unlubricated PEEK disc was tested versus a mild steel disc over a range of slip-ratios and three different contact pressure values which were associated with gear transmitting torques of 7.0 Nm, 10.0 Nm and 13.5 Nm respectively.

Table 1. Typical test conditions for PEEK discs running against steel discs.

Contact Pressure (MPa)	Slip Ratios		
	3.9%	14.29%	28.59%
56	√	√	√
48		√	√
39			√

3.1 Wear mechanisms and topographical analysis for EOS PEEK HP3 vs. Steel

Three general wear regimes were observable in all of the tests and the transition between them was dependent on the frictional profiles and generated surface temperature. These are a "bedded-in" period, a steady state running period, followed by a final region with a rapid wear leading (sometimes quickly too) specimen failure [1, 7-8].

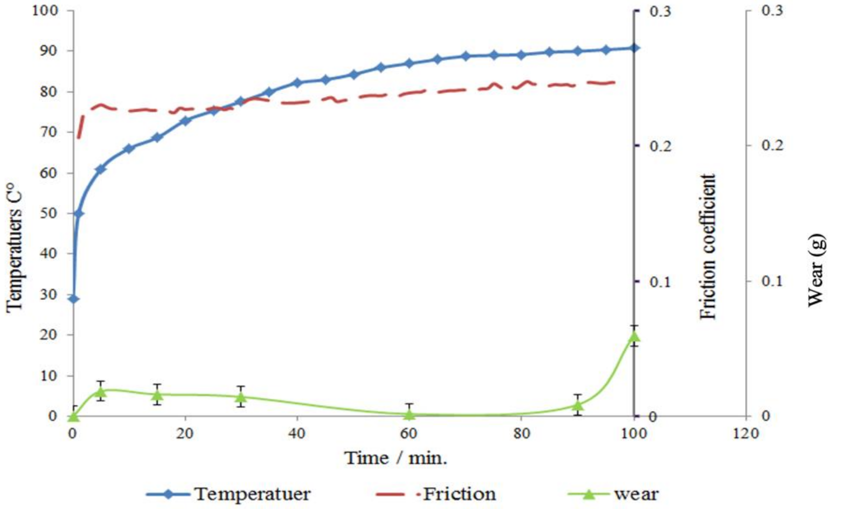

Figure 3. Wear, friction coefficient and surface temperature versus testing time under the conditions of slip ratio of 14.29% & a contact pressure of 56 MPa.

Figure 3 shows the results when one PEEK disc was tested against a mild steel disc with the rolling-sliding test rig shown in Fig.2 under the testing conditions given in Figure 3. Under these conditions, the maximum disc surface temperature was 90 C°, with a friction coefficient value of 0.24 occurring after 100 minutes. It was observed that the maximum surface temperature of 90 C° occurred after 100 minutes during a test. Also included in Figure 3 is the transient friction coefficient profile versus time, reaching a steady-state of friction coefficient values.

Under 28.57% slip-ratio Under 14.28% slip-ratio Under 3.9% slip-ratio

Figure 4. Optical images of the tested PEEK disc surfaces.

The optical images and wear tracks of the disc surfaces are shown in Figure 4 which were obtained under the testing conditions of 28.59%, 14.29% and 3.9% slip-ratios with a contact pressure of 56 MPa. All specimens had an average surface roughness of 3.3534 µm before a test. After testing, the average values of surface roughness over the middle of the test area were 1.304 µm, 1.210 µm, and 1.137 µm respectively under the slip-ratio of 28.59%, 14.29% and 3.9%. The depth of the typical wear tracks after tests are presented Figure 5. It can be seen that the wear track in the middle of disc contact region at the highest slip-ratio of 28.59% was deeper than the wear tracks tested under the other slip-ratios.

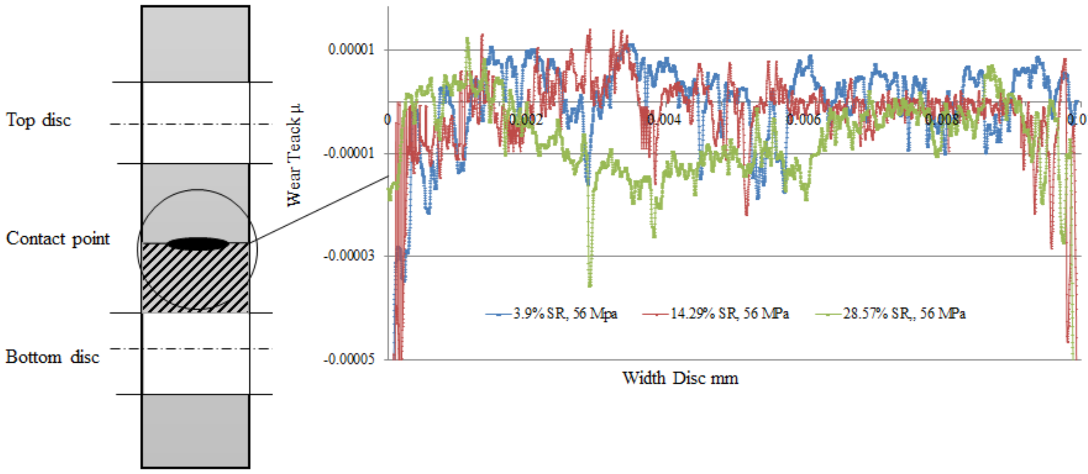

Figure 5. Wear track results of a tested disc under three individual slip-ratios, 3.9%, 14.28% & 28.57%, and one constant contact pressure, 56 MPa.

Figure 6 a) shows the disc surface of the additive manufactured PEEK which was tested against a steel disc at the contact pressure of 56 MPa and slip-ratio of 14.29%. Refer to Figures 7-8, the PEEK disc material in the middle of disc face width was softened at high severity tests with a large value of slip ratio. The test severity was obtained by an integration of the average thermal output generated from the contact area over a testing period of time. This PEEK surface softness could be a result from the discs being overheated due to friction during the contact, and contact surface yielding (permanent deformation) may play a role in such a materials softness too. It is evident that the disc surface was damaged and softened [1] as shown in Figure 6 b). It is suggested that the mechanism of such a PEEK material transfer was that the locally softened PEEK material in a contact point was torn and expelled by a frictional force from the contact point between two discs so that wear debris was generated. Some debris was also subsequently trapped on the steel contact surface and started to cause a cyclic loading and adhesion on the PEEK surface in the subsequent contacts.

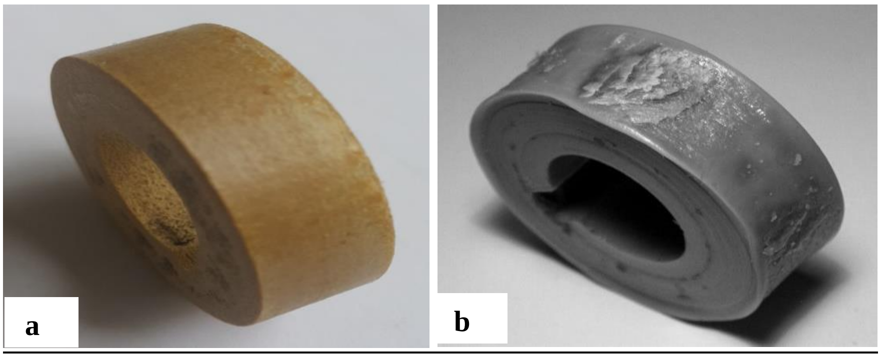

Figure 6. Surface damages incurred with 14.29% slip-ratio and contact pressure 56MPa; a PEEK disc against a steel disc, a) additive manufactured PEEK disc; b) steel disc**.**

Figure 7 shows that the average values of wear vary with both slip-ratios and contact pressure values. It can be seen that under the conditions of both high contact pressure and high slip ratio, the greatest wear (material loss) appeared with correspondingly higher values of surface contact temperature. Conversely, low values of contact pressure and slip-ratio gave a lower increase of surface temperature and less wear. In the region of high test severity, wear debris started to appear where they were expelled from the contact surfaces between two discs. Overall, it was observed that during the tests additive manufactured PEEK had much lower wear as well as a consequent lower surface temperature compared with extruded PEEK and polyamide 66 respectively [1,6]**.**

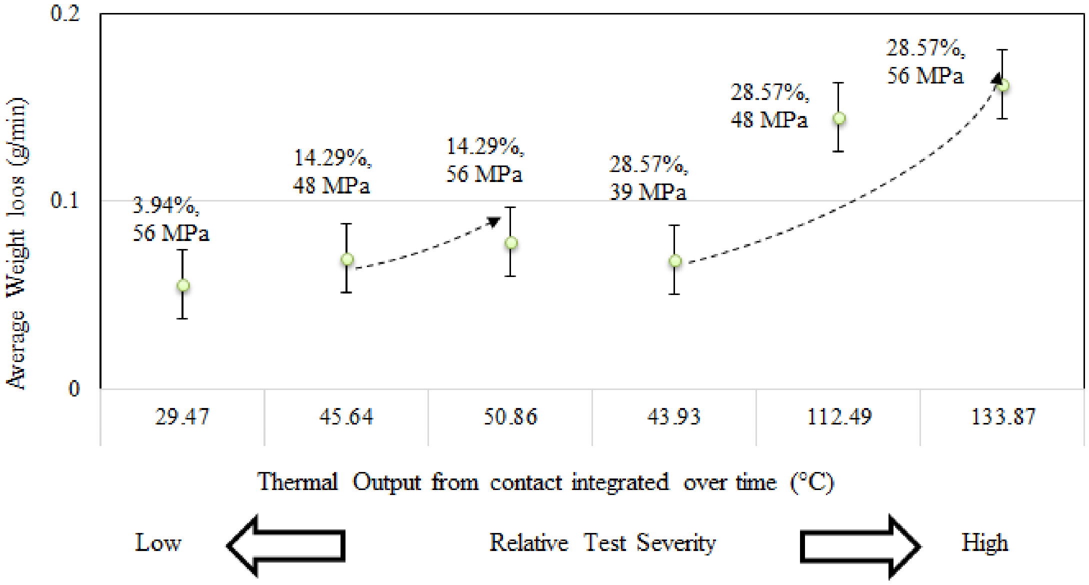

Figure 7. Average wear rate verses test severity for twin disc tests.

As shown in Figure 7, the average wear rate are correlated with the relative test severity. The test severity was obtained by an integration of the average thermal output generated from the contact area over a testing period of time and this allows the wear rates to be quantified based on testing conditions given in Table 1. As shown in Figure 7, the high values of slip-ratio and contact pressure led to a great increase of the contact temperature values and resulted in rather high wear rate, which were treated as a great severe stage. By contrast, the low values of slip-ratio and contact pressure resulted in a small increase of the contact temperature values and led to the less severe. As a result, the low wear rate occurred. It was observed that little wear could be visible during a test if the contact surface temperature was low. When the contact surface temperature was over the glass transition, the additive manufactured PEEK disc maintained its mechanical strength until approximately 190 °C as shown in Figure 8.

3.2. Friction and surface temperature

Figure 8 shows the maximum surface temperature ($T_{max}=T_i+T_f$) on the PEEK disc versus the coefficient of friction during each individual rolling-sliding test under the given test conditions. Table 2 summarises both the disc body temperature and flash temperature at a contact point during a test. Each disc body temperature (T_i) was measured with Fluke Ti25 infrared camera and flash temperature (T_f) was obtained using the Blok's equation [9]. It was noticed that the top disc in Figure 2 was cooler than the bottom one in Figure 2 because the bottom one was steel although the top disc rotated slightly faster than the bottom one.

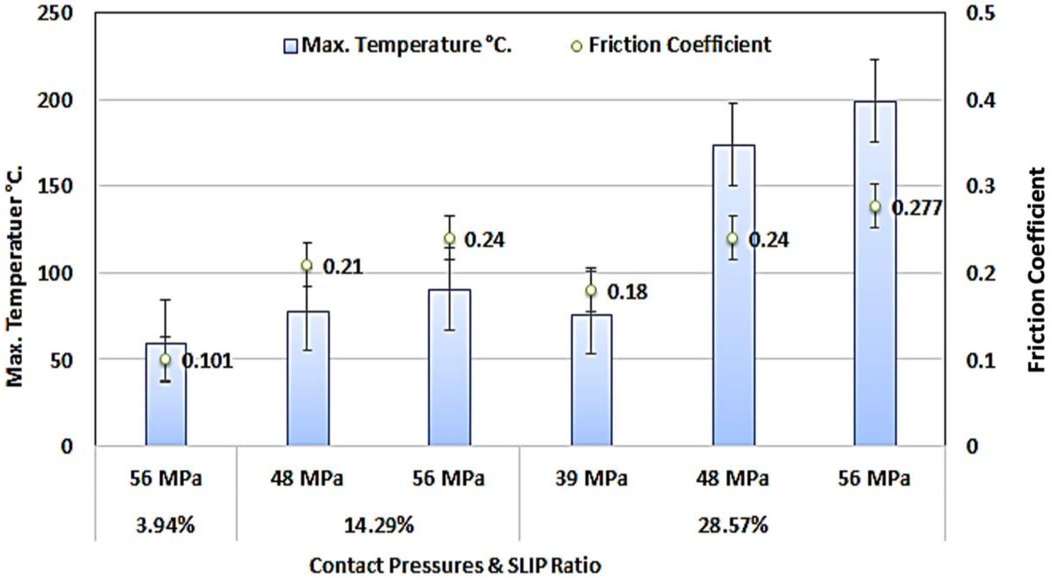

Figure 8. Maximum PEEK body temperature vs. friction coefficient under all test conditions.

Table 2. The projected body temperature (T_i) and the associated flash temperature(T_f) under the testing conditions.

The contact pressures MPa	**Slip Ratios**		
	3.9%	14.29%	28.59%
56	T_f = 24.27C°, T_i = 64.27C°	T_f =24.1C°, T_i = 91.1C°	T_f = 21.8C°, T_i = 184.8C°
48		T_f = 22.9C°, T_i = 80.9C°	T_f = 27.16C°, T_i = 120.16C°
39			T_f = 23.16C°, T_i = 70.16C°

The time steady state of an average values of coefficient of friction is shown in Figure 9. It can be seen that it varies with the values of contact pressure as well as slip-ratio. Both the greater value of contact pressure and the greater value of slip ratio led to take a longer period of time to reach the steady state. It took 50 minutes to reach the steady state under the severe test conditions with the maximum values of both slip ratio and contact pressure simultaneously which were 28.59% and 56MPa respectively. By contrast, under the lower value of contact pressure (39 MPa), a change in slip ratio from 28.59% to 14.29% had no measurable effect on time to equilibrium. This way was considered to be the least risky.

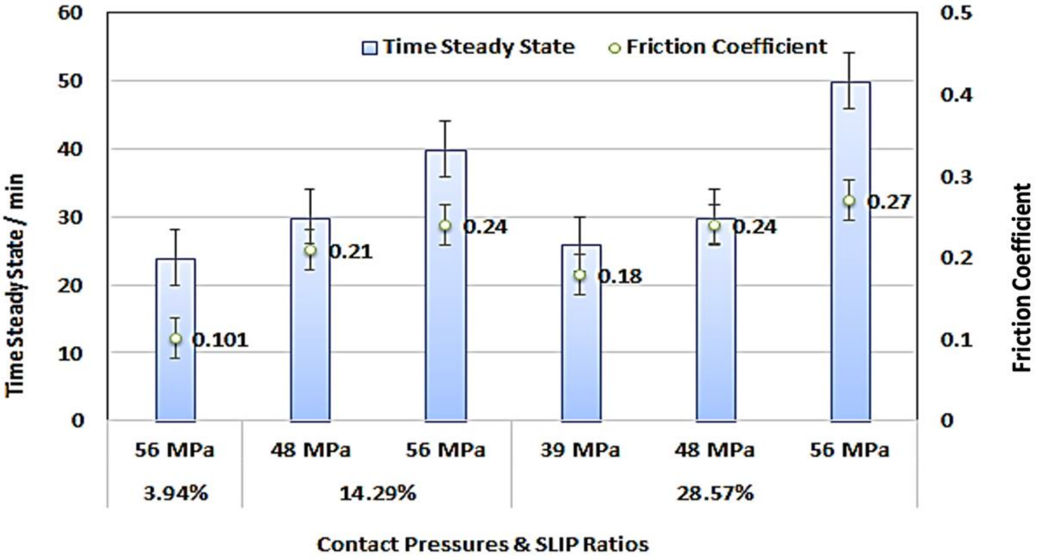

Figure 9. The time steady state against friction coefficient under all test conditions.

Table 3. Crystallinity of additive manufactured PEEK after testing.

Slip ratios %	The contact pressures (MPa)	Crystallinity %
3.9	56	37.50
14.29	48	38.16
14. 29	56	39.11
28.59	39	36.33
28.59	48	37.14
28.59	56	33.05

Enthalpic relaxation will occur when the additive manufactured PEEK is operated above or near its glass transition temperature (174.5°C) but below its crystalline melt transition (385°C). After their rolling-sliding contacts the crystallinity of the additive manufactured PEEK specimen was measured to see if there was any evidence of enthalpic relaxation. Table 3 shows all measured values of PEEK crystallinity, which are in the range of 33-39% for all those tested samples. Compared with the crystallinity value, 35.4%, of untested PEEK, it appears that the glass transition temperature of the material was exceeded. indicating strongly that enthalpic relaxation had occurred.

4. Conclusions

In this paper, tribological behaviour and wear mechanisms of additive manufactured PEEK were investigated using a rolling-sliding test rig with a steel counter face disc under a series of two controlled key parameters, contact pressure and slip-ratio. It was evident that the wear rates of additive manufactured PEEK were much lower than the wear rates from an extruded PEEK under an identical test condition. It was observed that the failure mechanisms on the contact surfaces made of additive manufactured PEEK were surface melting and contact fatigue failure particularly under the severe conditions of extreme high values of contact pressure and slip ratio. From these results it can be suggested that surface temperatures between a pair of gear teeth in mesh may be managed by a reduction of contact pressure and slip ratio in a design stage. This study has the potential to increase its service life of laser sintered PEEK gears.

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