TRIBOLOGICAL BEHAVIOUR OF THE LOW AND HIGH VISCOSITY PEEK AGAINST STEEL USING DIFFERENTS CONTACT PRESSURES

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Abstract:

In the market of polymers for tribological applications polyetheretherketone (PEEK) are often used for satisfying requests coming from industry regarding enhanced properties such as, thermal stability, friction and wear resistance. These properties promote the material to be used in so called high performance tribological applications. However, fundamental mechanisms governing friction and wear are not yet fully understood and neither is the influence of composition parameters. An important parameter is PEEK's viscosity during manufacturing process which is heated up to semi-solid state, between its glass transition and melting temperature. This paper studies the friction and wear performance of low and high viscosity PEEK and pure PEEK under dry reciprocating sliding contact. The tests were performed in large scale specimens under flat-on-flat configuration to determine the transitions in tribological behaviour at different contact pressures. Tests were carried out at controlled atmosphere with 25 °C and a relative humidity of 50%. Contact pressures parameters were 4, 8 and 10 MPa used at a sliding speed of 20 mm/s. Post mortem analyses were carried out by means of 2-D surface topography and optical microscopy. The results show that the pure PEEK exhibits low coefficient of friction and wear rate when the contact pressure increase and similar behave for high and low viscosity PEEK.

Keywords: polyetheretherketone PEEK, medium-scale test, injection moulding, viscosity, friction and wear.

1   INTRODUCTION

Polyetheretherketone (PEEK) is a thermoplastic engineering polymer, exhibits excellent thermal, mechanical, chemical and electrical properties. It is an attractive material for journal bearings and piston rings under various loading conditions. Its low coefficient of friction and comparatively low wear rate than other polymers has attracted its use a rubbing surface material in machineries. Its wear resistance has been significantly improved by incorporating fiber, nano, macro and micro particles. However, the smoothness, hardness and stiffness are not the only factors controlling the wear behaviour, but also the nature and stability of the transfer film and its adhesion to the countersurface affects the wear resistance.

Tribological characterisations are commonly obtained from small scale pin-on-disc, block-on-ring or flat-on-flat tests, using standard geometries. Small scale mechanical tests are preferred due there low cost, reduced time and easy handling of the test specimens. These methods provide fundamental information about friction and wear mechanisms and are useful for preliminary material classification. However, the global characteristic of material in real scale is unknown unless the commencement of failure in real components.

In previous investigations has been reported [1] that in selection of material required different factors or use real criteria in the tribological characterization of the material under conditions that simulate practical functionality, such as contact geometries, contact pressures, environmental conditions, mechanical stiffness, etc. Consequently, these can give its tribological effect expressed on different geometries and on scales ranging from nanotribology up to teratribology [2]. For extrapolation of tests results towards real working conditions, Czichos [3] provided a scheme from 'field tests' over 'large-scale' simulation on real components to 'laboratory tests' where the same amount of energy concentration and thermal input is assumed. For polymers, the friction and wear properties change, due to transfer of wear debris and formation of a polymer film on the steel countersurface where the tribological performance may be altered.

The main objectives of the current investigation is to evaluate the wear performance of these high performance polymer (PEEK) manufactured at low and high viscosity to compared between them under different contact pressure, and to shine some light on the relation between mechanical performance and tribological properties of these polymers. As the formation and aspect of a molten or plasticized polymer transfer film strongly governs the tribological performance, the sliding surfaces are microscopically analysed.

2   EXPERIMENTAL DETAILS

2.1   Methodology

The medium-scale reciprocating tribotester will be used to experimentally evaluate the tribological characteristics of the different materials. Two sliding couples (each consisting of polymer test specimen and countersurface plates) are tested in a flat-on-flat motion. The polymer specimens are mounted in two circular holders, fixed in a holder plate with the correct dimension of the polymer samples, inserted in the front and back sizes of the machine into a rigid vertical structure. The countersurface plates are positioned on both sides of the central sliding block. A detailed description of the test-rig is have been explained in our earlier work [4]. A schematic representation is shown in Figure 1.
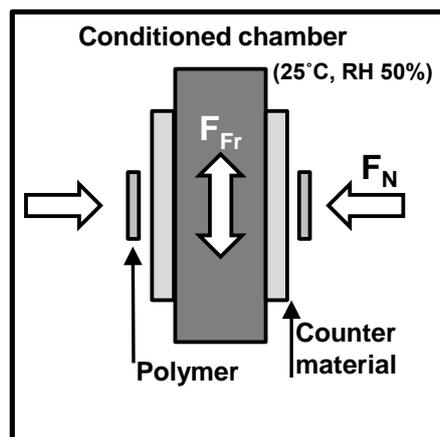

Figure 1: Medium-scale flat (MSF) tribotester:

The coefficient of friction μ is determined by the ratio of horizontal forced and the applied normal load. The polymer wear are determined from mass loss and validated using the thickness reduction measured by micrometer. The total friction force (F_{FR}) is measured by the force transducer. The coefficient of friction (μ) is calculated from the measured friction force (F_{FR}) and the normal force (F_N) according to equation 1, where in the factor of two is used because the friction force is the aggregate

of the two friction specimens. From the results of every logged cycle the maximum of the coefficient of friction (static coefficient of friction) and the coefficient of friction at the first pass through the centre of the stroke (dynamic coefficient of friction) are calculated. In the flat on flat sliding the measurements were made for the tangential friction force (FT) for a given a Normal load (FN). The ratio of FT/FN forces defined as the coefficient of friction (μ), which has two components the static (μ_{stat}) and a dynamic friction (μ_{dyn}). The initial peak in friction at the beginning of the reciprocating motion, is called the static friction at start (μ_{s1}), but also at each reversal of the sliding motion static friction occurs, with a maximum value $\mu_{s,max}$ and a minimum value $\mu_{s,min}$, indicated in the figure 2. The dynamic coefficients of friction are measured at the center of the sliding stroke and vary between maximum $\mu_{d,max}$ and minimum $\mu_{d,min}$.
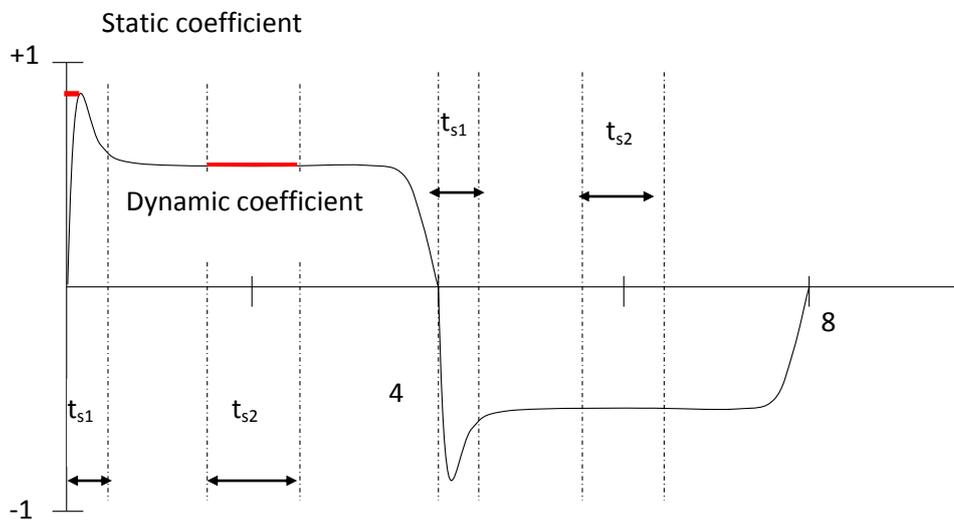
$$\mu = \frac{F_{FR}}{2 \cdot F_N} \qquad (1)$$

Figure 2: Graphical representation of defining coefficient of friction.

2.2 Test materials

The PEEK (beige colour) used in our investigations has excellent abrasion resistance and absorbs much less water than many thermoplastics, possesses excellent chemical and hydrolysis resistance, and can be utilized in steam or high pressure environments without any detrimental effects on properties [5]. Their selection is based on common tribological technology covering a broad range of mechanical strengths and moduli, and their ranking of friction coefficients and wear rates. As we describe before the materials are been used in this work is the Pure PEEK polymer at low viscosity and high viscosity those materials has been produced for INM- Leibniz Institute in Germany for which the physical properties of the test specimen are given in the table 1.

Table 1: Physical properties of the polymer test specimen

Properties	Pure PEEK-Low Viscosity	Pure PEEK-High Viscosity
Density (g/cm^3)	1.3	1.3
Volume flow rate (MVR) (cm^3/min)	70	10
Tensile yield stress (MPa)	100	95
Tensile strain at break (%)	30	>25
Elasticity Modulus (MPa)	3700	3500
Heat deflection temperature at 1.8MPa (°C)	155	153
Melting temperature (°C)	340	340

And for countersurface material commercially available steel 100 Cr$_6$ (DIN 1.3505) were used. Before each test, the surfaces were ground to an average surface roughness R$_a$= 0.20 μm measured parallel to the sliding direction. The measurements were conducted using a Surfascan 3D roughness tester, manufactured by Hommel somicronic with a stylus S6T (radius 2 μm, angle 90°). R$_a$ is calculated according to DIN EN ISO 4288 with an assessment length l$_t$ = 4.00 mm and cut off λ$_c$ = 0.80 mm for 0.1 μm < R$_a$ ≤ 2 μm; l$_t$ = 15.00 mm and λ$_c$ = 2.50 mm for 2 μm < R$_a$ ≤ 10 μm. Prior to each test the steel surfaces were cleaned with a cleaning solvent (petroleum ether) under ultrasonic vibration and then with acetone.

Table 2: Mechanical properties of the countersurface plate

Property	Steel (1.3505)
Yield strength (MPa)	1324
Hardness (HB)	147
Density (g/cm^3)	7.81
Modulus of Elasticity (MPa)	210000
Thermal conductivity (W/m*K)	46.6

The medium scale tests were performed a 6.5, 13 and 16 kN normal loads with a sliding velocity of 20 mm/s. This corresponds to an initial contact pressure of 4, 8 and 10 MPa. The total sliding distance is 1080 m with a sliding stroke of s = 80mm. Parameters such as normal stroke, sliding distance, velocity and normal load are given in Table 3.

Table 3: Experimental test conditions

| Test parameters	Medium-scale tribotester		
Dimension of the polymers samples	40 mm x 40 mm x 4 mm		
Dimension of the countersurfaces	200mm x 80 mm x 19 mm		
Lubrication type	Dry	Dry	Dry
Sliding Velocity	20 mm/s	20 mm/s	20 mm/s
Normal Load	6.5 kN	13 kN	16 kN

Contact Pressure	4 MPa	8 MPa	10 MPa
Sliding stroke	80 mm	80 mm	80 mm
Sliding Distance	1080 m	1080 m	1080 m
Ambient Temperature	25 °C	25 °C	25 °C
Relative Humidity	50%	50%	50%

3   RESULTS AND DISCUSSION

It is essential to take into account the selection of the material for bearing applications, the consultation of tribological literature or technical data is not enough. Friction and wear properties depend on the layout of the tribological system with specific contact geometry, normal load and sliding velocity.

From the two polymer materials, the friction coefficient as a function of sliding distance is presented in figure 3. The dynamic fiction coefficients representing steady-state values that are obtained at the end of the sliding test ignoring eventual instabilities at running-in. When examining friction coefficient changes with the sliding distance. It was observed that the increase in contact pressure cause the decrease of the coefficient of friction for the pure PEEK-low viscosity material, due to the increase of the surface heat and the heat resulted in the escalation of friction coefficient, this increased heat leads to the formation of a transfer film on the specimen and on the countersurface which protects the material and reduces the coefficient of friction.
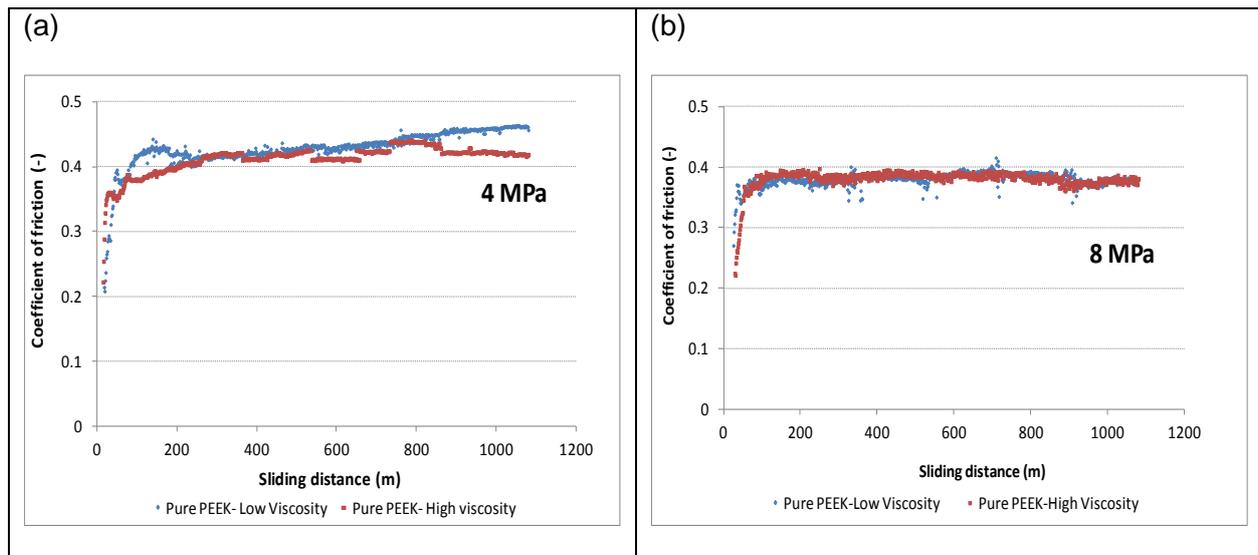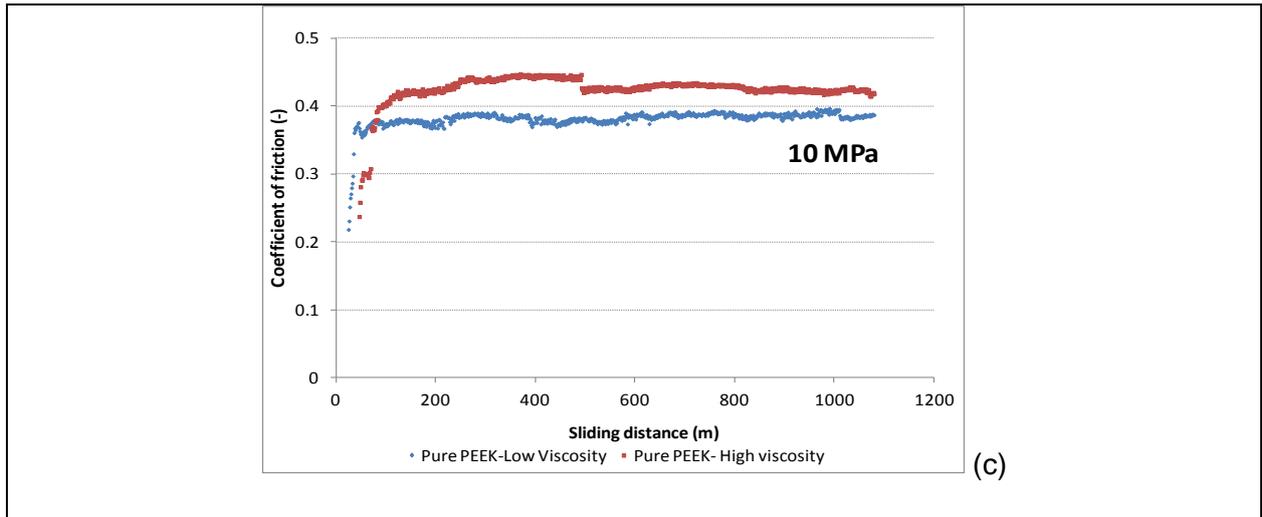
Figure 3: Variation of the coefficient of friction of the two materials with the sliding distance at different contact pressure and continue sliding velocity of 20mm/s; a) Contact pressure of 4 MPa that is equivalent to 6.5 kN as a normal load; b) Contact pressure of 8MPa equal to 13 kN and c) contact pressure of 10 MPa equal to 16kN as a normal load.

On analysing the tribological characteristics and comparing with earlier research [6] it is described that the coefficient of friction for pure polymers decreases or increases, depending on local deformation. The regular normal load effect with decreasing friction is limited to low contact pressures and low sliding velocities. At high contact pressures or high sliding velocities, an overload situation with increasing friction occurs through the combination of deformation and shear. The surface behaviour as well as the integrity of the polymer bulk properties is important because the materials become highly viscous due to the intrinsic property.

The calculated wear rates are based upon polymer sample weight-loss, representing 'real wear' or 'material losses', while dimensional measurements (total thickness reduction) also take visco-elastic deformation into account. Figure 3 illustrates the wear rate at the pure PEEK-low viscosity and the pure PEEK-high viscosity at the three contact pressures and sliding velocity of 20 mm/s. Wear rates as real material loss should be calculated from weight measurements, showing that the pure PEEK-low viscosity has low wear rate at 4 and 10 MPa contact pressure, and higher at 8 MPa. Wear rates for the pure PEEK-high viscosity are higher at the contact pressure of 10MPa and at 4 and 8MPa are lower.

Wear Rate (mm³/ Nm)

PurePEEK-HV

7.45E-6
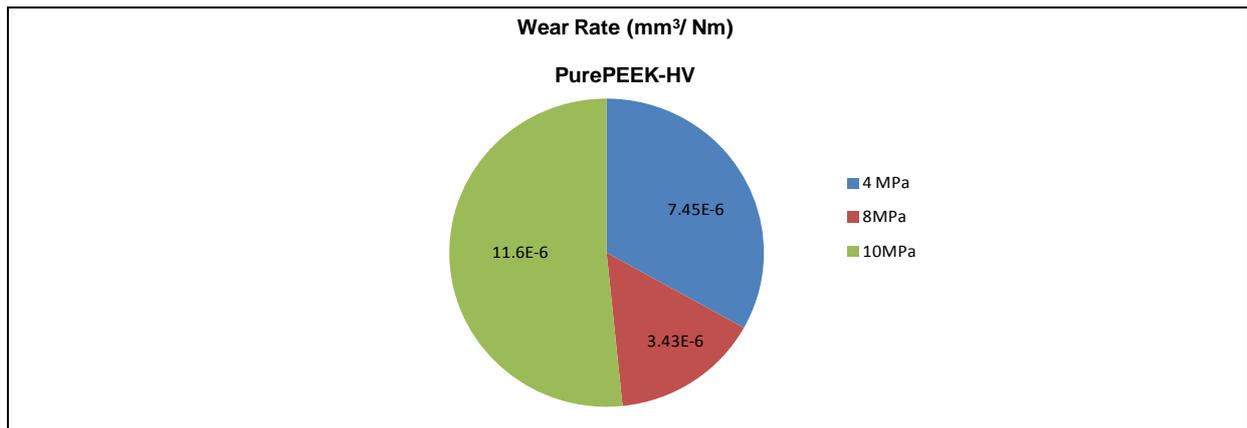3.43E-6
11.6E-6

- 4 MPa
- 8MPa
- 10MPa
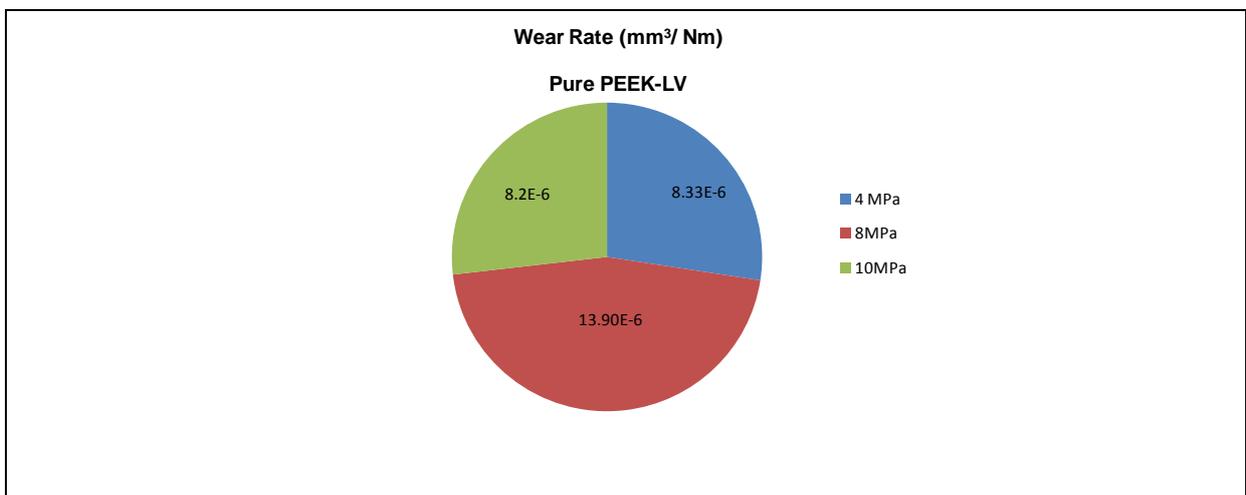
Figure 4: Comparison of the wear rate of the material measured by the material loss at medium-scale test with three contact pressures and sliding velocity of 20mm/s

When the pure PEEK-low and high viscosity are sliding against steel plates, beige coloured discontinuous film is deposited on the steel surface. This formation of thin film is favourable for low friction but unpredictable wear behaviour. Wear rates cannot be easily compared due to transitions in wear mechanisms and efficiency of film formation on the polymer surface or the steel countersurface. In the Figure 4, it can be seen that the pure PEEK-low viscosity with a contact pressure of 8MPa and the pure PEEK-high viscosity shown the highest wear rate for 10 MPa contact pressure. At low contact pressure both material showed similar wear behaviour, but on higher contact pressure (10 MPa) PEEK low viscosity performs better. Considering 8 MPa the wear behaviour was completely reversed by having low wear rates for pure PEEK high viscosity material. The variation in the wear behaviour at high contact pressure is due to the movability of the wear debris into that contact zone are less effective.

3.1   Wear Mechanism

The results obtained from the optical microscopy of the countersurface and PEEK- low viscosity are presented in the Figure 5 for the medium-scale test at a contact pressure of 10 MPa and 4MPa sliding velocity of 20 mm/s thus evidencing different wear process. Figure 5 (a) and (b) shows a combination of adhesive and abrasive leading to debris detachment in the polymer [4] The deposition of PEEK is distributed over the sliding area. In the figure 5 (b), (c) and (d) a layer in the polymer and the countersurface material can be observed, these layers are called third-body layers or films and composed of wear debris from polymer surface and possibly steel surface as well. When wear debris from one surface coats the counterface, the film is called transfer films or layer. In both materials at contact pressures 10 MPa and 4 MPa has material removal from surface via plastic deformation.

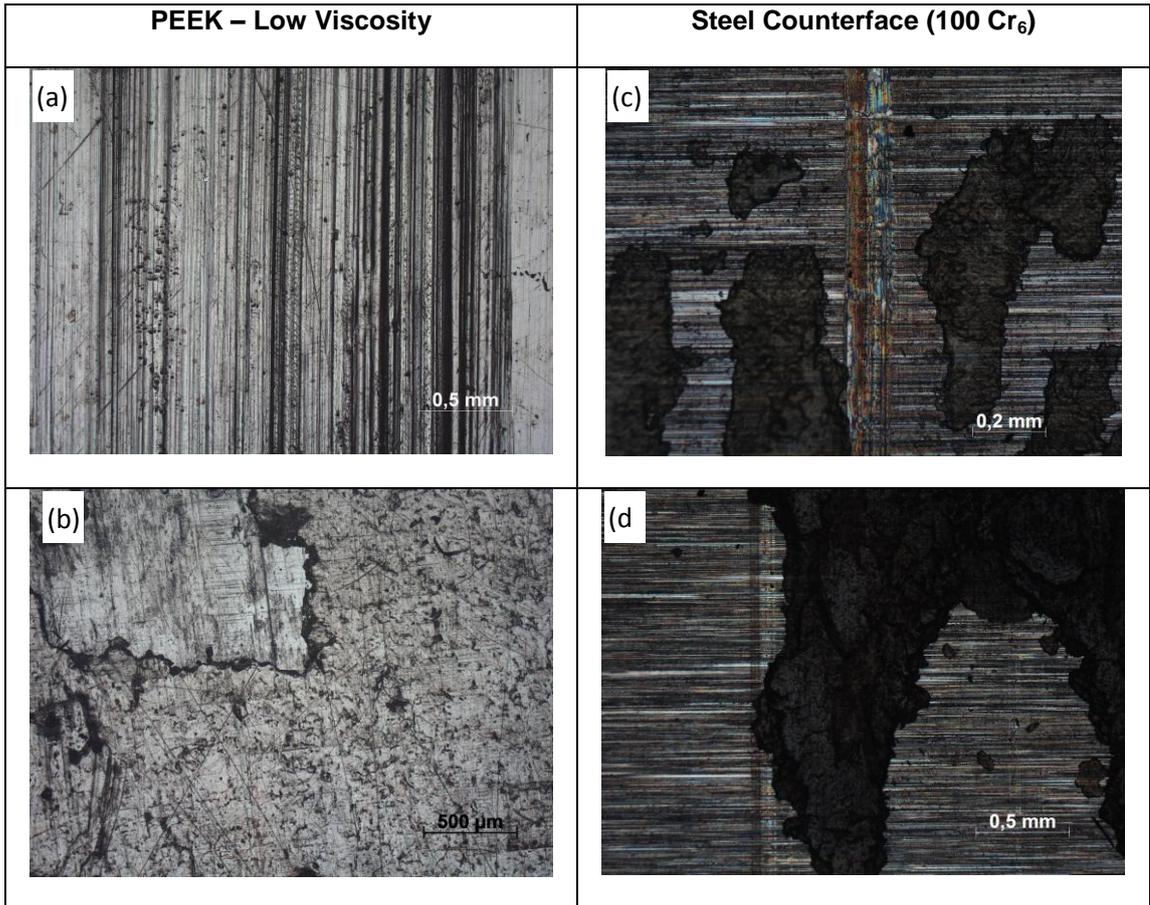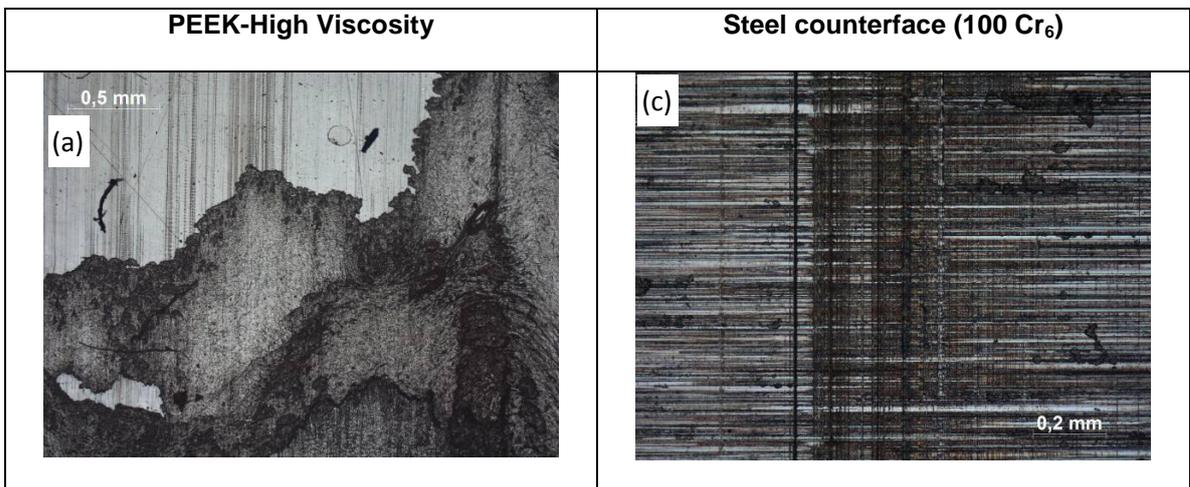| PEEK – Low Viscosity	Steel Counterface (100 Cr$_6$)
(a)	(c)
(b)	(d

Figure 5: Optical Microscopy of Pure PEEK-low viscosity and steel counterface after sliding distance under contact pressure of 10 MPa and 4 MPa with a sliding velocity of 20 mm/s.

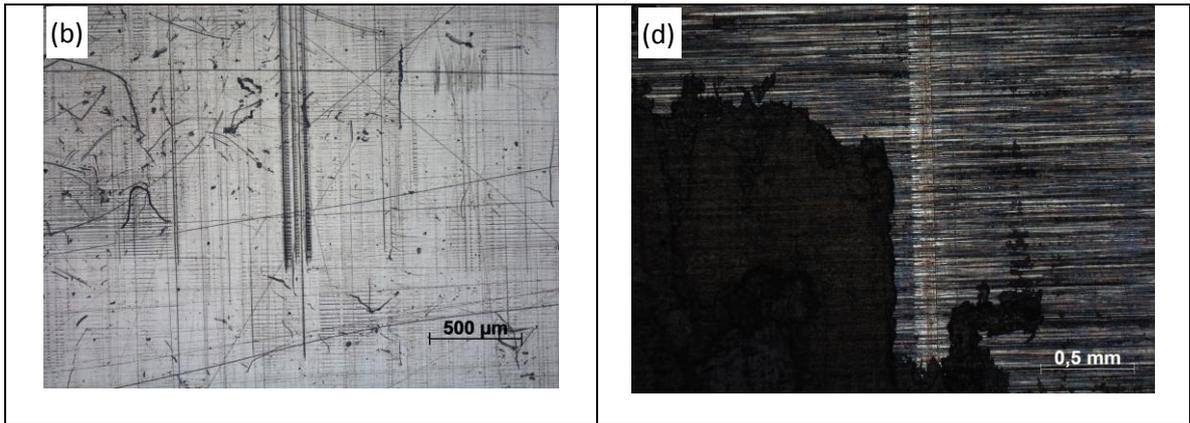| PEEK-High Viscosity	Steel counterface (100 Cr$_6$)
(a)	(c)

Figure 6: Optical Microscopy of PEEK-high viscosity and steel counterface after de sliding distance under contact pressure of 10 MPa and 4 MPa with a sliding velocity of 20 mm/s.

Pure PEEK-high viscosity surfaces are examined by means of optical microscopy in figure 6. The presence of polymer on the steel counterface can be observed as a film. It is vastly found on the middle of the contact zone, see figure 6 (a). Abrasive wear patterns parallel to the sliding direction can be seen in the polymer; figure 6 (b) and (c). The re-adhered wear debris film polymer (from the polymer to the steel and from the steel to the polymer) is observed in the steel counterface having a black colour in the picture but is in the same colour of the polymer (beige), see Figure 6 (d). The appearance of the PEEK-high viscosity sliding surface is different from its original look, by having a dull aspect change after sliding.

It is worth nothing that the PEEK-high viscosity is more prone to be adhered to the steel counterface thus presenting higher stick-slip phenomenon [7]. The figure 6 (b) shows chevron marks parallel to the sliding direction on the polymer surfaces indicative of a stick-slip process. This stick-slip produces very loud noise ad it can seen in detail after 3 cycles during the first stroke and at the beginning of the following strokes. This transfer films are always thick and discontinuous with debris particles progressively growing around a fixes nucleus or containing agglomerated plasticized polymer, reducing the performance through vibrations and torsion within the sliding interface [8].
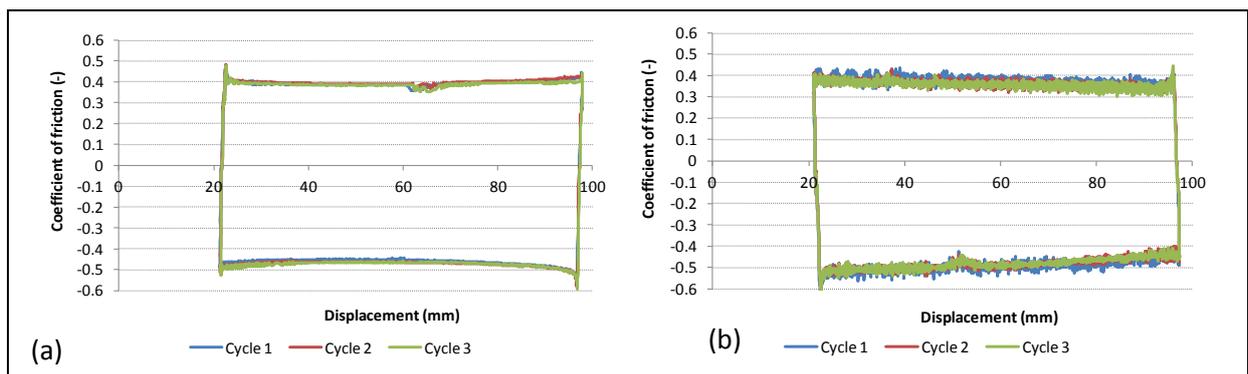

Figure 6: Detail of the coefficient of friction over the displacement measurements in the Pure PEEK-high viscosity of a) contact pressure of 4 MPa and b) contact pressure of 10 MPa at sliding distance of 20mm/s.

4 CONCLUSION

This paper considered the use of polymer materials in highly loaded bearing or sliding applications selected on acceptable friction, adequate wear rates. The influence of counterface type on friction and wear can be effectively illustrated on a medium-scale test rig. It was shown that:

The friction of pure PEEK-low viscosity decreases with increasing contact pressure compared with pure PEEK-high viscosity. However, the Pure PEEK-high viscosity shows the opposite behaviour and this can be attributed to the different mechanism such as formation of transfer layer and wear debris entrapment.

The main differences in transfer layer and polymer surface aspects in medium-scale behaviour are thus attributed to mechanical effects such as wear debris circulation in the interface and the high or low viscosity of the polymer.

5 ACKNOWLEDGEMENTS

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