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Effect of surface finishing, temperature and chemical ageing on the tribological behaviour of a polyether ether ketone composite/52100 pair

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ABSTRACT

Polyether ether ketone (PEEK) composites and AISI 52100 steel are high-performance materials that are often selected for high stress tribological applications under solid and hydrodynamic lubrication. In this study, the viability of these materials as a pair for boundary-lubricated systems was evaluated. Tribotests to evaluate different characteristics were conducted: (i) the effect of metallic surface finish (1 μm polished, 9 μm polished, shot peened and ground); (ii) the effect of temperature (room temperature and 90 °C); and (iii) the effect of long-term PEEK exposure to lubricant oil (i.e., chemical ageing). An AMTI tribometer equipped with a hermetic chamber and a heating system was used for reciprocating sliding tests with a 10 mm stroke, 2 Hz frequency and 2 h duration. The tests used a cylinder-on-disc configuration (polymer on metal), a tetrafluoroethane atmosphere and a 100 N normal force. The wear tracks were analysed using a light interferometer, SEM and optical microscope to assess the wear mechanisms, including transfer film formation. The surface skewness and transfer film establishment were the main factors affecting the friction coefficient. In contrast, the wear of the PEEK composites was mainly affected by the surface bearing index and chamber temperature. Moreover, transfer films were observed only on counterbodies that had a surface roughness (S_q) of at least 0.030 μm. Finally, accelerated ageing of PEEK composites was performed in an autoclave at 180 °C and 3 bar pressure for 7 days in the presence of an ester-based lubricant oil and tetrafluoroethane atmosphere. DSC, DTG and FTIR techniques indicated that the filler/matrix interfaces of the PEEK composites were dissolved by the ester-based lubricant oil. Chemical ageing showed a significant effect on the friction steady state regime. Instead of a stable value, the friction coefficients of the aged composites increased slowly and continuously.

1. Introduction

The introduction of alternative refrigerants (HFCs and isobutene) and lubricants (synthetic polyolester and polyalkylene glycol) associated with the need for more energy efficient compressors completely changed the severity of the tribological contacts, increasing operational failure for traditional designs in refrigeration industry [1]. Additionally, an interest in transitioning towards oil-less compressors is desired to eliminate the reduction in refrigerant flow on the thermodynamic efficiencies of refrigeration cycles [2].

In particular, polymer composites containing solid lubricants are appearing as a promising choice for controlling friction and wear in hermetic compressors [3]. Polymeric materials are often used in tribological applications in which solid lubrication is required [4] or the operation conditions include corrosive substances [5]. Moreover, it is well known that polymers show improved tribological properties when slid against metal surfaces compared with when rubbed against other polymers [6,7]. This behaviour is attributed to the ability of the polymer to form protective layers on hard counterface, which shields the polymer from wear and usually reduces system friction [6,7]. However, this effect is negligible if the counterface is unable to keep the transfer film adhered [7,8].

The counterface roughness plays a key factor in transfer film formation and retention [9]. Surfaces showing deep and sharp valleys improve the physical anchoring of transfer films [10], whereas tall and distant peaks produce sparse films and enhance polymer ploughing [11]. Thus, despite transfer film formation, the polymer

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surface ploughing due to hard asperities significantly affects the tribological properties. According to Wieleba [12] the asperity shape has a great influence on the friction coefficient, whereas the asperity size has a great influence on the polymer wear. Moreover, roughness aligned perpendicular to the direction of sliding leads to increased wear rates [13].

Recently, several researchers have investigated the tribological performance of solid lubricated polymer composites on regular lubricated systems and found a beneficial synergistic effect [5,14–16]. However, the long-term exposure of polymers and their composites to solvents can trigger a significant increase in the wear rate due chemical ageing [17,18]. Although considered one of the most chemically stable polymers, unfilled PEEK is also susceptible to chemical ageing when subject to long-term exposure with certain substances, e.g., mineral lubricants and oils [19]. Moreover, the incorporation of fillers such as carbon fibres (CF) and lamellar lubricants, common in tribological applications, can produce weak interfaces that allow solvents to diffuse through a chemically inert polymeric matrix [20]. The dissolution of fillers/matrix interfaces reduces its reinforcement behaviour, leading to a composite material with lower wear resistance [21,22].

The main goal of the present work is to investigate the impact of surface finishing, chamber temperature and chemical ageing on the tribological behaviour of a commercial grade, solid, lubricated PEEK composite running against AISI 52100 bearing steel under dry conditions. In addition, a harsh cylinder-on-disc configuration and reciprocating movement were chosen as the test conditions. The root mean square surface roughness (S_q), skewness (S_{ks}), kurtosis (S_{ku}) and bearing index (S_{bi}) were investigated using a white light interferometer. Optical and SEM image analyses provided further insights regarding the possible wear mechanisms and transfer film formation. Long-term exposure of PEEK composites to ester-based lubricant oil and a tetrafluoroethane atmosphere was performed in an autoclave at 180 °C and 3 bar pressure for 7 days. DSC, DTG and FTIR were utilized to investigate the possible structural changes of the PEEK composite after chemical ageing.

2. Materials and methods

A commercially available 10 wt% PTFE, 10 wt% graphite and 10 wt% carbon fibre (CF) filled PEEK composite was selected due to its superior self-lubricating and wear characteristics [4]. The PEEK composite sample was provided as an 11-mm-thick injection moulded plate. The plate was machined to 4 ± 0.1 mm-height cylinders with a diameter of 8 ± 0.1 mm. Discs of hardened AISI 52100 bearing steel (ϕ=30 mm and 10-mm-height) were chosen as the counterbody material. Table 1 presents the nominal mechanical properties of the selected materials.

The tribological behaviour of the PEEK/52100 pair was investigated as a function of (i) the metallic surface finish (polished 1 μm, polished 9 μm, shot peened and ground); (ii) the chamber temperature (30 and 90 °C); and (iii) the chemical ageing due long-term exposure of the PEEK to an ester-based lubricant oil.

The AISI 52100 discs were provided with a ground (CBN grinding wheel, #180) surface finish. The polished surfaced finishes were produced by sanding the metallic discs with 600 and 1000 mesh abrasive sand paper followed by polishing with diamond abrasives of 1 or 9-μm diameter. Part of the 1 μm polished discs was shot peened by glass beads of particle sizes from 107 to 215 μm (selected by sieving). After the surface finishing step, the discs were subjected to ultrasonic cleaning in ethanol for 15 min. Finally, the metallic discs were kept under vacuum to avoid corrosion. A white-light interferometer (Zygo New View 7200) was used to evaluate the resulting topography. A Gaussian filter (800 μm) was applied to surface roughness analysis to remove waviness from sample surfaces.

Table 1
Mechanical properties of the PEEK composite and AISI 52100 steel.

Material	Young modulus (GPa)	Hardness (Mpa)	Tensile strength (MPa)	Poisson's ratio
PEEK	11	–	150	0.4
52100	210	7845	2240	0.3

Dry tribological tests were conducted in a servo hydraulic AMTI tribometer equipped with a hermetic chamber, heating system, 2 channel load cell and close-loop actuators control (load and displacement). This apparatus was configured in a cylinder-on-plate mode (Fig. 1) with linear reciprocating movement under a constant normal load of 100 N. Each test had 2 h duration, 2 Hz frequency and 10 mm stroke. A tetrafluoroethane atmosphere (R134a, refrigerant gas) composed the test environment. Before the initiation of each tribological test, the refrigerant gas was purged three times using a mechanical vacuum pump to eliminate contaminants in the atmosphere. Each polymeric cylinder is able to run up to 5 tribological tests. The polymer sample carrier allows the polymeric cylinders to be carefully rotated in order to position a virgin surface to the next sliding test.

The polymer wear rates were calculated using wear volume measurements (Fig. 2) obtained from white-light interferometry [23]. The results are the average of at least 3 tests for each condition. The wear tracks were analysed using white-light interferometry, scanning electron microscopy (SEM, Jeol JSM-6390LV) and optical microscopy (Olympus BX60) to obtain further information regarding the wear mechanisms and tribo-layer formation. Before image analyses, the polymeric cylinders were subjected to ultrasonic cleaning in ethanol for 15 min.

The chemical ageing of the PEEK samples was performed according to the ASTM D543 standard [24] in a Carl-Roth autoclave with working volume of 275 ml, as well as with temperature and pressure control. In this procedure, polymer cylinders were fully immersed in an ester-based lubricant oil and tetrafluoroethane refrigerant gas mixture at 180 °C and 3 bar pressure for 7 days. The oil was previously dehumidified under vacuum (~0.9 mbar) for 3 h. Before and after the ageing process, a Mettler Toledo precision balance (10^{-5} g) was used to weigh the polymeric cylinders to obtain oil absorption information. The aged samples were conditioned in a receptacle containing lubricant oil at room temperature for 60 min, and then they were quickly rinsed in acetone and wiped dry with a paper tissue before weighing.

The impact of chemical ageing on the PEEK structure and composition was investigated using differential scanning calorimetry (DSC) and thermogravimetry (TG) analyses in a Netzsch Jupiter F3 simultaneous thermal analyser. The thermal profiles of the DSC and TG runs consisted of heating ramps from 50 °C to 450 and 800 °C,

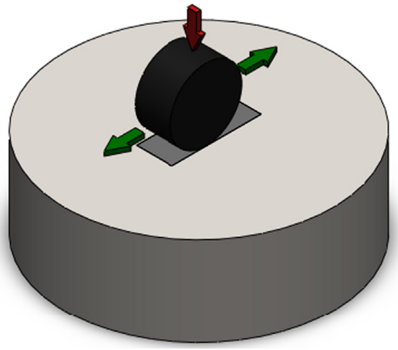

Fig. 1. Cylinder-on-plate configuration.