Wear 309 (2014) 35–42

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

The wear of PEEK in rolling–sliding contact – Simulation of polymer gear applications ☆

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ARTICLE INFO

Article history:
Received 10 June 2013
Received in revised form
19 September 2013
Accepted 21 September 2013
Available online 11 November 2013

Keywords:
Wear testing
Gears
Polymers
Rolling–sliding
Surface analysis

ABSTRACT

The wear and friction in the pitch region of the centre of polymer gear teeth are not well understood. The transition around this point of the tooth between rolling and sliding has an important effect on the durability of polymer gear drives and can be simulated using a twin-disc configuration. This paper investigates the rolling–sliding wear behaviour of two poly-ether-ether-ketone (PEEK) discs running against each other with a simplified method of analysing and understanding the dynamic response of high performance polymeric gear teeth.

Tests were conducted without external lubrication over a range of loads and slip ratios, using a twin-disc test rig. The wear and friction mechanisms were closely related to surface morphology, with changes in crystallinity correlating with the severity of operating conditions. Observed failure mechanisms were also related to the structure of the contact surfaces, and included surface melting and contact fatigue.

Overall the PEEK discs were capable of running at low slip ratios for both low and high loads. Their performance reduced with an increase of the slip ratio. The results presented can be used in conjunction with the design process to allow the PEEK to be engineered for a specific high performance gear contact conditions.

1. Introduction

With a growing awareness of engineering polymers, there is increasing application of polymers and polymeric composites to machine elements. The ability to economically manufacture and run unlubricated contacts at increasing temperatures (through the use of high temperature polymers such as poly-ether-ether-ketone (PEEK) is making their application more desirable.

The majority of published work on the tribology and wear of non-conformal polymer pairs relates to the performance of gears. For a pair of gears the dominant operating parameters such as sliding velocity and load, and the geometric parameters such as module and curvature of the contacting surfaces vary with the contact position on the tooth profile. Consequently, gear action is a very complicated process to understand. An alternative method of studying gear action is to apply the same load and speed conditions to a much simpler geometry. An example of such a simulation is the use of two cylindrical discs loading against each other in edge-to-edge contact, each rotating at different speeds. By varying the relative speeds of the discs (i.e. changing the ratio of sliding to rolling velocity, the so-called 'slip ratio') and the normal load, the conditions experienced by gear teeth in contact may be approximated [1].The simulation of gears can never be truly representative however, since changes in sliding velocity, tooth flexibility and differences in the thermal conditions make contact conditions very different. In addition, slip ratios in twin disc testing tend to be limited to around 30%, whereas slip ratios above 30% are found throughout the majority of the gear meshing cycle.

Nevertheless, twin-disc tests provide fundamental information about materials behaviour in rolling–sliding motion under non-conformal contact. They should be seen as complementing the applied information from direct gear testing and as contributing to a more fundamental understanding of polymer tribology under rolling–sliding conditions [1–5].

Previous work, using the twin-disc configuration, has compared the tribological performance of a range of engineering polymers and their composites, namely polyoxymethylene (POM) [1,2], polyamide 46 (PA46) [3], polyamide 66 (PA66) [2,4–6], glass–fibre reinforced PA66 [2,7,8], PA66 and POM filled with 20 wt% of polytetrafluoroethylene (PTFE) [9], and short fibre, aramid and carbon-reinforced PA66 [3]. These materials were tested over a range of rolling speeds and slip-ratios to study their wear and frictional properties and their potential damage mechanisms.

It was found that initially the fibre grades were capable of withstanding a high loads; however, as the surface layer of the material was removed and the reinforcing filler was exposed, the

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http://dx.doi.org/10.1016/j.wear.2013.09.014

wear rate increased. This limited the materials use to high load, low cycle applications. In the unreinforced materials, friction was shown to correlate well with both temperature and wear.

The mechanical behaviour of PEEK is widely reported [10–13]. These results are not directly relevant to the non-conformal contact found in engineering components such as gears [1,2,14]. However, they do give an indication of the high performance of the material.

Literature covering twin disc testing of PEEK is limited. Avanzini et al. looked at the mechanical response of both filled and unfilled PEEK when run against a steel counterface in a rolling contact. They found that transverse cracks on the surface formed deep radial cracks in the material and that wear rate was related to pressure, velocity and hardness [15]. Similarly, Berer et al. investigated PEEK in rolling contact discussing the influence of lubricant and pre-cracks on the surface pitting behaviour of the material [16]. However, both investigations were limited as the discs were only run in rolling (i.e. both discs rotating at the same speed), thus the use of this in the simulation of gear tooth contact is limited.

Despite this, PEEK would appear to be an ideal gear material; its high relative thermal index for mechanical contact with impact (a parameter determining the maximum service temperature at which the critical properties of the material such as toughness and impact strength will remain within acceptable limits for a given mechanical application with impact over a long period of time [17]) suggests that it is capable of withstanding the high temperatures and stresses associated with high performance polymeric gearing without significant thermal degradation. Therefore, this paper will investigate the rolling–sliding wear behaviour of two unreinforced poly-ether-ether-ketone (PEEK 450G) discs running against each other, and the use of this as a simplified method of analysing the dynamic response of high performance polymeric gear teeth.

2. Materials and methods

Fig. 1 shows the twin-disc test rig that was used for unlubricated, rolling–sliding tests. Two cylindrical discs were mounted on spindles contained in a friction block and a pivoted loading block. An electric motor (1) provided an input speed of 1000 rpm, using two toothed belts (2) and a pair of speed change gears (7). The discs were driven at a controlled speed with the relative slip ratio between the contacting discs adjusted by altering the gear ratios. The system is capable of simulating the non-conformal contact found in common machine components such as gears and cams. Loads were applied to the system by a weight (5) attached to the upper pivoted loading block (4) to provide a normal force between the two discs. The lower block was mounted on vertical leaf springs and strain gauges were used to determine the sliding frictional force by noting the tangential force on the lower disc. Wear of the samples was approximated by detecting the displacement of the upper block using a linear variable displacement transducer (LVDT) to record the displacement of the disc centres.

The test discs were machined from an unreinforced PEEK 450G extruded bar [17].

All specimens were polished to a surface roughness of approximately 5 μm whilst maintaining the cylindricity of the discs. Fig. 2 shows the sample geometry.

The test discs were placed on the shafts in the twin-disc test rig and tests were run for a range of loads and slip ratios, shown in Table 1. During the tests, the friction, wear and temperature data for the system were collected.

The tribological and mechanical properties of polymers are much more sensitive to temperature than those of metals; therefore it is necessary to establish the maximum contact temperatures so that their effects on the wear behaviour can be considered. In this investigation, a Fluke Ti25 infrared camera (temperature range −20 °C to 350 °C and accuracy ±2 °C or 2%) was used to measure temperature.

To determine whether the surface of the discs has undergone thermal ageing/enthalpic relaxation during testing, the crystallinity of the samples was investigated using differential scanning calorimetry (DSC). The Perkin Elmer DSC 7 unit used in this investigation consisted of a sample and a reference cell, both of which have separate heaters and platinum resistance temperature sensors. The heaters are coupled so that the differential power needed to maintain the two cells at the same temperature, can be measured [18,19]. This allowed the mass fraction of the crystalline phase in the polymer to be established, knowing that the theoretical heat of fusion for the pure crystalline phase of PEEK was (130 J/g).

Finally, the wear on the contact surfaces was characterised using optical methods and a JEOL JSM-6060 scanning electron microscope (SEM).

3. Theory

3.1. Gear kinematics

In polymeric gears, the compliance of the material means that the path of contact extends beyond the theoretical path for a perfectly stiff gear mesh (Fig. 3) [20]. When the path of contact is extended, the load distribution between meshing teeth and the sliding velocity are also altered.

The slip ratio of a pair of meshing gears refers to the ratio of the sliding velocity at the point of contact, to the rolling velocity. For two discs, rotating at V_1 and V_2 respectively, the slip ratio can be described by Eq. (1)

$$\text{slip ratio}(\%) = 2\frac{V_2 - V_1}{V_1 + V_2} \tag{1}$$

Restrictions on the test rig limit the obtainable slip ratio to below approximately 30%. Therefore, twin-disc tests traditionally assess a material's mechanical response to conditions found in the region surrounding the pitch point of gears, where the velocity of sliding is low (see Fig. 4). Sukurmaran et al. modelled a polymer–metal gear contact using a twin disc set-up. It was shown that the wear rate was low and that the main mode of failure was plastic flow [22]. However, there was little consideration of how simulating plastic gears would be different from modelling steel tooth contact.

Fig. 4 shows the theoretical slip-ratios for a pair of meshing gear teeth without deflection and the influence of the extension in the path of contact. The theoretical position of each twin-disc test will model different meshing positions on a simulated gear tooth depending on the extent to which deflection affects the system. In addition, from Fig. 4 it can be seen that slip ratios of up to 30% obtainable using twin disc tests, will simulate both the regionS surrounding the pitch-point and the theoretical first point of contact when large deflections occur (note that the gear teeth used in this investigation were based on the Birmingham standard geometry, i.e. a spur gear, 2 mm module, 30 teeth, 20° pressure angle, 1:1 ratio, [23]).

For steel discs, twin-disc testing can be used to simulate the conditions found at the pitch point of a steel gear tooth. However, this kinematic model shows that when large deflections occur, due to the high compliance of polymeric materials, the path of contact is extended; thus allowing tooth conditions to be modelled for premature contact.