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Efficiency and running temperature of a polymer–steel spur gear pair from slip/roll ratio fundamentals

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ABSTRACT

A new methodology to predict the transient operational temperature of a polymer–steel gear pair under loaded running is presented. For the involute gear form, rolling and sliding leads to a loss of gear efficiency and generation of heat in the contact zone. The power dissipated is used to set the conditions for a series of rod on disc experiments. The rod-on-disc data are processed in a time averaging procedure, which allows prediction of the complete gear temperature. This is assessed with analytical and finite element models to validate the predicted temperature rise against the experimental data. The significance is that the experimental procedures may be used to assess gear thermal performance without testing full gear pairs.

1. Introduction

Spur gears that are machined or injection moulded from polymers are becoming increasingly prevalent in geared systems since they can be manufactured cost effectively, especially when moulded. They also have a lower inertia than metallic gears, which can be advantageous in terms of the dynamic response of a gear train used in low power transmission applications. In addition, as the number of polymer gears manufactured per year rivals that of metallic gears there is a desire to utilise them in higher power applications. Metallic spur gears have been well-researched and developed and it is now possible to design them with a high degree of confidence, taking account of strength and wear. However, it is less straightforward to calculate the strength of polymer spur gears due to the nonlinear properties of polymers and the limited work that has been done to investigate their wear mechanisms. This paper investigates the contact mechanism between two straight cut spur gear teeth (one metal and one polymer) and how it results in heat generated in the zone of contact.

The contact in a straight cut involute spur gear pair has both rolling and sliding elements as first documented by Breeds et al. [1]. Pure rolling occurs at the point at which the contact is in line with the centres of both the pinion and the gear; however, this occurs only at an instantaneous point. As the contact approaches this point and then moves away from it the sliding velocity decreases and then increases, respectively. This action can be modelled using the concept of equivalent cylinders, as reported by Hamrock et al. [2] who associates, for each point in the contact sweep, two cylinders of differing radii in contact with relative velocities determined by the rotation of pinion and gear. The sliding velocity can then be calculated through the contact sweep, which will vary through the stroke.

The geometry of a gear is such that fine details of the size and shape of the teeth are superimposed upon the overall diameter of the circular gear. A full thermal analysis of the complete gear geometry would therefore be complex and an alternative predictive model based on the equivalent cylinders analogue would be preferable. This alternative model would also require experimental validation, for example, from an axially aligned steel rod in sliding contact with a polymer disc. The manner in which experimental and predicted results are compared would be critical for the validation process and this provides a focus for the procedures described in this paper.

The works of Hooke et al. [3] and Breeds et al. [1] make substantial inroads into understanding how spur gears run together and what the contact mechanics are of the gear teeth. In particular, the actions of rolling and sliding between the driven and driving gear are described. Furthermore, they indicate how this geometry driven contact, so particular to involute spur gears, may influence the efficiency of any given gear pair as well as resistance to wear, which are both instrumental in temperature rise. With reference to polymer–steel contact in involute gears a study was conducted using a Bowden–Leben stick-slip machine, which is a conventional

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tribometer utilising a pin sliding against a flat surface (Bowers et al. [4]). For steel running against nylon, values of 0.37 and 0.34 for static and dynamic friction, respectively, were published. Clearly, the materials chosen for the gears will have a large effect on the friction and associated efficiency, which were measured by Walton et al. [5]. The efficiency ranged between 88% and 98% depending on material, load and speed. Overall, the material is a driving factor in the increase or decrease of efficiency, but the geometry, hence slip ratio is also important. Xie and Williams [6] made progress in predicting the coefficient of friction and wear between a randomly rough hard surface and a softer surface. They used a technique developed by Greenwood and Williamson [7] and expanded it to include specific plastic microcutting of the softer material by the harder. Although progress has been made in the link between this and the actual contact mechanism, much is still to be done to quantify it completely. Indeed, in medical prosthetics, there has been much experimentation to validate a particular geometry of ball and cup of defined materials. Fisher et al. [8] found that surface roughness contributes greatly to the wear of a polymer in contact with a metal. They also concluded that the wear was not dependent on sliding velocity, however, the maximum sliding speeds used were 240 mm/s, which are lower than those generally experienced by gear teeth.

Blok [9] describes the concept of flash temperature, which provides a method for estimating the likely temperature between two contacting and sliding surfaces. If the flash temperature for a polymer–steel spur gear pair is above the melting point of the polymeric material, failure of the component will clearly be imminent. This has been expanded and improved upon on by Samyn and Schoukens [10] and also by Conte et al. [11] with inclusion of thermal diffusivity for the material in question. A numerical solution has been developed specifically for the application to spur gear teeth by Mao [12], who accounts for the effects at the tooth tip as the mesh starts and finishes, but it is considerably more complex than the Blok model. Attempts to reduce the running temperature to see if that materially affects the wear rate of the gears were carried out by Kim [13] and Duzcukoglu [14] by drilling small holes through the base of the root of the tooth to let air circulate more freely across the tooth flank. These studies found that reducing the running temperature of the gears also reduces the wear rate. Other experiments include loaded running of gears for temperature measurement and wear measurement, as in the work of Hooke et al. [15].

Another test method uses a back-to-back apparatus with one electric motor driving through the gear pair under investigation to the driven motor, which acts as a generator and so provides the load. This was undertaken by Senthilvelan and Gnanamoorthy [16] and surface features were observed that are relevant. However, no further analysis or conclusions for wear mechanisms or temperature rise were given. Hooke et al. [15] used a four-square rig with a single electric motor to drive two sets of spur gears connected across two parallel shafts. The driven gears were manufactured from case hardened steel, whilst the others were test polymer gears, as reported by Mao et al. [17,18]. The load was applied to the system through a lever arm, even as the gears became worn. These studies were concerned with how temperature and differing materials affect the wear of the gears. Acetal was used as the gear test material and it was concluded that it has a critical limit in terms of slip/roll beyond which complete failure of the material occurs due to thermal effects.

Analytical models have been constructed that predict the temperature rise around a contact area such as in the work of Vick and Furey [19] who used a Green's function approach. For steel running against a polymer the temperature rise should not exceed the polymer softening or melting temperature as this would clearly result in a catastrophic failure. This is the basis for a concept of the pressure–velocity limit for a polymer as proposed by Archard [20]. In a study by Walton et al. [21], load sharing of polymer gears was investigated using computational finite element techniques. They were concerned only with the loading between the gear teeth. A thermoelastic model can be created using finite element techniques as done by Taburdagitan and Akkok [22]. It is of interest as it illustrates some of the difficulties associated with producing this type of model. The model mesh was refined around the gears and the driven gear was considered loaded via a torsional spring at its centre. The conclusion was that tip relief of the gear teeth is important to the temperature rise as applying it can help to reduce the slip speed when the driving gear initially touches the driven gear and load transfer occurs. In a study by Unal et al. [23] of extremely high pressures of steel rubbing against a polymer, it was found that the wear rate of a polymer in this case is not strongly dependent on the pressure applied.

In this paper, an experiment involving an axially aligned steel rod applied to the circumference of a polymer disc is described. This experiment was augmented to run a full gear pair, of which the running temperatures were also measured. An analytical thermal model is formulated to predict the temperature rise in the axially aligned rod on disc experiment. A finite element model was also employed as an alternative method for prediction, though limited to a fixed heat source on the disc. This simplification is used to reduce the complexity of a full gear model and the mesh density required at the contact. Lee et al. [24] present a case in which a high mesh density is implemented for asperity–asperity interaction. Finally, a novel method of time averaging is presented to directly correlate the aligned rod on disc experiment with full the gear pair experiment.

2. Geometry, flash temperature, loadings and heat flux evaluation

In this section, pertinent evaluations are made that are appropriate for geometric and material parameters associated with the experimental system and gears considered in Section 3.

2.1. Geometry

A feature of the involute profile that is known, but not generally considered significant, is that slip occurs between the teeth flanks. This results in a reduction in efficiency of around 1–2% [5]. However, in an unlubricated polymer–steel gear pair it gives rise to heat generation. In the line diagram shown in Fig. 1, two contacting surfaces are represented by two separate cylinders of radii r_a and r_b. The rotational speeds of these cylinders are equal to those of the gears, respectively. This technique is described by Hamrock et al. [2] and the slip speed is

$$v = (r_{bg}\sin\alpha + s)\omega_b - (r_{ag}\sin\alpha - s)\omega_a \quad (1)$$

where r_{ag} is the pinion pitch radius, r_{bg} is the gear pitch radius, α is the pressure angle (rad), s is the distance of the point of contact from the centre line, ω_a is the rotational speed (rad/s) of the pinion, and ω_b is the rotational speed (rad/s) of the gear. Accordingly, $r_a = r_{ag}\sin\alpha - s$ and $r_b = r_{bg}\sin\alpha + s$.

2.2. Flash temperature

Blok [9] proposed that if two surfaces are rubbed together, heat will be generated at the interface giving rise to a flash temperature. Because of the transient and constrained nature of the contact, this temperature rise will be higher than expected for the load and speed conditions of a gear pair. The flash temperature is