Wear 332-333 (2015) 822–826

Contents lists available at ScienceDirect

Wear

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

The wear and thermal mechanical contact behaviour of machine cut polymer gears

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ARTICLE INFO

Article history:
Received 2 September 2014
Received in revised form
29 January 2015
Accepted 30 January 2015

Keywords:
Polymer gears
Wear
Wear rate
Friction
Surface temperature
Tip relief

ABSTRACT

The present paper will concentrate on an extensive investigation of machine cut acetal gear wear and thermal mechanical contact behaviour. The results for machine cut acetal gears will be compared to previously published results obtained for polymer gears manufactured through injection moulding. The machine cutting manufacturing process can be economical for small batch runs due to the expense of the mould for injection moulding. Injection moulding becomes economical for larger batches. A new and unique polymer gear test rig has been employed to investigate the polymer gear wear behaviour. The unique test rig design allows the effect of misalignment on polymer gear engagement to be considered and the gear surface wear to be recorded continuously. Extensive experimental tests have been carried out to investigate machine cut acetal gear wear performance. Further examinations have been carried out using a scanning electron microscope to understand the gear wear mechanisms. An equation has been presented to predict polymer gear flank temperature and correlated well with the tests.

1. Introduction

Polymer gears offer huge potential for high-technology applications and unique advantages over metal gears: low cost, low weight, high efficiency, quietness of operation, functioning without external lubrication, etc. They are now considered for applications from low-power, precision motion to high power transmission, even in such challenging environments as healthcare and automotive engineering. For example, there are reports in automotive engineering of a 70% reduction in mass, 80% reduction in inertia and up to 9% reduction in fuel consumption by using polymer gears instead of metal [1]. However, applications of polymer gears remain limited due to a lack of performance information and design standards. It is well known, for example, that polymer gears are very sensitive to temperature variations however a detailed understanding of this sensitivity and of how their mechanical properties degrade with increasing temperature is lacking in the literature. Understanding their thermo-mechanical behaviour remains very challenging because of the severe non-linearity and high real-life sensitivity to small changes in polymer gear temperature.

Current polymer gear design methods, e.g. British Standard 6168 [2], derive from metal gear practice where a gear tooth rating is determined by bending strength or surface durability. These methods have been shown to not correlate well with test results for polymer gears [3,4]. The temperature dependence in the latest VDI 2736 standard [5], as with the British Standard 6168, is mainly based on Hachmann and Strickle's approach [6] with a few minor modifications. One modification for the effect of geometry on the degree of tooth loss as defined by Niemann [7] and one for the effect of relative tooth engagement time. As a result, in terms of temperature dependence, the VDI standard does not offer much of a step forward in knowledge. Apart from Hachmann and Strickle's early attempt to predict polymer gear temperature other formulations can be found in the literature a notable example is Gauvin et al.'s equation [8] however this equation is limited to polymer against steel gears.

Potential use of polymer composite gears in power transmission is limited by a lack of fundamental understanding of their actual mechanical and, especially, thermal behaviour. There are four highly typical failure modes in polymer gears, wear, pitting, root and pitch cracks: while similar failures can occur in metal gears, the underlying failure mechanisms in polymer gears are dominated by thermal factors, this is not the case with metal gears. In most of the many experimental studies on gear running temperatures, surface temperature measurements were carried out after stopping the gears: such methods are inaccurate because the flank temperature drops very rapidly once the gear stops [9]. Recently, Letzelter et al. [10] monitored a nylon 6/6 gear body temperature using an infrared camera, reporting friction as the main heat source. Numerical models proposed for elucidating the mechanical contact behaviour of polymer gears, such

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http://dx.doi.org/10.1016/j.wear.2015.01.084
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as transmission error, mesh stiffness and load sharing [11,12], have all used perfect tooth profiles at room temperature. Many experimental studies have meshed polymer gears with steel pinions [13–15], exploiting steel's relatively good thermal conductivity. Recent experimental comparisons between carbon fibre reinforced PEEK and nylon gears [16–18] showed that the load capacity under high running temperature of the former is superior to that of other composite gears. However, despite much empirical testing of different polymer composite gears, there is almost no information available to predict the thermo-mechanical contact performance of real tooth profiles.

2. Experiments and gear specifications

A unique test rig, as shown in Fig. 1, was designed and manufactured at The University of Warwick to be able to investigate the effect of misalignment on polymer gear contact and to continuously measure the wear of the gear surfaces under constant load conditions. Polymer gears can be tested, in much the same way as metal gears, using a back to back test configuration where the gears are loaded by winding in the torque to a prescribed level. The difficulty with polymer gears comes in maintaining a constant torque while continuous wear occurs. The main difference in the design of this rig is that the bearing block locating the test gears was made to pivot, with the gears loaded by a moment arm and adjustable weight providing a constant torque to the mesh even through the wear process. When the motor is switched on the reaction forces between the test gears balance the externally applied torque such that the bearing block and loading arm are maintained in balance. This modification maintains a constant torque on the test gears irrespective of tooth wear. This loading method permits large amounts of wear without significantly affecting the applied torque – a feature unique to this configuration of the test rig. As the test gears wear, the bearing block can rotate about the pivot by relatively large angles. Because of this, and the associated differential movement, the closed loop drive shafts are free to slide axially on their universal joints. The test rig was designed with a mechanism to provide assembly misalignments to the tested gear pair. The possible misalignment types which can be applied are shown in Fig. 2. Misalignments are achieved by finely controlling the assembly blocks' location (Fig. 1(b)). During the tests four test parameters are continuously recorded: torque, speed, wear and time to failure. Wear is measured indirectly by recording the movement of the bearing block using a non-contacting magnetic displacement transducer. It should be noted that wear is given in terms of the reduction in tooth thickness, measured at the pitch point, and not as the volume of material removed, as is the normal procedure for recording wear measurements. Wear and life are recorded on a data-logging system using a dedicated microcomputer. It may be noted that the tooth deflections cannot be separated from the actual tooth wear using this rig. However, the wear rate is the main factor to be investigated in the current approach and the recorded wear rate has been successfully used to predict the gear performance as described in Section 4.In this study tests using *machine cut* acetal gears were carried out with the aim of comparing with previously published results obtained for polymer gears manufactured through injection moulding [19]. The cost can be much lower for small batch production of polymer gears using machine cutting when compared to injection moulding due to the mould design and manufacture cost. The gears tested were machined with uniform sectioned rims and flanges to standard machine cut practice. All test data presented in this paper is for acetal against acetal spur gears with a speed ratio of one in unlubricated conditions. The material properties of the currently studied machine cut acetal gears and the previously published injection moulded gears are shown in Table 1. The machine cut gears were manufactured by Ondrive. The acetal used is homopolymer and the geometry of the gears tested is shown in Table 2. The shrinkage of the machine cut gears with an average outside diameter of 63.88 mm (the nominal diameter being 64 mm) is slightly lower than the shrinkage for the injection moulded gears where the average outside diameter was 63.65 mm.

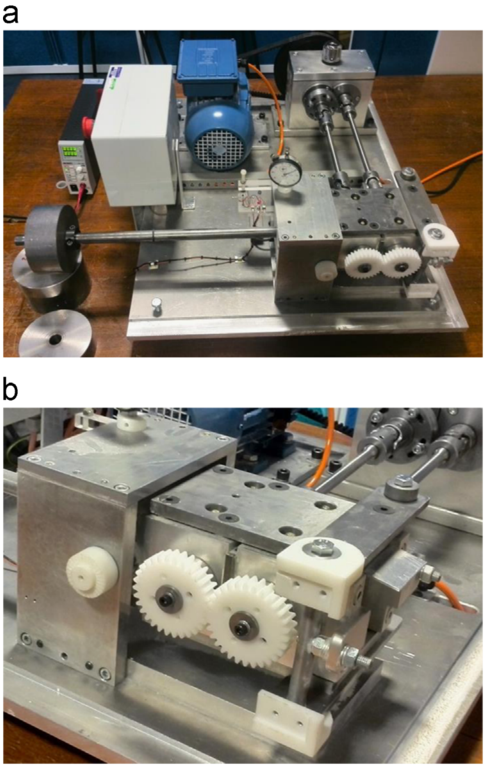

Fig. 1. Polymer gear test rig. (a) Overview. (b) Polymer gear assembly view.

3. Test results and discussions

Extensive experimental investigations on machine cut acetal gears have been carried out under a load range of 6–9 N m at a running speed of 1000 rpm. Fig. 3 (smoothed) shows an example of acetal gear wear behaviour under a load of 7.5 N m and a running speed of 1000 rpm. The wear can be divided into three phases, a running-in, a linear and a final rapid wear period. It was noted there was little wear debris during both the running-in and linear wear stages. In the final wear stage, the wear rate increases rapidly as does the amount of wear debris. After gross wear (nearly 33% of tooth thickness), the gears eventually failed in thermal bending (as shown in Fig. 3). This gross deformation is not always a plain fracture but is caused by high loads giving rise to softening of the acetal. The gear teeth are, probably, momentarily melted and as a result the teeth jump out of mesh. When this happened the rig automatically shut off. It was observed that when the gears cooled down the teeth appeared to regain some of their unbent forms. This wear behaviour for machine cut acetal gears is very similar to that previously observed in injection moulded acetal gears [19].

Due to the benefits shown during the authors' research on testing injection moulded acetal gears [19], the incremental step loading method has been mainly employed for the machine cut acetal gear tests. In this method a single test gear pair is used and the test gears are loaded at constant load for a short period of time (e.g. 1 h) the load is then incremented (normally by 0.5 N m) for another short period of time. This process continues until a sharp increase of the wear rate. Fig. 4 shows test results for an incremental load test of a machine cut acetal gear pair running at 1000 rpm. This method was compared to conventional endurance testing where gear pairs are