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The dominant effect of temperature on the fatigue behaviour of polymer gears

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ABSTRACT

The testing procedures and reported tribological performance of polymer gears, which are seeing ever-increasing use by industry, still lack consistency and detail. One of the key parameters that affect a polymer's mechanical properties, interface contact conditions and, consequently, the wear and fatigue behaviour, is the temperature. Temperature is well known to have a critical influence on all polymers, much more so than on metals or other materials. However, the temperatures – even for the same load and velocity – vary greatly with testing devices, gear sizes and shapes, surrounding environment, as do the cooling and heating rates. Moreover, the temperature, either root, flank or bulk, also varies with the operating conditions, meaning that even in the same S-N curve data at different stresses we actually obtain different temperatures. This suggests that the results from different tests and even different load levels, which are not temperature controlled, cannot be directly compared due to the important influence of the temperature on the polymers. This work presents the results of POM gears tested against steel gears under well-controlled temperature conditions, providing various S-N curves obtained at 30 °C, 50 °C and 70 °C that were kept constant at the gear root for three torque values (1.0 N m, 1.2 N m and 1.4 N m), and these are compared to data obtained under conditions that are typically considered to be "room temperature", which is in fact an uncontrolled temperature. The results confirm the important effect of the temperature on the fatigue life of POM gears, i.e., when kept at low temperature (30 °C), the fatigue life of POM gears is greatly improved.

1. Introduction

The use of plastic gears dates back to the 1950s, but they are nowadays gaining increasing attention due to their potential to substitute the metal gears in various applications, i.e., automotive, medical, food, to mention only a few [1,2]. The main advantages of plastic gears over metal ones are the ease of production with low manufacturing costs, good noise-damping properties, good tribological properties without lubrication, as well as chemical inertness [3]. The main disadvantages that limit the use of plastic gears are their poorer mechanical properties, lower thermal conductivity and stability, i.e., lower operating temperatures, as compared to metal.

It is well known that due to their thermal properties, polymers are very sensitive to the temperature in tribological contacts. This obviously suggests frictional heating, since a relatively small increase in the temperature can make a significant and step-change deterioration in the mechanical and tribological properties [3–5]. In addition, the temperatures developed in the tribological contact can also vary significantly with the counter-face material [6–8]. The temperature is difficult to predict theoretically, because the material's mechanical properties and deformation go thorough significant modifications within the contacts, and possibly even more with the uncertainty in the real contact area [8,9]. Currently, the gear temperature can be predicted based on standards [10,11], mostly derived from metal gear practice, for a very limited number of plastic materials. However, a comparison of the allowable endurance limits of the standards with the results obtained from the gear testing reveal that large discrepancies exist [12–14]. Accordingly, some kind of contact-temperature measurements seems to be a more pragmatic option. An infrared camera [12–16] has frequently been used to evaluate the average surface temperatures in a tribological contact.

The heat generated during the operation of polymer gears has two sources: the heat generated by frictional losses and the heat generated by hysteresis losses [17]. Surface-temperature measurements reveal an increase in the temperature with an increasing gear-pair coefficient of friction, torque (load) and speed, and that a rise in temperature causes an increase in wear and fatigue failure under high stress [13,14,16,18,19].

In order to understand polymer-gear failures, the fatigue life, the wear and the wear mechanisms have been widely studied for

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different polymer gears [8,12,13,16,19–21]. The most common failure modes for polymer gears are a decrease of the tooth thickness due to wear, melting due to thermal overload and tooth root/pitch fracture due to mechanical overload [8,12,13,16,19,22]. Compositional modifications (reinforcements, internal lubricants, nanocomposites) [8,12,14,16,20,22], gear processing [23], gear geometry [12], counterface material [8,12], as well the material on the driving/driven gear [19] can all influence the surface temperatures generated and thus influence the failure mechanisms, fatigue and wear rates.

Some of the most frequently used materials for polymer gears are polyacetals (POM), due to their good wear resistance combined with good strength and toughness. In particular, POM gears are well-known for their good fatigue behaviour [24], even without reinforcements, and are a common polymer gear material, especially in the mass production of polymer gears. However, a dramatic increase in the wear rate above the critical torque has been reported [13,14,21] for POM gears, which is also consistent with the results of a model-based pin-on-disc test [25] that connected this behaviour to the maximum temperature, reaching the melting point (175 °C) or the maximum long-term service temperature (110 °C).

Based on such an observed influence of the increased temperature on the POM wear performance it is reasonable to assume that the gear fatigue life can also exhibit a strong dependence on the ambient and, most importantly, the gear root temperature. Indeed, a limited number of studies have investigated polymer-gear performance at elevated temperatures [13,22], as well at a decreased running temperature [26,27], and revealed the influence of temperature on the wear and/or fatigue behaviour. For example, Mao et al. [13] reported a substantially reduced torque at which the transition from low to high wear occurs as a response to increased ambient temperature. The influence of a well-controlled gear-root temperature on the polymer-gear fatigue life is, however, lacking in the literature.

The aim of this study was to investigate the influence of torque and well-controlled temperature conditions on the fatigue life and wear performance of POM gears, and compare it with results obtained in typical "room-temperature" conditions where the temperature is not controlled. The influences of three torque levels and three pre-set POM gear-root temperatures, as well as the uncontrolled temperature, on fatigue life and efficiency were investigated.

2. Experimental

Polyoxymethylene or polyacetal (POM) gears were mated against a steel (1.2312, DIN 40CrMnMoS8-6) gear (SS). The plastic gears were injection moulded from commercially available homopolymer (Delrin 100P NC010) granules. An involute gear geometry was selected because of its common use and the specifications of the gears are collected in Table 1. Despite the fact that the hardness values of POM and SS cannot be directly compared, they are given in the table for completeness.

The fatigue tests of spur gears were performed on a polymer-gear testing rig for small polymer gears, as shown schematically in Fig. 1a. The test rig consists of a driving shaft with a servomotor that is used to control the operating speed of the driven shaft with a magnetic brake unit that provides a braking torque. Both shafts are equipped with torque cells. The driving shaft has adjustable lateral y-position that enables to adjust operating gear centre distance for gear properties, temperature and humidity variations, as well as the driven shaft has adjustable lateral x-position for ease of installation of new gears. The test rig makes it possible to study the efficiency, wear, temperature and cycles to failure of the operating gears in real time. The efficiency is calculated based on the measured input and output torques and transmission ratio, which is 1.18. With the use of an infra-red (IR) thermal camera, the real-time operating temperature can be measured and controlled using a feed-back loop, which is linked to the IR camera measurement of gear root temperature.

Table 1
Geometry and specification of running spur gears. *From manufacturer's data sheet.

	Driving SS gear/ pinion	Driven POM gear/ wheel
Module	1	1
Number of teeth	17	20
Face width (mm)	6	6
Standard pressure angle (°)	20	20
Profile shift	0	0
Roughness – R_a (μm)	0.60	0.36
Hardness*	51 HRC	120 (Rockwell-R)
Melting temperature* (°C)	1500	178
Thermal conductivity* (W/m K)	33.3	0.4
Modulus of elasticity* (MPa)	21,0000	2900

An Optris PI400 (Optris GmbH, Germany) thermal camera was used to measure the surface root temperature of the driven gear, as shown in Fig. 1b. The area of the temperature measurement was approximately 1 mm^2, which corresponds to about 100 pixels. Based on the measurements and calibration procedure, the emissivity of the driven test gear was set at a constant value of 0.92.

The measurements were conducted without any lubrication, at different torques, i.e., at 1.0, 1.2 and 1.4 N m, which corresponded to 26.3, 30.7 and 34.8 MPa tooth-root stress (calculated according to [10]). The speed was constant at 1500 r/min. The temperature in the tests was ambient, i.e., at an uncontrolled temperature, denoted as NC-T, which was maintained at 24 ± 2 °C during testing and 40 ± 5% (room temperature). However, other tests were performed at a controlled gear-root temperature in an atmospheric chamber where the driving-gear-root temperature was set to 30 °C, 50 °C or 70 °C. The gear tests were conducted for up to 2×10^6 cycles or up to failure – whichever came earlier. The operating centre distance was regulated to accommodate the thermal expansion of the polymer gears. Each test was repeated at least three times.

In order to understand the influence of the load and the temperature on the gear-failure mechanisms and their causes, additional tests were performed and stopped after a selected intermediate number of cycles. Each time a new test was run up to the number of cycles, determined on the basis of previously measured fatigue-life data. For the study at room temperature the tests were stopped at 0.1, 0.3, 1 and 2 million cycles, whereas for the study at controlled temperatures, they were stopped at 0.3, 0.6 and 2 million cycles. The wear of at least four teeth on each gear was analysed using an optical microscope (Nikon, LV150).

3. Results

3.1. *Experiments at "room temperature", i.e., the uncontrolled temperature*

The fatigue life of the POM gears running against a steel gear as a function of torque at the uncontrolled temperature is shown in Fig. 2. At a torque of 1.4 N m the POM gears failed after $526 \times 10^3 \pm 45 \times 10^3$ cycles. A decrease in the torque to a value of 1.2 N m resulted in an improved fatigue life of the POM gears, as revealed by a more than 2 × increase in the number of cycles to failure, i.e., $1283 \times 10^3 \pm 141 \times 10^3$. When running at 1 N m, the polymer gears did not fail until 2×10^6 cycles, when the test was stopped.