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Overload and Lifetime Test of Machine Cut Polymer Gears

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Abstract: The weight of polymer gears is increasing continuously due to their advantageous properties. This is the reason why in recent years traditional metal gears have been replaced by polymer counterparts in plethora applications. Despite their benefits, their load-carrying capacity is limited. The polymer gears become unable to operate and their teeth generally fail when the load exceeds a defined limit. It is required to explore the limit of polymer materials in gear field. In this work, the gears are manufactured by machine cutting. This paper aims to investigate the limit of load-carrying capacity and the lifetime of POM and PA6 G gears.

Keywords: polymer gears; machine cut gears; gear lifetime; overload test; polyamide 6

1. Introduction

Gears are one of the most important components of any mechanical transmission system. Gears are made from metallic and non-metallic materials. The significance of non-metallic gears, like plastic gears, is increasing continuously due to their advantageous properties, e.g. low cost, low weight, high efficiency, quietness of operation or running without external lubrication, etc. [1].

However, the application of plastic gears is limited by the performance information and design standard because their actual mechanical and thermal behaviour are not fully known [2]. On the other hand, it is well known that the plastic gears have a limitation due to the low strength of polymeric materials. So, they become unable to operate and their teeth generally fail when the load exceeds a defined limit. Therefore, it is required to explore the limit of polymer materials in gear field. Moreover, the level of gear performance is bound up with their failure modes.

There are four frequent failure modes in plastic gears, like wear, cracking at pitch circle, cracking at root, and pitting, although similar failures can take place in metal gears, the underlying failure mechanisms in plastic gears are still dominated by thermal factors [3]. The data obtained from previous studies on plastic gears shows that the unlubricated plastic gears fail due to local melting, surface wear, and pitting [4-6]. The failure at pitch circle occurs when the strength of teeth decreases because of loosening material triggered by the high temperature. A study found that the fracture of teeth generally occurs near the pitch circle that is caused by abnormal wear [7]. This type of failure takes place typically in case of unlubricated gears [8]. The high contact stresses on the teeth of plastic gears cause tooth surface failure, such a pitting, and ridging. However, the lubricated gears, in general, fail due to bending stresses at the tooth root that causes tooth breakage [9]. Despite design standards and literature, there is no detailed data about the failures in the tooth surfaces, the geometry, and the material structure of the gear, moreover, their interactions are also not known.

The Lewis formula can be found in any design standards to calculate the allowable output. This formula includes torque, angular velocity, characteristic geometry, and coefficients, which take into account the operating conditions, but does not consider the proportion of torque and angular velocity. Although, a difference in their ratio can cause a dissimilar failure mode for plastic gears. For instance, if the output is produced with high torque and low revolution then a fracture will probably occur at the tooth root because stress is concentrated there. Otherwise, gear damage modes will be wear, surface fatigue or thermal failure.

Therefore, this article focuses on the limit of load-carrying capacity and the lifetime of POM and PA6 G gears, by taking into account the effect of the ratio of torque to angular velocity. Two different cases, which are a combination of high torque – low speed and high torque – high speed, are investigated by overload and lifetime test to find the answer how significant they are for heat generation or deformation.

2. Materials and Methods

2.1. Gear materials and details

Magnesium-catalyzed cast polyamide 6 (PA6) and extruded polyacetal – copolymer (POM-C) were obtained from Quattroplast Ltd., Budapest, Hungary, in the form of semi-finished products (rods), and its trade name is DOCAMID 6G-H and DOCACETEL C, respectively. The general properties of tested materials are listed in Table 1 [10] [11].

The polyamide was produced by casting technology with anionic polymerization of caprolactam ($C_6H_{11}NO$). This manner allows for greater toughness, and impact resistance compared to the sodium-catalyzed system.

The polyacetal was produced by the extrusion process. It is an unfilled copolymer type of POM, which is more resistant to thermal aging than POM-H. Moreover, it is hydrolysis-resistant and can withstand strong alkalis.

Table 1. Characteristic properties of test materials.

Property	***DOCAMID 6G-H (PA6)***	***DOCATEL C (POM-C)***
Density (g/cm^3)	1.15	1.41
Yield stress (MPa)	85	67
Elasticity modulus (N/mm^2)	3300	2800
Thermal conductivity (W/mK)	0.38	0.39
Melting temperature (°C)	220	166
Shore D hardness	81	81
Notched impact strength (Charpy) (kJ/m^2)	13	6
Flexural strength (MPa)	109	91
Elongation at break (%)	130	32

For the overload and lifetime tests, spur gears with an involute geometry were selected due to its common use. The investigated plastic gears are made by machine cutting. The specifications of the gears are summarized in Table 2.

Table 2. Gears specifications

	Driving steel gear[1]	***Driven POM C and PA6 gear[1]***	***Driving and driven PA6 gear[2]***
Module (mm)	1.25	1.25	1
Tooth number	47	47	60
Face width (mm)	12	12	10
Pressure angle (°)	20	20	20
Contact ratio	1.614	1.614	1.785

1: Gear for overload test; 2: Gear for lifetime test

2.2. Test rig for overload test

A unique test rig, which was designed and manufactured at Szent István University, is used for one extreme case of failure to investigate the overload resulting from a combination of high load and low speed, where torque is continuously increased until fracture. The test rig simulates the situation when gear gets stuck. The test rig, as shown in Fig. 1, can investigate the load-carrying capacity of polymer gears and to continuously measure the torque and angular displacements of gears under dry-run conditions without wear by a load cell and an incremental rotary encoder, respectively.

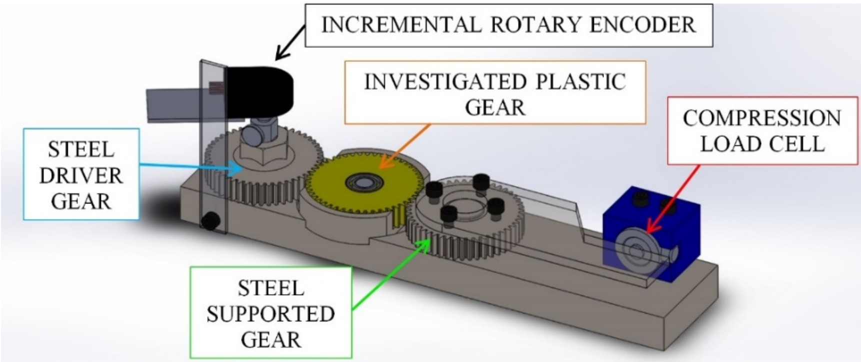

Figure 1. Test rig for overload test

It consists of three identical geometry gears and two sensors. Two of three gears, which are made from steel, are responsible for the transmission of the load because of its higher strength. The plastic gear, which aligns between the steel gears, are investigated. For a recording of values, an HBM Spider8 amplifier was used.

2.3. Test rig for lifetime test

For the investigation of fatigue failures, a test rig, as shown in Fig. 2, is usually used where the gears are loaded by predefined torque and speed. The main goals of these tests are to determine the tribological behaviours, the failure modes, and the temperature behaviour of a plastic gear pair under dry-run conditions. The test rig is used for an overloaded condition to investigate the lifetime of the gears due to a combination of high load and high speed. In all cases, the tests last until the gears fail.

The test rig is made up of several components. These components are stand, motor units, electrical and measuring systems, and accessories. To measure speed, angular velocity fluctuations, angular deviations between axles, angular accelerations, the test rig is equipped with incremental encoders with a resolution of 5,000 pulses per revolution. Torque values are recorded by two torque measuring cells with a measuring range of 0 to 17.5 Nm. For a recording of the required parameters, an HBM Spider8 data acquisition system was used [12].

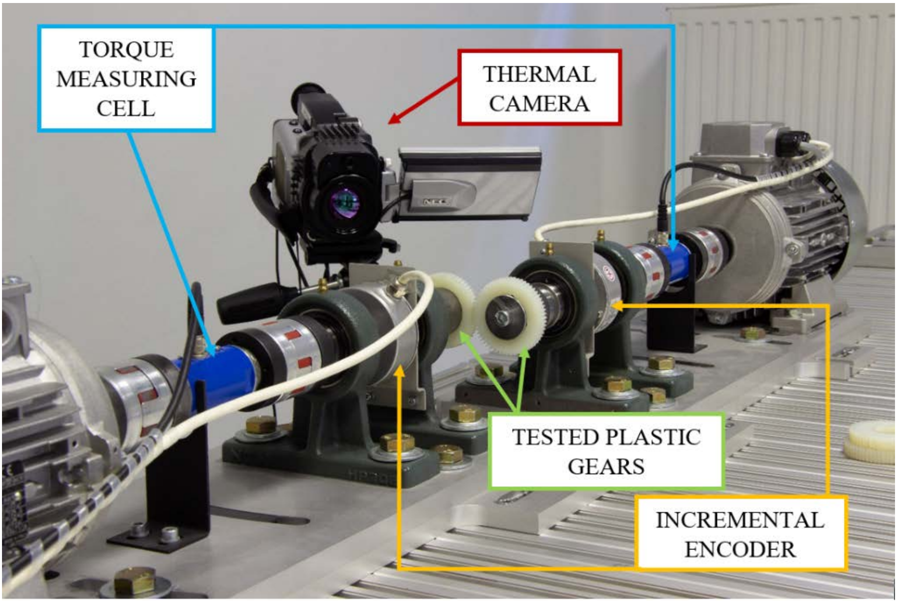

Figure 2. Test rig for lifetime test

For temperature measurement of the gears, a thermal camera was used. The infrared detector of the camera has high resolution (640 x 480), a sensitivity of 0.03 ° C, and a temperature measuring range from -40 °C to + 500 °C.

3. Results and discussion

3.1. Overload test

The goal of this test is to determine the level of torque and deformation of the PA6 and POM gears at the time of tooth fracture. 5 repetitions per material were performed. During the tests, a preload was applied before the main load in all cases. The measurements were performed under the same test conditions.

A characteristic curve is shown about the typical load capacity of the PA6 and POM gears in Fig. 3, where the values of torque and angular displacement appear as a function of time. The fracture of the teeth of PA6 gears occurred under a load of

83 Nm and angular displacement of 9.3°. The teeth of POM gears have more load carrying capacity, because their failure occurred at a load of 94.7 Nm and when the gear rotated approximately 6.3°.

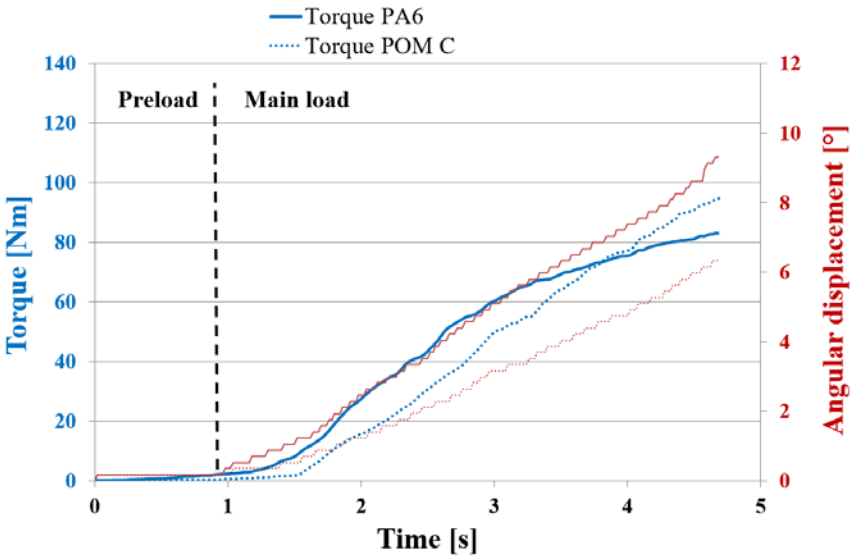

Figure 3. Characteristic curve of PA6 and POM gear in overloaded test

The torque and the angular displacement are related pairs for gear tests, and their relationship is crucial. It is important how the torque changes in view of the angular displacement. Therefore, a supplementary test with a lower speed of a load was carried out with cast PA 6 gears.

It can be seen in Fig. 4., the speed of the initial load and then the main load changes during the measurement, so the angular displacement is not constant during the time unit. It is also clear that a kind of hardening occurs, when the speed of load starts to increase, the material responds with hardening, like a tensile test. It is known from fracture mechanics that the stress rate plays a particularly important role in the tough and brittle behaviour of materials. The teeth of the PA6 gear were broken at an angular displacement of 9.3° and a torque of 117.2 Nm. The deformation stayed the same, however, the material had time to deform, so it showed more toughness and had a higher load capacity.

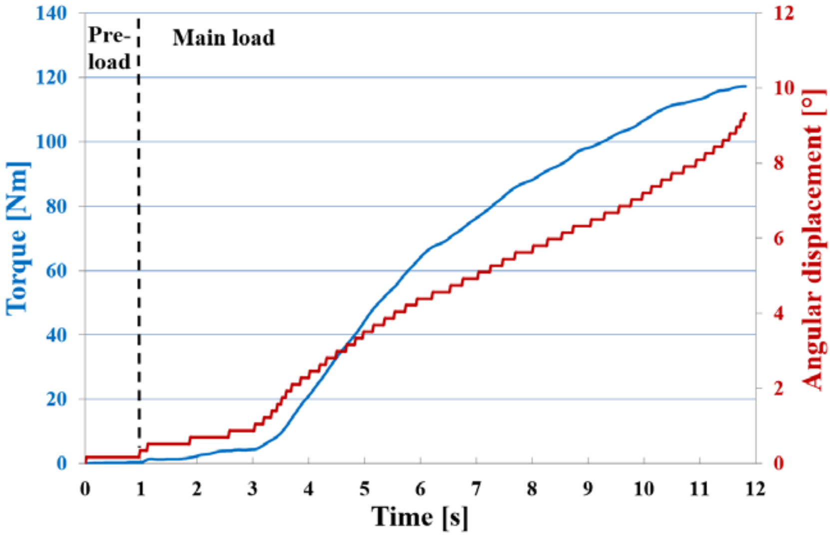

Figure 4. An overloaded test of PA6 gear with lower stress rate

The aggregate results of overloaded tests are shown in Fig. 5. PA 6 gears failed at an average load of 81.2 Nm and angular displacement of 9,2°, while POM gears failed at 99.1 Nm and a rotation of 6,6°. The PA 6 gears tested at lower load speed failed at an average load of 119.7 Nm and angular displacement of 9,5°. The obtained deformation results are supported by the literature as well as the datasheets of the plastics company for both materials. The elongation at break of PA 6 is 130%, while that of POM C is only 32%, i.e. approximately a quarter. This can also be seen in the deformation measured in angular displacement. The teeth of the PA 6 wheels withstood about 140% more deformation at the time of fracture than the POM C wheels. Surprisingly, POM C gears were failed at an average load of 122% higher than PA 6 gears. This is unexpected because POM C has a lower yield point than PA 6. This fact is pointed out that the yield strength of the material is not sufficient to assess the tooth failure of plastic gears. Additional material properties such as fatigue limit, surface adhesion, the combined effect of heat conduction can override the importance of strength.

The results of a supplementary test at a lower stress rate have indicated that if the performance is the same, i.e. the product of torque and angular velocity is constant, but their proportions are different, then the failure process will be different. At the PA 6 gears, the material behaved more brittle due to the higher speed of load, as it did not have enough time to deform.

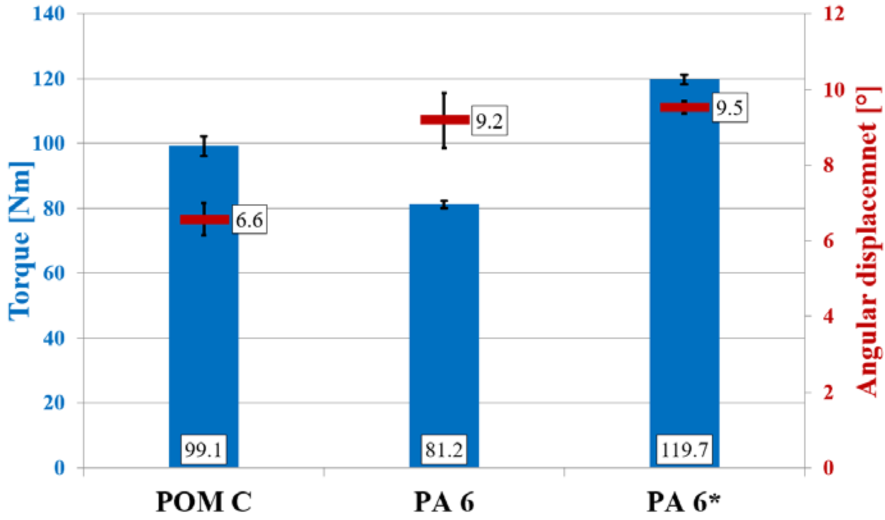

Figure 5. The main results of overloaded tests

There is a microscopic image of a broken PA6 gear to analyse the fracture in more detail (see in Fig.6). It can be seen that their teeth were strongly deformed, underwent a permanent deformation, and the loaded teeth fractured below the pitch circle. In most cases, two teeth are broken off completely. During meshing, not only two teeth were loaded, however, the nonfractured teeth also suffered non-recoverable deflection.

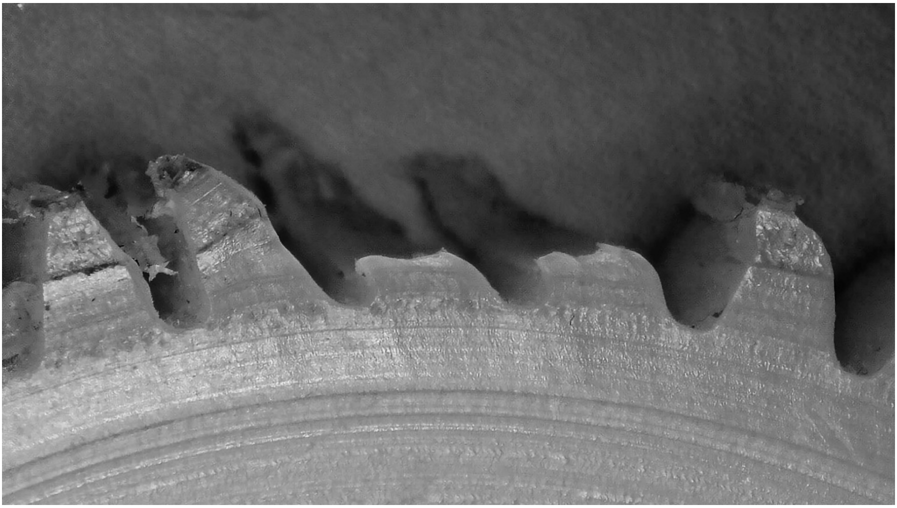

Figure 6. The fractured teeth of a PA6 gear

A microscopic image is shown about the failure of a POM C gear in Fig. 7. Their teeth behaved more brittle than PA6 because three of their teeth broke approximately along a straight line, the fracture surfaces were even. There is no significant sign of deformation at these gears.

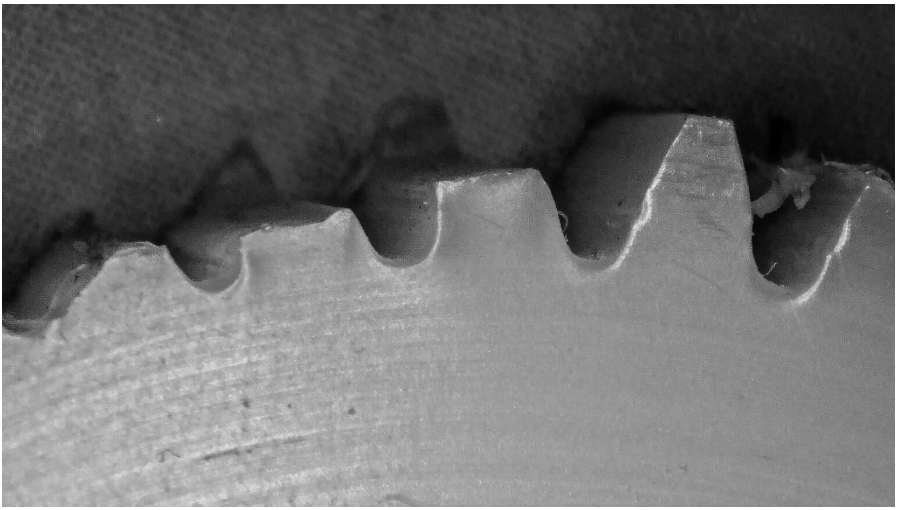

Figure 7. The fractured teeth of a POM gear

3.2. Lifetime test

For the lifetime test, firstly, the high speed - high torque corner point was studied with PA 6 gears.

Based on the literature and the possibilities of the measuring system, the constant load of 10 Nm and the constant rotational speed of 1000 rpm were chosen. The applied load and rotational speed are very significant for plastic gears, especially for plastic-plastic material pairing.

The lifetime test is capable of investigating how long the plastic gears can operate or how the temperature of the gear changes under this extreme condition. During the test, the temperature was measured by a thermal camera, as shown in Fig. 8. For plastic gear, the heating causes serious problems because the mechanical properties of the material deteriorate with increasing temperature.

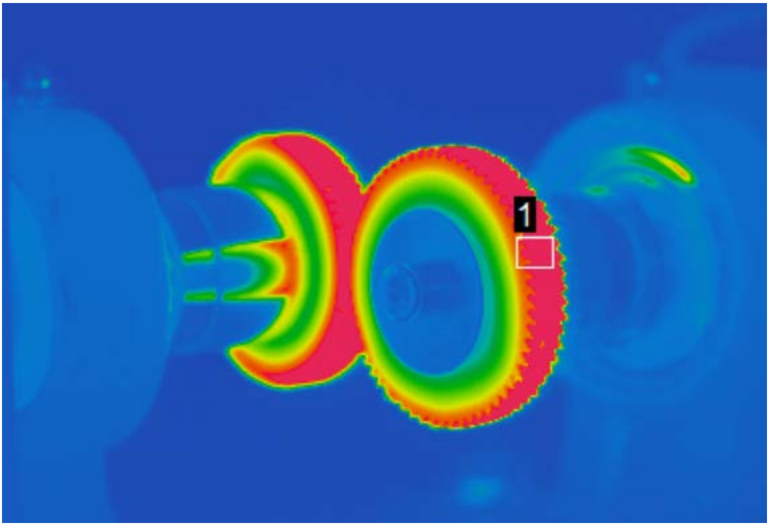

Figure 8. Thermal image of PA6 gears with sampling area

The rise of the average temperature of a PA6 gear is demonstrated in Fig. 9. For the given gear geometry, the running time was approximately 12 minutes, which corresponds to 12,000 cycles (revolutions). During the time from start-up to failure, the average temperature change of the gear surface is 88.5 ° C. Starting from room temperature (23 °C), the surface of the tooth could reach 100-110 ° C, while the environment of the tooth could reach 80-90 ° C. In the air, for long-term use, the cast PA 6 can be used safely up to 105 ° C according to the manufacturer's data [11]. So, at such a high temperature, the strength of PA 6 deteriorated strongly, such as the yield strength, which decreases by a quarter at 100 °C, or the modulus of elasticity, which decreases by a third at the same temperature. The temperature change measured on the tooth surface is also confirmed by the data in the literature [13]. All data are mean values of at least two repetitions.

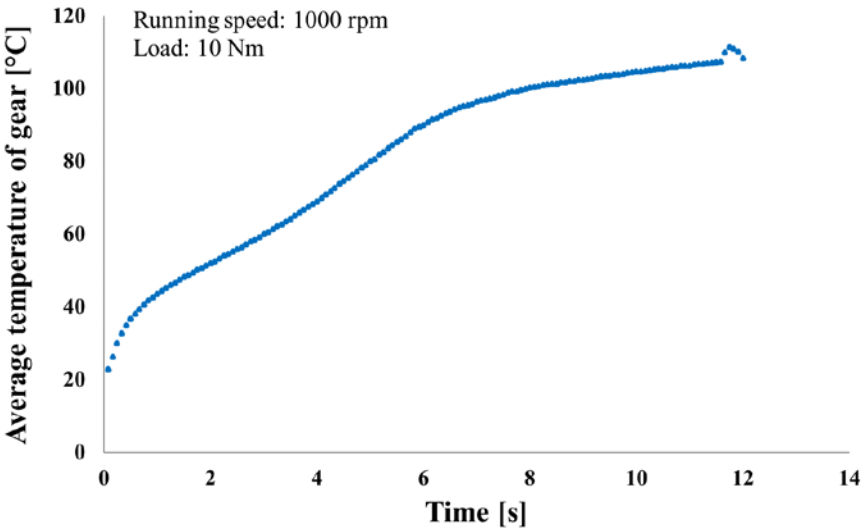

Figure 9. The heating of a PA6 gear

The result of lifetime tests proves also that one of the most critical factors in the failure of gears is heating. Due to the poor thermal conductivity of plastics, the heat generates and remains in and around the contact zone. This is the main reason why it is not recommended in technical practice to use a plastic-plastic gear pairing in a highly loaded system. For example, for a plastic/steel gears pairing, the steel pinion can dissipate most of the heat by conduction of heat, thus achieving a much longer service life.

The failure of gear at constant high load and high speed is indicated in Fig. 10. The teeth of a PA6 gear suffered permanent deformation. Softening or melting of the teeth can be recognized. There was no breakage of the teeth, however, strong wear was observed at the tip of the teeth. The malfunction occurred abruptly after 12,000 cycles. As a result of the melting of the gear, the tooth meshing discontinued.

It can be clear that the heat generated, and its dissipation plays a particularly important role in polymer gears. Using oil or water as a lubricant can multiply its lifetime.

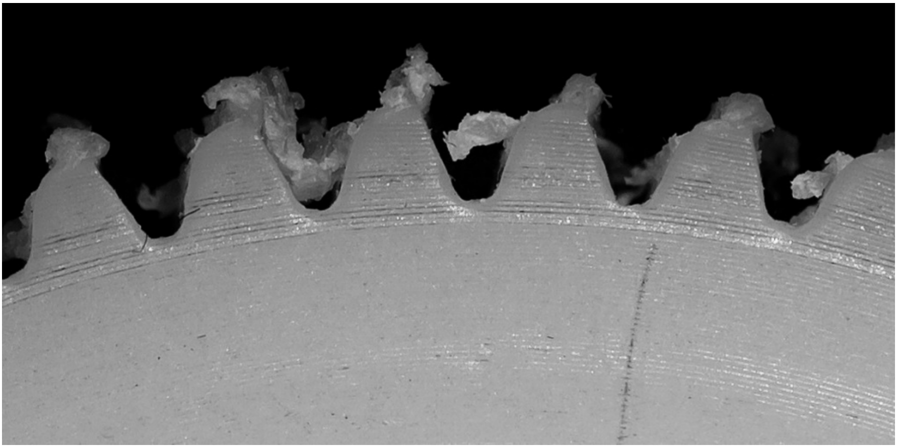

Figure 10. The melting of the teeth of a PA6 gear

4. Conclusion

The limit of the load-carrying capacity of POM and PA6 gears was examined, furthermore, the lifetime of PA6 gears was investigated in this study. The results of overload tests showed that POM C gears underwent a higher load of 122% at the time of fracture than PA6 gears. However, the deformation of PA6 gears is approximately 140% greater than the POM gears. The POM gears behaved more brittle under load than PA gears that can also be seen on the fractured teeth. The results of supplementary overload tests pointed out that the stress rate plays an important role in the load-carrying capacity of plastic gears. According to the results of lifetime tests, it is proved that one of the most critical factors in the failure of plastic gears is heating. Due to the poor thermal conductivity of plastic materials, the heat generates and remains in and around the contact zone that results softening or melting of teeth.

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