A Comparative Study of Polymer Gears Made of Five Materials

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Introduction

Polymer materials have been used for many gear applications due to several advantages over metal gears, including their light weight, good damping resistance and low cost. Polymer gears are currently being designed for applications, from traditional low-power motion transmission to middle- and even high-power transmission — especially within automotive engineering. Currently, there are a few design standards for polymer gear applications (Refs. 1–2) which have been mainly developed by modifying the existing metal gear design methods. However, it may be noted that the design guidance is only available in detail for POM and PA materials. This is a major limitation of the existing design methods, as new polymer materials are becoming available continuously. Furthermore, there is little evidence in the literature showing the validity of the methods, and in some cases poor correlation has been shown between the standards and test results (Refs. 3–4). As a result, the use of polymer gears in higher-power applications is not widely accepted due to the lack of understanding of their performance.

Polymer materials — especially their elasticity and strength — are very sensitive to temperature variations, and one of the main challenges for polymer gear applications is to understand the gear thermo-mechanical contact performance. It has been known that the available design methods for polymer gear performance prediction are still limited with regards to the effects of temperature and that the existing polymer gear surface temperature predictions require much further study regarding their practical applicability. For instance, most of the polymer gear surface temperature estimation methods are based on the approach of Hachman and Strickle (Ref. 5), assuming that polymer gear tooth heat transfer is not significantly affected by lubrication. However, it has also been reported that polymer gear performance has been significantly improved under lubrication conditions (Ref. 6).

Although the typical failure modes in polymer gears (wear, pitting, root and pitch cracks) can also occur in metal gears, the failure mechanisms of polymer gears are much more dominated by the gear temperature. Yousef (Ref. 7) has reported that methods for measuring gear surface temperature after stopping the tests are inaccurate because the gear body temperature drops very rapidly soon after the gears stop running. Letzelter et al (Ref. 8) have reported a non-stop gear temperature measurement approach using an infrared camera with the measurements carried out on PA 6/6 gears. To use the steel's relatively good thermal conductivity, some experimental work has concentrated on meshing polymer gears with steel pinions (Refs. 9–11). Recently, it has also been shown experimentally that the load capacity of carbon fiber-reinforced PEEK gears under high running temperature is much improved to that of PA gears (Refs. 11–14).

As the injection molding techniques for polymer gears have rapidly developed, it is necessary to learn more about the performance of injection-molded gears under different operating conditions. The study of injection-molded polymer gear performance is important due to the significantly lower cost of injection-molded gears when compared to machined gears.

(a) Dry running conditions

(b) Oil lubricated conditions

Figure 1 Two gear test rigs.

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Experimental Test Rig and Gear Specifications

A unique test rig suitable for dry running conditions — with a fixed speed ratio of 1:1 and a center distance of 60 mm — has been employed in this study (Fig. 1a). A similar rig suitable for oil-lubricated conditions is also available at the authors' lab but was not employed here (Fig. 1b). All the tests described in this paper are under dry running conditions. The effect of lubrication is the subject of further, ongoing investigation. The unique capabilities of the rig have been introduced in the authors' previous research (Ref. 15); these include the capability to misalign the gear engagement and to record the gear surface wear continuously with constant load without the requirement to stop the test. A weighted block is used to apply the continuous torque, with the wear rate measured indirectly by recording the linear movement of the weighted block. It is worth noting that a limitation to this set up is that the results from the rig cannot separate the tooth deflections from wear. However, the wear rate obtained has been successfully used to understand and predict the polymer gear load capacity, as described in the authors' previous research (Ref. 15).

Injection molding using five polymer materials has been used to manufacture the gears for this study: PC (polycarbonate); POM (Polyoxymethylene); HDPE (high-density polyethylene); PA (Polyamide, nylon 46); and PEEK (Polyether ether ketone, or PEEK650). The gear center distance has been adjusted to account for the effects of polymer gear shrinkage following injection molding. Measurements were carried out to assess the amount of shrinkage. For the gears having a nominal outside diameter of 64 mm, the following average outside diameters were observed — 63.45 mm for PA; 64.91 mm for PC; 63.70 mm for HDPE; 64.11 mm for PEEK; and 63.52 mm for POM. The material properties of the polymer gears are shown in Table 1 and the nominal geometry of the tested gears is summarized in Table 2.

Table 1 The five material properties

	HDPE	PC	POM	PA46	PEEK650
Specific gravity (g/cm^3)	0.96	1.20	1.42	1.18	1.30
Tensile strength (MPa)	23	66	70	105	155
Flexural modulus (MPa)	900	2400	2900	3300	3600
Coefficient of friction	0.1	0.31	0.21	0.28	0.21
Melting temperature (^{o}C)	131	155	178	295	343

Table 2 Nominal geometry for all gears

Module (mm)	2
Tooth Number	30
Pressure angle	20^o
Face width (mm)	17
Thickness (mm)	3.14
Contact ratio	1.67

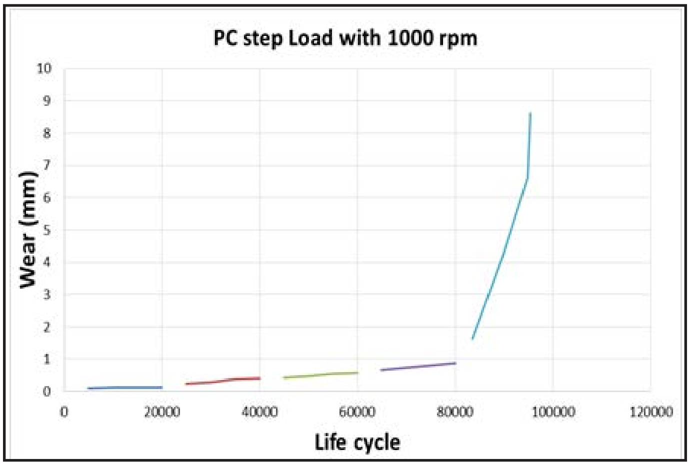
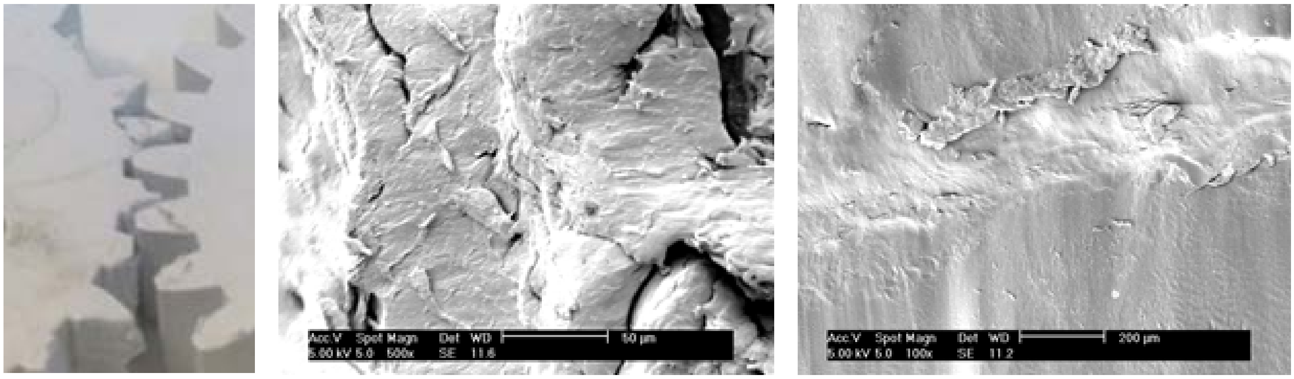


Figure 2 Experimental results for polycarbonate gears.

Test Results and Discussion

Gear engagements of same materials. The incremental step loading test method (Ref. 4) has been employed for the tests. During the incremental test, only one single-polymer gear pair is tested. The tested gears are loaded at a designed constant load for a certain period (e.g., 1 hour), after which the load is incrementally increased to a designed value for another certain period. This process of incremental load increase continues until a rapid wear rate increase is observed and the experimental test is completed. This method has previously been compared to normal endurance tests, where different gear pairs are run at each load until failure. It has been shown that the incremental test method is a very effective way to achieve the performance evaluation for new gears (Ref. 3). From the experiments, it can be seen that with a properly designed run time for each load, an adequate wear rate value will be obtained, as can an adequate result for the transition torque at which the wear rate accelerates rapidly. The main benefit of using the incremental loading method is that an overview of a new gear pair's performance can be obtained within one day, compared with the several weeks required to perform full endurance



(a) Overview (b) pitch point SEM 500 times (c) pitch point SEM 100 times

Figure 3 Experimental results for polycarbonate gears.

testing on multiple gear pairs at multiple torques. Figure 2 shows the experimental results for an incremental load test of a polycarbonate gear pair running at 1,000 rpm. The gears were loaded at 3 Nm for one hour, after which the load was increased to 4, 5, 6 and 7 Nm for one hour running under each load. Under 7 Nm the polycarbonate gears failed due to pitch fracture.

The polycarbonate gears fractured only on the driver (Fig. 3). A possible reason for this may be linked to the difference in wear patterns between the driver and the driven gears as shown (Fig. 4). The driving gear's tooth root wear is higher due to a higher friction force at approach than the recess friction force. The reason for the difference in friction force is that during tooth meshing, the rolling action of the teeth on the two engaged gears in approach is towards each other, whereas in recess the teeth rolling action is away from each other. The pitch point fracture for the driver is likely related to the tooth wear pattern, combined with the high temperature at the tooth surface around the pitch point.

Figure 5 shows wear rate against torque for gear pairs manufactured using the 5 different polymer gear materials. The wear rate considered here is the material depth removed per cycle, given by the linear wear period slope as shown (Fig. 2). All tests were run at a constant speed of 1,000 rpm. The experimental results show that, for all polymer gear pairs tested, below a certain load the gear surfaces wear slowly and a relatively long life for the gears will be achieved (nearly 10^7 cycles), while above a critical torque wear rate accelerates rapidly and leads to rapid failure. The observed critical torques for each gear pair are about 6 Nm for polycarbonate (PC); 8 Nm for POM; 8.5 Nm for PA; 11 Nm for PEEK; and 4.7 Nm for high-density polyethylene

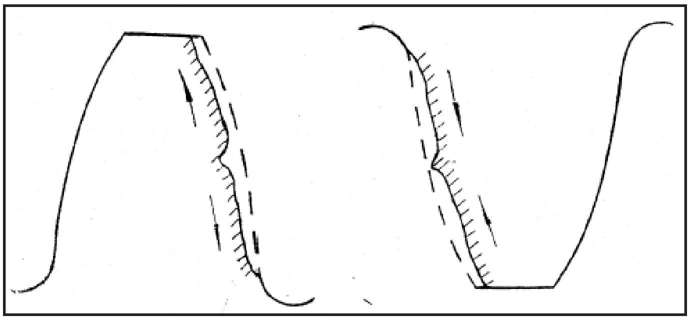


Figure 4 Gear surface wear (Ref. 2).

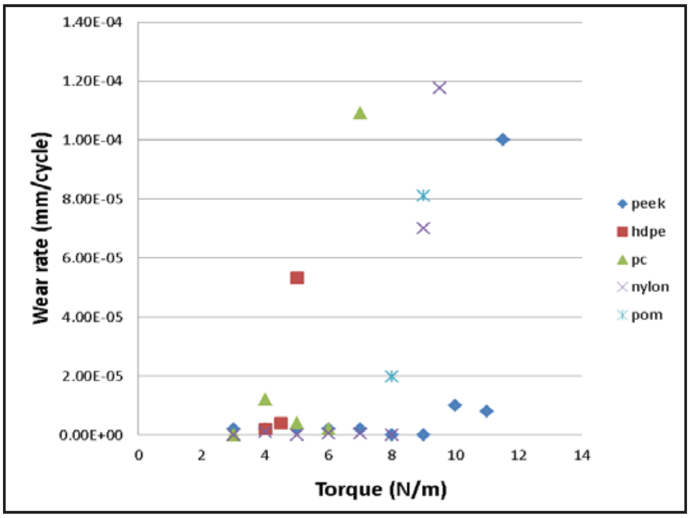
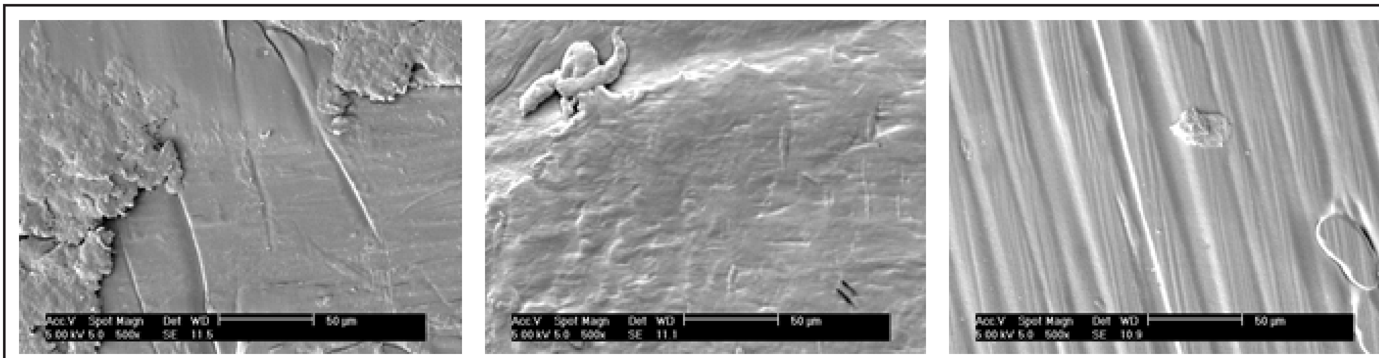
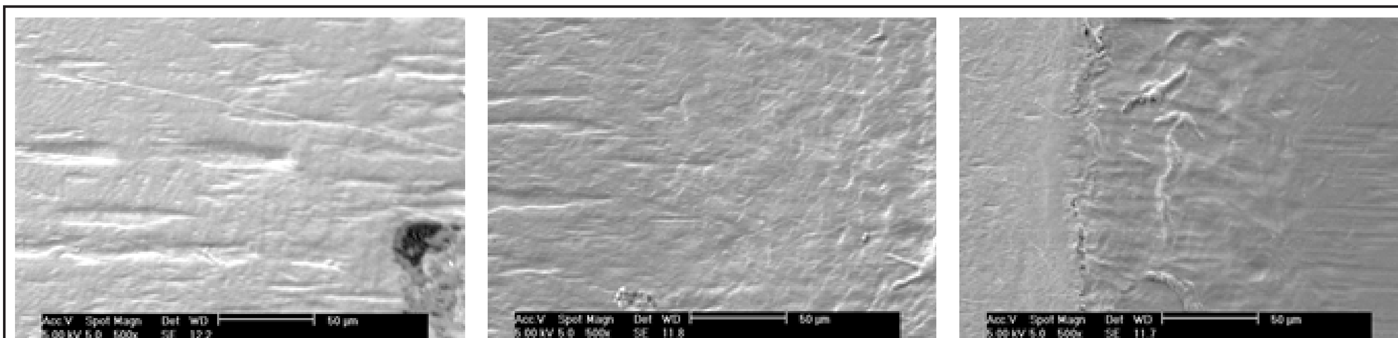


Figure 5 Wear rate against load for the same five polymer gear pairs.



(a) Tip (b) pitch (c) roof

Figure 6 PEEK gear tooth SEM results.



(a) Tip (b) pitch (c) roof

Figure 7 PA gear tooth SEM results.

(HDPE). Above the critical torques, the polycarbonate gears failed due to pitch fracture; the POM gears failed due to thermal wear (the tooth surface maximum temperature reaching the POM material melting temperature (Ref. 15); the PA and PEEK gears failed due to excessive surface wear; and the HDPE gears failed due to large deformation. The large deformation failure of the HDPE gears was expected, given its low modulus of elasticity (approximately one-third of the other polymers considered (Table 1)). HDPE has been considered in this study and is of interest to polymer gear applications — particularly low-load, high number of cycle applications — due to its very low co-efficient of friction.

As the wear performance for both injection-molded and machine-cut POM gears has been discussed extensively in the previous literature (Refs. 3–4, 15), more focus in this study has been placed on investigating the PEEK and PA gear performance. Figure 6 shows SEM results for the PEEK gears, while Figure 7 shows SEM results for the PA gears. Although the sudden wear rate increase mechanisms for PEEK and PA are not clear at the moment, the high tip wear for both gears are expected due to high friction load in tooth tip region (Ref. 3).

Gear engagements of dissimilar materials. Incremental load tests were also performed running paired gears of different materials — again at a constant speed of 1,000 rpm. Figure 8 shows torque against wear rate for different combinations of running POM and PEEK gears; POM against POM; PEEK against PEEK; PEEK (driver) against POM; and POM (driver) against PEEK. It is very interesting to note the significant performance variation for dissimilar material engagement. The best performance was observed in the test with POM as the driver and PEEK as the driven gear, showing a transition torque of about 13 Nm. Next in terms of performance came PEEK against PEEK (11 Nm), PEEK against POM (10 Nm) and then POM against POM (8 Nm). Similar results have previously been reported by one of the authors for POM paired with PA (Ref. 4). The mechanism for good performance of POM as the driver is discussed as follows.

It has previously been shown that the main failure mode for POM gears is wear due to thermal effects (Refs. 4, 15). It has been argued that the tooth pressure angle will be increased with the tooth surface wear and the increase in tooth pressure angle will make the tooth wear even more quickly (Ref. 15). The typical wear form for POM is schematically shown (Fig. 9). The reason for the acceleration in wear as the pressure angle increases is because the torque T applied to the test gears is constant, i.e. — $T = F_n r$. When the gear tooth wears, the pressure angle increase causes the arm r of the normal contact force F_n about the gear center to reduce. However, the torque is constant, hence the normal contact force F_n' must increase, resulting in higher friction force. The friction force is the dominant factor causing POM tooth thermal wear and wear rate acceleration.

Further, it has been confirmed that the friction force is higher in the tooth tip area than the root area for the driven gear (Ref. 4), but higher in the tooth root area than the tip for the driving gear. This was discussed with regards to the polycarbonate gear tests earlier. As a result, more wear occurs at the root than the tip when POM is the driver, whereas more wear occurs at the tip than the root for the driven POM gear. Tip wear accelerates the gear wear much quicker than root wear and thus POM gears perform worse as the driven gear and better as the driver.

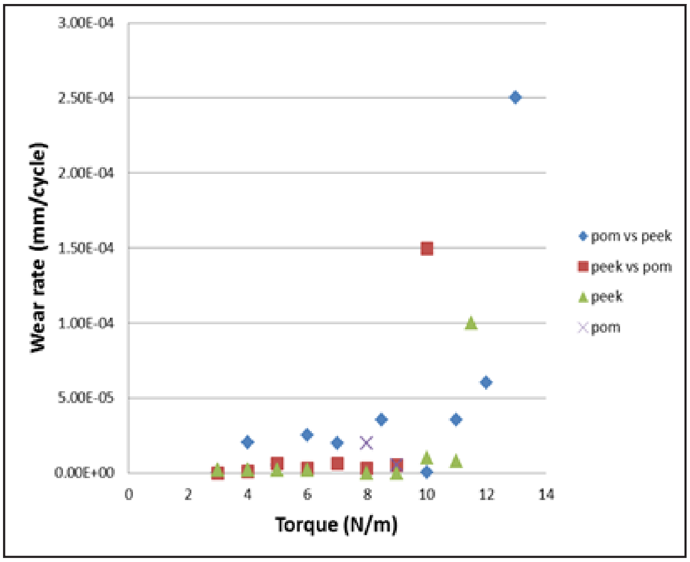


Figure 8 **Wear rate against load for POM and PEEK gears.**

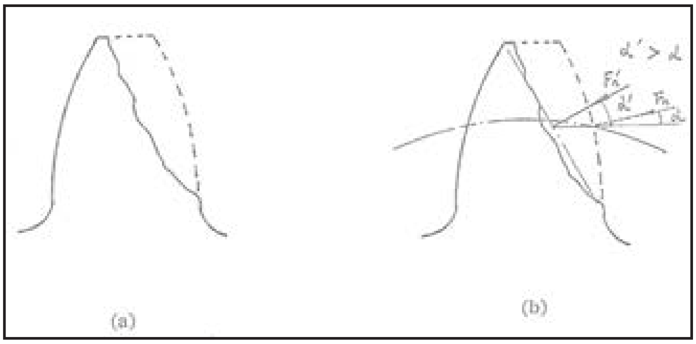


Figure 9 **Typical wear form for POM gears (Ref. 2).**

Conclusions

The wear behavior of polymer gears made of five different materials has been investigated using an existing polymer gear test rig. Step loading tests at a constant speed of 1,000 rpm were performed.

Significant differences in failure modes and performance have been observed for the five polymer gear materials for gear engagements of gears, with the same material as each other. The observed critical torques for each gear pair are about 4.7 Nm for HDPE; 6 Nm for PC; 8 Nm for POM; 8.5 Nm for PA; and 11 Nm for PEEK. The polycarbonate gears showed pitch point fracture failure related to the gear surface wear pattern, while the POM gears tested failed due to thermal wear. For POM the gears' surface will wear slowly, with a low, constant wear rate if the gear pair load is below a transition value. The wear rate increases rapidly when the gear load is equal or higher than the transition torque value. The transition torque has previously been shown to relate to the point where the gear tooth maximum surface temperature is equal or above the POM melting temperature. For the PA and PEEK gears, progressive wear was the main failure mode observed. Further endurance tests are needed to understand their wear mechanisms. The high-density polyethylene gears' performance was poor — as expected — and large deformation failure was observed due to the material's low modulus of elasticity.

For dissimilar material gear engagement between POM and PEEK, it is interesting to note that the best performance was achieved with POM as the driver and PEEK as the driven gear, when compared to POM against POM, PEEK against PEEK and PEEK against POM.

It may be noted that only dry running condition test results have been reported in this paper, and that lubrication effects are under further investigation. Preliminary results of the current research show an increase of over 40% for the load capacity of lubricated PEEK against PEEK as compared to dry running gears.

Injection molding process capabilities (including mold design and manufacture) have been established at Warwick University and research is ongoing with regards to the performance of reinforced polymer gears. Initial research results showed significant performance improvement for 28% glass fiber-reinforced POM gears when compared with the performance of unreinforced POM gears (Refs. 16–17).

For more information. Questions or comments regarding this paper? Contact Ken Mao at *K.Mao@warwick.ac.uk.*

References

1. BS 6168, "Specification for Non-Metallic Spur Gears." British Standards Institution, London, 1987.
2. VDI 2736 Blatt 2. "Thermoplastic Gear Wheels, Cylindrical Gears, Calculation of the Load Carrying Capacity," 2014.
3. Mao, K. "A New Approach for Polymer Gear Design," *Wear*, 262, pp. 432–441, 2007.
4. Li, W., A. Wood, R. Weidig and K. Mao. "An Investigation on the Wear Behavior of Dissimilar Polymer Gear Engagements," *Wear*, Vol. 271, pp. 2176–2183, 2011.
5. Hachman, H. and E. Strickle. "Nylon Gears," *Konstruktion*, Vol.3, No.18, pp. 81–94, 1966.
6. Chen, J.H. and F. M. Juarbe. "How Lubrication Affects MoS2-Filled Nylon Gears," *Power Transmission Design*, pp. 34–40, 1982.
7. Yousef, S.S. "Techniques for Assessing the Running Temperature and Fatigue Strength of Thermoplastic Gears," *Mechanism and Machine Theory*, Vol. 8, pp. 175–185, 1973.
8. Letzelter, E., M. Guingand, J. Vaujany and P. Schlosser. "A New Experimental Approach for Measuring Thermal Behavior of Nylon 6/6 gears," *Polymer Testing*, 29, pp1041–1051, 2010.
9. Gauvin, R., H. Yelle and F. Safah. "Experimental Investigation of the Load Cycle in a Plastic Gear Mesh, *Int. Symp. On Gearing and Power Transmission*, Tokyo, pp. 473–378, 1981.
10. Tsukamoto, N. "Investigation About Load Capacity of Nylon Gears," *Bulletin of JSME*, Vol.27, No. 229, 1984.
11. Van Melick, Ir. HGH and HK van Dijik. "High Temperature Testing of Stanyl Plastic Gears: a Comparison with Tensile Fatigue Data," ***Gear Technology*** magazine, pp. 59–65, April 2010.
12. Kurokawa, M., Y. Uchiyama and S. Nagai. "Performance of Plastic Gear Made of Carbon Fiber Rinforced Poly-Ether-Ether-Ketone," *Tribology International* 32, pp. 491–497, 1999.
13. Kurokawa, M., Y. Uchiyama and S. Nagai. "Performance of Plastic Gear Made of Carbon Fiber-Reinforced Poly-Ether-Ether-Ketone: Part Two," *Tribology International* 33, pp. 715–721, 2000.
14. Kurokawa, M., Y. Uchiyama, T. Iwai and S. Nagai. "Performance of Plastic Gear Made of Carbon Fiber-Reinforced Polyamide 12," *Wear,* 254, pp. 468–473, 2003.
15. Mao, K., P. Langlois, Z. Hu, K. Alharbi, X. Xu, M. Milson, W. Li, C. J. Hooke and D. Chetwynd. "The Wear and Thermal Mechanical Contact Behavior of Machine-Cut Polymer Gears," *Wear*, pp. 822–826, 2015.
16. Ramakrishnan, R. and K. Mao. "Minimization of Shrinkage in Injection Molding Process of POM Polymer Gear Using Taguchi DOE Optimization and ANOVA Method," *International Journal of Mechanical and Industrial Technology*, Vol. 4, Issue 2, pp. 72–79, 2017.
17. Mao, K., D. Greenwood, R. Ramakrishnan, V. Goodship, C. Shrouti, D. Chetwynd and P. Langlois. "The Wear Resistance Improvement of Fiber-Reinforced Polymer Composite Gear," *Wear*, pp1033–1039, 2019.

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