The Wear Resistance Improvement of Fibre Reinforced Polymer Composite Gears

Ken Mao, Dave Greenwood, Ramkumar Ramakrishnan,* Vannessa Goodship, *Chetan Shrouti, Derek Chetwynd and Paul Langlois+*
School of Engineering and WMG, University of Warwick, Coventry, CV4 7AL, UK
[1]SMT, 67-69 Hounds Gate, Nottingham. NG1 6BB, UK
** The corresponding author: k.mao@warwick.ac.uk*

Abstract

This paper presents experimental investigations into the wear performance of non-reinforced POM (Polyoxymethylene) and 28% GFR POM (glass fibre reinforced POM) gear pairs; polymer running against polymer is a little studied but important system. All the gears were manufactured locally by injection moulding. The injection mould design and manufacturing process are briefly described and progress in the control of injection moulding processes for polymer and fibre reinforced polymer gears is discussed. A specifically designed polymer composite gear test rig was used for this research. Performance differences for the POM and GFR POM gears are observed, notably their loading capacity and failure modes. Both POM and GFR POM gear pairs, showed a clear wear transition torque for a given running speed. Above the transition torque the wear rate accelerated rapidly causing thermal failure, while below the transition torque the gears had a very low specific wear rate. Significant performance enhancements were seen for the GFR POM gears, with an increase of around 50% in load carrying capacity when compared to the non-reinforced POM gears. The wear mechanisms are briefly discussed, noting that most data available for polymer gear design is not representative of these polymer against polymer pairings.

Key words: wear rate, friction, glass fibre reinforcement, polymer gears, surface temperature

1. Introduction

Fibre reinforced polymer composite gears offer unique advantages over metal gears for a wide range of industrial applications, including their low weight, low cost, high damping resistance and ability to function with grease or without external lubrication. However, the extensive research so far carried out to understand the gears' behaviour in order to achieve high power transmission, especially in motorcycle and electric vehicle lightweight gearbox applications, heavily concentrates on metal-polymer gear pairs. There is very little literature directly relevant to the design of polymer-polymer gear pairs, which are of increasing technical interest in many fields.

The existing polymer gear design methods (e.g. British Standard 6168 [1] and German VDI 2736 standard [2]) are based on metal gear tooth bending strength and surface contact fatigue approaches with modifications to use polymer material properties instead of steel. However, the current approaches still have significant limitations for bending and contact fatigue failure because of both the thermal behaviour and the larger relative deflections of polymer gears. Crucially, polymer gears may fail under failure modes not covered by the existing standards [3] because the polymer's thermal performance is much lower than that of steels. The first notable progress on the calculation of temperature for polymer gears seems to be that made by Hachmann and Strickle [4] and both the British and German Standards are based on their method. However, their original gear temperature calculation was limited to lubricated nylon against steel gears only. Although much research has followed Hachmann and Strickle [4], there have been no large steps forward, e.g. Gauvin et al's equation [5] is limited to polymer against steel gears. On the empirical side, the many gear surface and body temperature measurements carried out to understand polymer gear thermal behaviour have usually been achieved by stopping the tested gears. Such methods are inaccurate because both the gear surface and body temperature drop significantly once the gear stops [6]. An indirect measuring method had been reported by Letzelter et al [7] monitoring a nylon 6/6 gear body temperature using an infrared camera; this method has been shown to give more accurate results.

Another weakness of the current polymer gear design standards is the limited material information published. For example, there is no information included for polymer composite gears. Recent experimental comparisons between carbon fibre reinforced PEEK and nylon gears [8] showed that the load capacity under high running temperature of the former is superior to that of other composite gears. It has been found that glass fibre reinforced nylon gears show better wear resistance in comparison to unfilled gears due to the improved elastic modulus and compressive strength [9 & 10]. Short-fibre reinforced high temperature resistant thermoplastic materials are now being used as sliding elements that were formerly composed only of metallic materials. There is some research on fibre reinforced POM (Polyoxymethylene) wear, but most uses standard tribology test methods, e.g. pin on disc tests in [11]. Hardly any work looks at GFR POM (glass fibre reinforced POM) gears. Gear contact behaviours are very different from, say, twin disc contact because gear sliding and rolling behaviours change at every contact point [12]. Also, most previous work concentrated on polymer against steel, but when a polymer gear drives a steel gear, the entire deformation will be on the former due to its low elastic modulus [13] and the contact conditions are affected by steel's relatively good thermal conductivity [14]. There is urgent need for data on GFR POM gears against GFR POM gears.

Despite the currently available literature, the information on polymer composite gear design and performance is still very limited and their application remains restricted by this lack of performance information, design standards or agreed testing methodologies.

2. Injection mould design, process and functional requirements

The polymer gear injection moulding processes used an Engel 140T machine, with the experiments conducted using aluminium mould inserts for both POM and GFR POM materials. Initially, PP (Polypropylene) gears were moulded to understand the molten polymer filling pattern. This was followed by POM and GFR POM gears injection moulding. The processes were carried out with different injection moulding parameters and subsequently tested for shrinkage, porosity and crystallinity.

The aluminium mould inserts (Fig.1) used for both POM and GFR POM gears used a radial gate design [15]. Contour design was eliminated from these mould inserts to aid easy part ejection; with contours in the mould the cooled polymer is gripped on the contour face making part ejection tougher. If a contour design is used it is recommended to use an ejector pins mechanism, which helps in reducing the wall thickness in certain regions, and helps in reducing the overall cooling time of the part. In this study the process is conducted without ejector pins. The moulded gear was ejected manually by tapping threads in the hub hole. The radial gating method was used for the designed mould inserts (Fig.1) because of existing assembly insert space limitations. The mould unit consists of two halves: the right side insert (RSI) is assembled to the fixed side of the mould cavity, which is the injection side of the machine, while the left side insert (LSI) slides on the guideways on the movable side of the cavity.

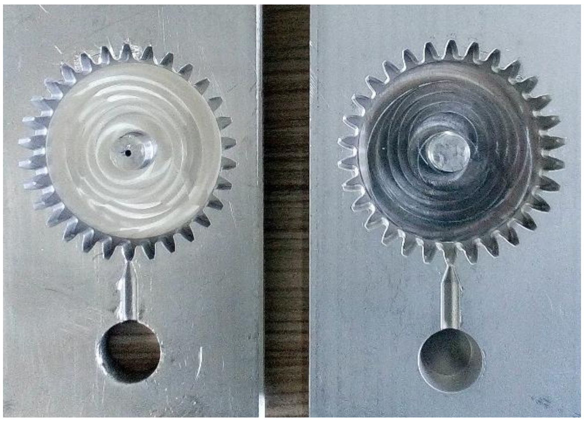


Fig.1 Aluminium mould inserts RSI and LSI

For the POM and GFR POM gear injection moulding process a design of experiments approach was used to investigate the sensitivity of the moulded gears to various process parameters [16]. The packing pressure was identified as the most significant process parameter, showing 70% and 55% effects on the part shrinkage and warpage respectively. The gears moulded with a packing pressure ranging from 70 to 110 MPa were found to be of acceptable quality.

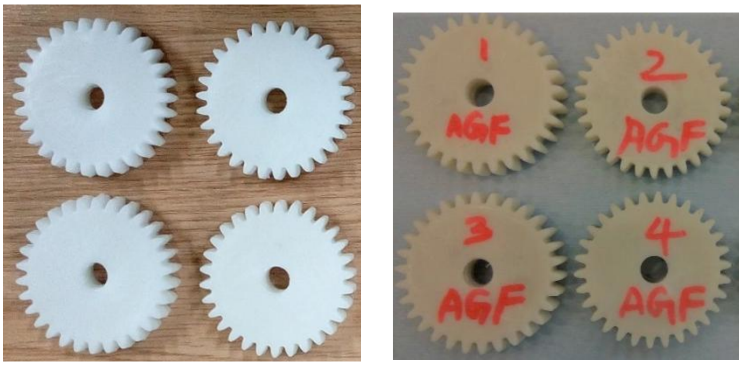


Fig.2 Moulded POM (4 left) and GFR POM gears (4 right)

Fig.2 shows samples for four POM gears (left) and four GFR POM gears.

All the measured values for investigating functional requirements (e.g. porosity, crystallinity, shrinkage) were obtained through the average of four tested samples, as were the test data (e.g. wear rate and transition torque) throughout the whole paper. Porosity evaluation was performed using a Nikon 225/320 CT scanner. The Computed Tomography technique is now very widely used to evaluate the internal features of an object through 3-dimensional scanning. High-resolution is achieved by projecting onto the object high-energy X-rays of up to 320 kV source voltage. The output is a 3D model fully populated by voxels. The major advantage of CT scanning is that it is a non-destructive testing method to evaluate internal features such as pores. In this work, the porosity percentage was assessed at 3.74% and 0,34% for POM and GFR POM gears respectively.

Table 1 DSC results summary

Material	Melting temperature (peak) in ^{0}C	Crystallization temperature (peak) in ^{0}C	Degree of crystallinity in %
POM	176	147	51.13%
GFR POM	170	143	28.06%

Crystallinity and thermal transitions evaluation was done by differential scanning calorimetry (DSC) and thermal stability and glass fibre content evaluation by thermal gravimetric analysis (TGA). DSC is a widely used technique to analyse the thermal transitions of a polymer material by measuring the heat flowing inside and outside of a polymer material against the temperature. DSC is also used to determine glass transition temperature, crystallisation temperature, melting temperature, melting enthalpy and percentage crystallinity. The percentage crystallinity is determined by comparing the melting enthalpy of a sample with the reference melting enthalpy of a 100% crystalline polymer of the same material. Table 1 summarises the main DSC results.

The actual glass fibre content present in the injection moulded reinforced POM material was evaluated using TGA within an air environment. The sample was heated in an alumina pan from room temperature to a maximum temperature of about 1000 ^{0}C with a heating rate of 10 ^{0}C/min. As the melting of glass fibre starts only after 1400 ^{0}C, the polymer portion of the sample will undergo complete thermal decomposition, and the remaining glass fibre content by percentage weight is determined. The glass fibre content by percentage weight for the reinforced POM gears in this study was about 28%.

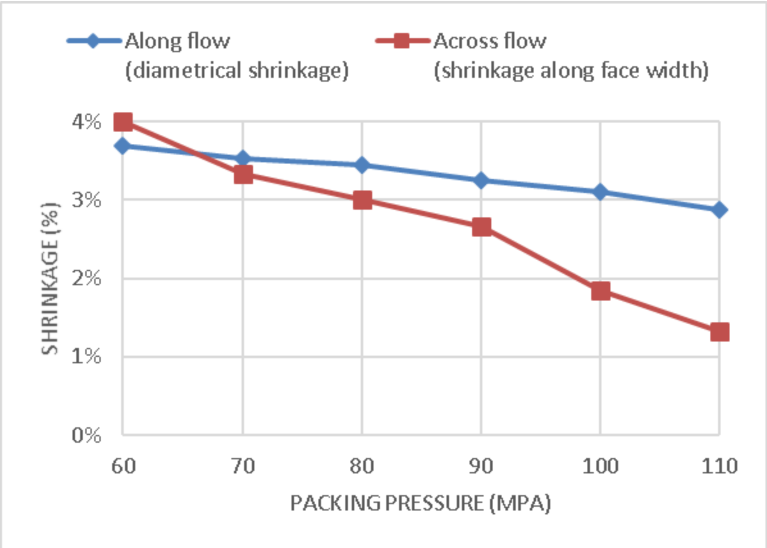


Fig.3 POM gear shrinkage against packing pressure

The shrinkage along flow (diametrical shrinkage) and shrinkage across flow (shrinkage along face width) were evaluated for the POM and GFR POM gears moulded at different packing pressures ranging from 60 MPa to 110 MPa. Both shrinkage along flow and shrinkage across flow decreased with the increase in the packing pressure as shown in Fig.3 and Fig.4. It is also observed that the shrinkage across flow is less than the shrinkage along flow at higher packing pressures for the POM gears while the opposite was true for the GFR POM gears. The minimum shrinkage for both POM and GFR POM gears occurred when they were moulded with a packing pressure of 110 MPa: for POM it was 2.88% along flow and 1.33% across flow; for GFR POM, 1.76% along flow and 2.13% across flow.

The observed decrease in the percentage porosity of the POM gears with the increase in the packing pressure is due to the better packing of polymer molecules at higher pressures. The molecules then undergo much less movement during the cooling phase, resulting in lower porosity levels.

GFR POM injection moulded gear samples were cut and examined using a scanning electron microscope to measure the average fibre length and average fibre diameter. Fig.5 shows example images. The glass fibre length ranged between 200 µm and 500 µm in size, while the fibre diameter ranged between 5 µm and 10 µm.

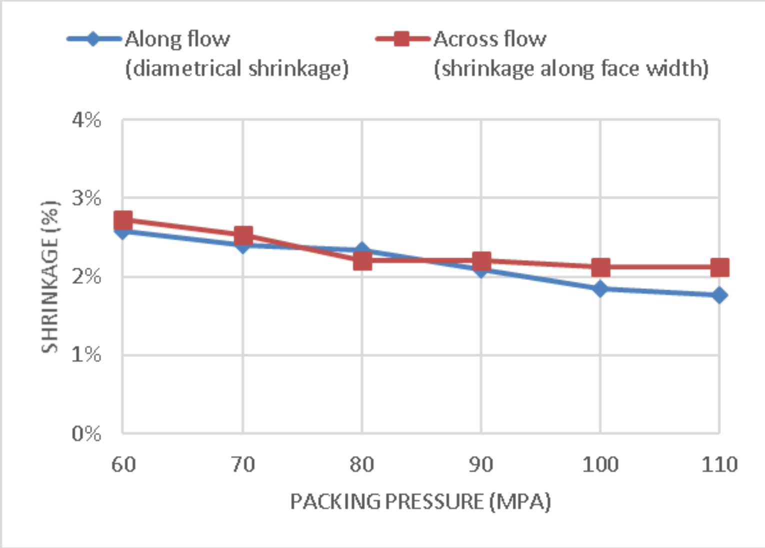


Fig.4 GFR POM gear shrinkage against packing pressure

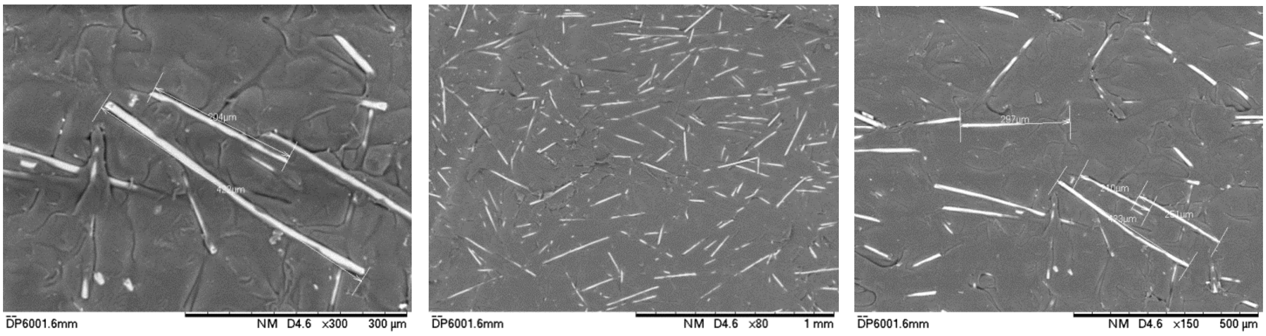


Fig.5 SEM observations for injection moulded GFR POM gear (before its loading tests)

This evaluation confirms the fibres present in the POM matrix to be short sized fibres [15]. The fibres in the gear tooth flank surface were seen to be in random orientations, as expected for gears moulded using a radial gated runner system.

3. Experiments and gear specifications

A unique, specialised polymer composite gear test rig (Fig.6) was employed to investigate the glass fibre reinforced polymer gear performance. Fully described elsewhere [3], this test rig has two immediately important features: the abilities to include deliberate controlled misalignments and to measure the wear rate continuously under constant load. The current work builds on initial progress in understanding the effects of misalignment on polymer gear performance [17]. Four test parameters are continuously recorded: torque, speed, wear rate and time to failure. Wear rate is measured indirectly by recording the movement of the bearing block using an LVDT (linear variable differential transducer) connected to a data-logging system. Note that this test method expresses wear in terms of the reduction in tooth thickness around the pitch point instead of using volume loss and that it cannot distinguish tooth deflections from the actual tooth thickness reduction [3]. However, the wear rate, a critical

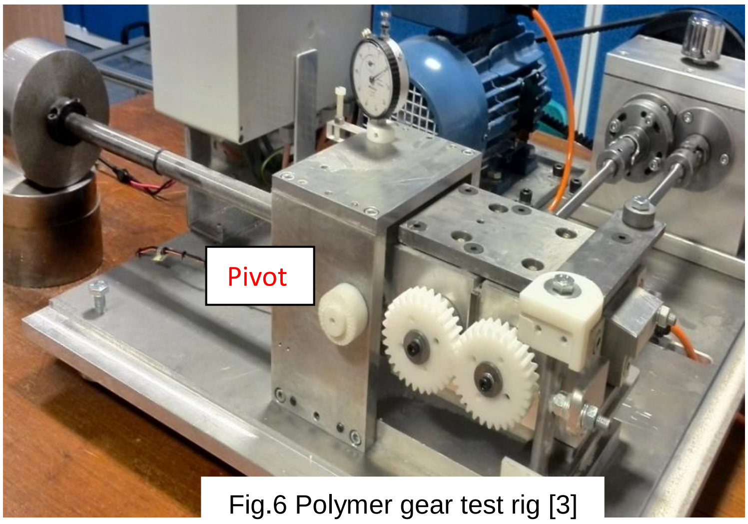


Fig.6 Polymer gear test rig [3]

parameter to monitor the gear life, can be recorded accurately by this test method. It has been shown previously that this measure of wear rate can be successfully used to predict polymer gear performance [3].

Experimental tests were carried out on both the GFR POM and POM gears to investigate the effect of glass fibre reinforcements on the gear performance. All test data presented in this paper are for either GFR POM against GFR POM or POM against POM spur gears with a speed ratio of one in unlubricated conditions. The material properties of the currently studied POM (Delrin 500P NC010) and GFR POM (Hostaform C9021 GV1/30) gears are shown in Table 2 and the nominal geometry of the gears is shown in Table 3. The shrinkage of the gears which leads to an average outside diameter of 63,73 mm (the nominal diameter being 64 mm) is close to the shrinkage seen for gears injection moulded by an external supplier, where the average outside diameter was 63.65 mm, and machine cut gears, where the average outside diameter was 63.88 mm [3].

Table 2 POM and GFR POM material properties

Property	POM	GFR POM
Density (kg/m^3)	1420	1600
Tensile modulus (MPa)	3100	9200
Flexural modulus (MPa)	2900	7800
Deflection temperature (^{0}C)	158	160
Melting temperature (^{0}C)	176	170

Table 3 Gear specifications

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

4. Test results and discussions

The tests were carried out using the established step loading method [3] with a running speed of 2000 rpm; POM gears were predominantly investigated at 1000 rpm in previous studies. Both the POM and GFR POM gear pairs were run for a duration of 20,000 cycles at each load step, with successive load increases of 0.5 Nm for the POM gears and 1 Nm for the GFR POM gears.

The POM gear pairs were tested with an initial torque set at 3 Nm, increasing by 0.5 Nm after every 20,000 cycles. The overall results are presented in Fig.7, showing that the POM gear wear rate increased dramatically (greater than a factor of 2) when the gear load reached and exceeded 7.5 Nm. There is a clear transition torque at about 7.5 Nm. This observed transition torque is lower than that reported for similar POM gears running at 1000 rpm, e.g. a transition torque of 8.5 Nm is stated in [3]. The lower transition torque for 2000 rpm is expected due to the higher sliding speed. The driving gear consistently failed due to severe thermal wear, Fig.8 (a) showing some evidence, but the driven gear was observed to have less severe thermal wear and less thinning across the tooth thickness. These behaviours likely arise from the gear tooth contact mechanisms [18]. The approach contact load is higher than the recess contact load because of the hard, non-involute, tip contact due to bending. Further, there is a reciprocating motion as the contact moves from non-involute

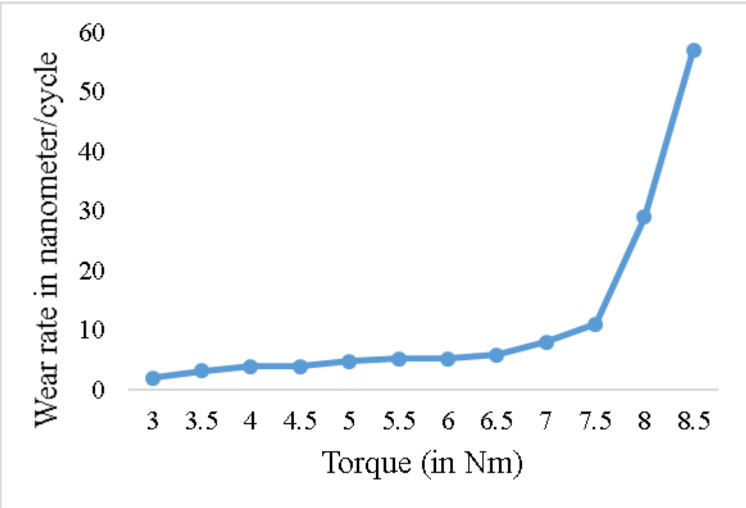


Fig.7 Wear rate against torque for POM gears

(a) (b)

Fig.8 Tested POM gears (a) the driver (b) the driven premature contact to normal line of action contact. That leads to more wear during the approach process where the driver's tip contacts the driven gear's root. The wear at the driving gear's tip will result in a pressure angle increase which can cause the gear wear to accelerate [3]. The percentage crystallinity of the tested gear tooth samples dropped to 43.4% from 51% before the tests, probably because of high local heating, as discussed later. Because POM gear hardness and wear resistance are properties dependent on crystallinity [19], this drop in crystallinity (i.e. hardness and wear resistance reduction) may be a symptom of the severe wear period (after the transition torque).

A previously developed method is employed here to predict the POM gear loading capacity, via the transition torque, for cases where the maximum surface temperature reaches the melting point of the material [3]. The maximum surface temperature (θ_{max}) is expressed as the sum of ambient (θ_a), body (θ_b) and flash (θ_f) temperatures:

$$\theta_{max} = \theta_a + \theta_b + \theta_f = \theta_a + k_1 T + k_2 T^{3/4} \qquad (1)$$

where

$$k_1 = \frac{3.927\mu}{bc\rho Z(r_a^2 - r^2)} \qquad k_2 = 1.11\mu \frac{\left(V_1^{1/2} - V_2^{1/2}\right)}{2r^{3/4}b^{3/4}\sqrt{k\rho c}}\left(\frac{\pi E}{R}\right)^{1/4}$$

with T: transmitted torque, ρ: specific gravity, k: thermal conductivity, c: specific heat, a: half contact width, r_a: outside radius, r: reference radius, b: tooth face width, V_1 and V_2: sliding velocity for gear 1 and gear 2 respectively.

Equation (1) predicts for the tested POM a transition torque of 7.15 Nm and a melting temperature of 176°C. This calculation correlates closely with the test results and so tends to confirm the importance of melting in the wear processes. Furthermore, both results correlate well with previously tested machine cut and injection moulded POM gears obtained from an external supplier [3], which provides additional confirmation of the quality of the injection moulding process

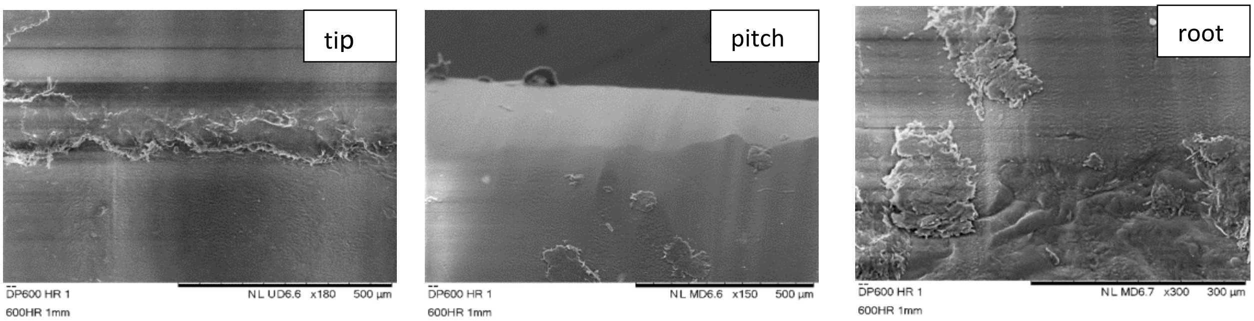


Fig.9 Typical SEM results for 7.5 Nm loaded POM driving gears at 2000

undertaken.

Typical SEM images of a worn POM driving gear tooth are shown in Fig.9. The wear at both tooth tip and root regions is much more severe than in the pitch region because of the much higher sliding speed at both tip and root, but close to zero sliding near the pitch point. Similar observations have also been obtained for the driven gear as illustrated in Fig.10.

The GFR POM gears were tested with an initial torque of 6 Nm increased by 1 Nm after 20,000

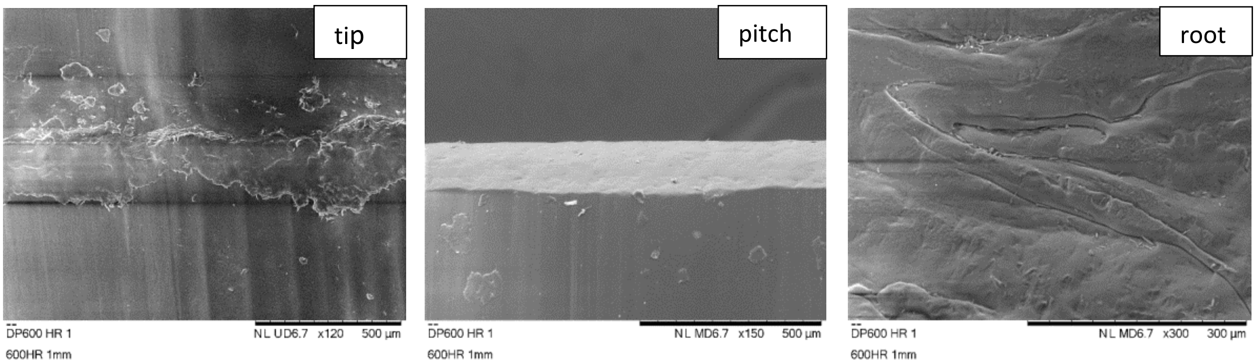


Fig.10 Typical SEM results for 7.5 Nm loaded POM driven gears at 2000

cycles at each torque level. The overall results are presented in Figure 11. A rapid increase in the wear rate was observed for loads around 11 Nm (the transition torque) and above. This significant increase of transition load observed for the GFR POM gears when compared to the POM gears (from 7.5 to 11 Nm) indicates around a 50% load capacity increase.

Both the driving gear and driven gear were found to have failed due to the gross thermal tooth bending (Fig.12). Further running of the gear pair after the transition torque increased the wear rate very rapidly as the temperature of gear teeth increased and made them more soft and flexible. This temperature rise causes the gear tooth to melt and bend, leading eventually to failure (the fibre has little effect on melting temperature, see Table 1). The wear difference between the driver and driven gears shown in Fig.12 is mainly due to the friction forces as discussed for POM gears (Fig. 8). The SEM results for the GFR POM gear samples before and after test are illustrated by Fig.13. The glass fibre lengths in the untested gear samples were in the range of 200 µm to 500 µm, while in tested gear samples the glass fibre lengths ranged between 30 µm and 100 µm. Reduced lengths of the glass fibres shows that fibres were being broken during testing because of the high loads on the gear tooth. The voids around the fibres after the test are also attributed to the local effects of fibre fracture.

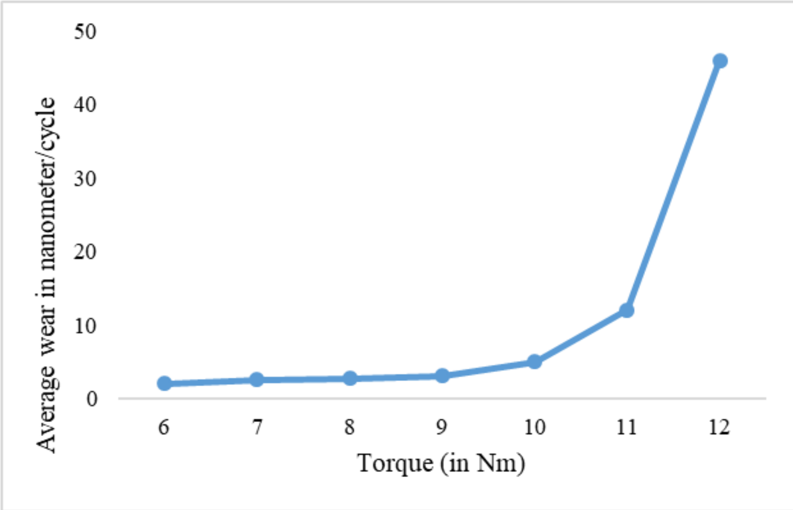
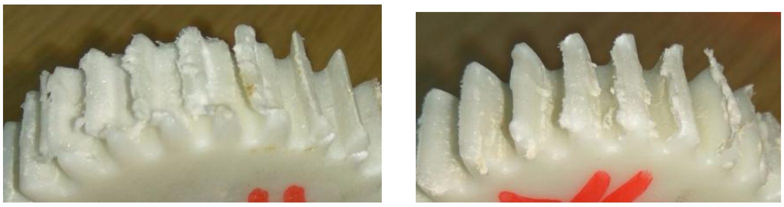


Fig.11 Wear rate against torque for GFR POM gears



(a) (b)

Fig.12 Tested GFR POM gears (a) the driver (b) the driven

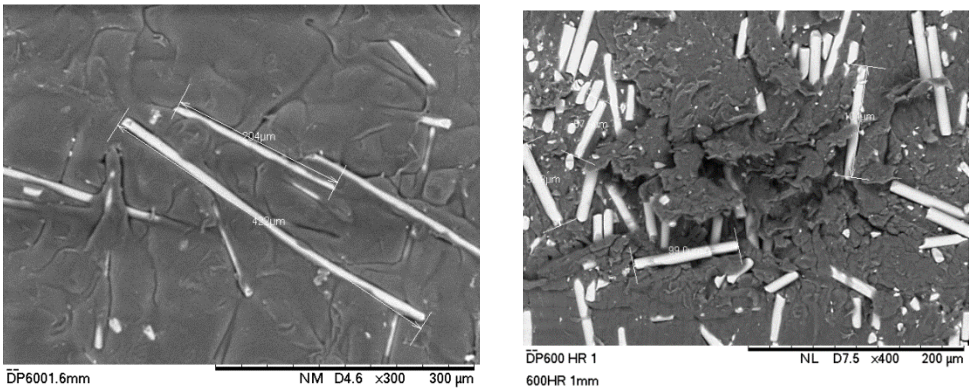


Fig.13 SEM results for GFR POM gears before (left) and after (right) tests

Post-test evaluations indicated that the percentage crystallinity of the driving and driven gear tooth samples after testing were 30% and 33.3% respectively, compared with the average crystallinity before testing of around 30% to 32%. In contrast to the non-reinforced POM gears, the GFR POM gears showed no significant change in crystallinity after testing. The elastic modulus (both tensile and flexural) of GFR POM gears is almost three times that of the unfilled ones (Table 2). For the same loading condition (e.g. 7.5 Nm), much higher tooth deformation would be expected for the unfilled gears, which would consequently generate much higher friction [18]. It is expected that the crystallinity level will change more if the teeth are at much higher surface temperatures for longer durations. This is the case (nearly 20% reduction) for the unfilled gears. However, the failure of GFR POM gears is being mediated by gear surface fibre failure mechanism up to much higher loads (e.g. 11 Nm). Because the glass fibres are brittle, the surface fibre fractures cause a rapid and significant drop in the local elastic modulus (i.e. a large deformation) and consequent high local friction heating. This sudden friction increase and elasticity drop as the fibre fractures lead to a quick final thermal bending failure for the GFR POM gears, as shown in Fig. 12, within too short a time to affect crystallinity. Also, note that any fibres with special adhesive bonding to the POM may generate high resistance to any micro structure change for the GFR POM gears [16].

There is a clear load transition for both the GFR POM gears and the POM gears with the GFR POM gears further showing around a 50% load capacity increase (from 7.5 to 11 Nm). However, the average wear rates of the POM and GFR POM gears for loads below their transition torques were found to be very similar at 5.31 nm/cycle and 4.55 nm/cycle respectively.

Wear rates for both GRF POM and POM gears below their critical load can be related to thrust bearing wear tests carried out by Friedrich [20], who expressed the wear volume, V_w, as

$$V_w = k_s F s \qquad (2)$$

where

k_s is the specific wear rate,
F the normal force, and
s the sliding distance.

If this equation is revised for spur gear tooth profiles, the specific wear rate can be expressed as

$$k_s = \frac{Qbd}{2TN} \qquad (3)$$

where

Q is the wear depth (as measured in the tests),
b is the gear face width,
d is the gear pitch circle diameter,
T is the torque transmitted,
N is the number of cycles corresponding to the wear Q.

Using the relevant parameter values, Equation (3) gives a specific wear rate of 5.84 $\times10^{-15}$ $m^3N^{-1}m^{-1}$ for the POM gears and 4.98 $\times10^{-15}$ $m^3N^{-1}m^{-1}$ for the GFR POM gears. These values may be compared to a reported figure of 3 $\times10^{-15}$ $m^3N^{-1}m^{-1}$ for POM against steel thrust bearing test [20]. The POM against steel data is not safely representative of the behaviour of polymer against polymer pairs.

5. General conclusions

Injection mould design and local, small-scale, manufacture of polymer gears by injection moulding have been successfully demonstrated, with relatively optimised moulding process parameters achieving high quality injection moulded polymer composite gears. A unique polymer gear test rig with the capabilities to simulate assembly misalignments and to continuously measure wear was then used to investigate the performance of polymer composite gear pairs. Material and performance testing confirmed that the locally moulded gears are as good as those provided by external professional manufacturers. The work thereby confirms the practicality of an effective and economic path for the widespread parametric studies and optimisation of polymer against polymer gear pairs to provide urgently-needed good design data and standards.

28% GFR POM gear pairs showed significantly enhanced performance, with about 50% better load capacity, compared to non-reinforced POM gear pairs. Clear transition torques, above which wear rates increased rapidly, were observed for both POM and GFR POM gear pairs for the given running speed and geometry. The gear surfaces have a low specific wear rate while loaded below their critical values. Optical and SEM examinations indicated principally thermal wear associated with local surface melting after the transition load. Close correlation of experimental data with a published model indirectly confirms this interpretation. The wear rate of POM gears increases dramatically above the transition load because the gear operating temperature approaches the material melting point. The percentage crystallinity of the POM gears was initially higher than for the GFR POM gears, but dropped by 20% during the tests; there was no significant change for GFR POM gears. Surface fibres in GFR POM gears were broken, with significantly reduced lengths, during performance testing. Local bending resistance appears to drop significantly once the fibres break, leading to rapid thermal bending failure. The crystallinity data supports this model. Overall, it is clearly demonstrated that the design of polymer against polymer gear pairs cannot safely rely on existing data: new and specific large studies are needed.

References

[1] BS 6168, 'Specification for Non-metallic Spur Gears', British Standards Institution, 1987.
[2] VDI 2736 Blatt 2 - Thermoplastic gear wheels, cylindrical gears, calculation of the load-carrying capacity, 2013.
[3] K. Mao, P. Langlois, Z. Hu, K. Alharbi, X. Xu, M. Milson, W. Li, C. J. Hooke and D. Chetwynd, ' The Wear and Thermal Mechanical Contact Behaviour of Machine Cut Polymer Gears', Wear, pp 822-826, 2015.
[4] H. Hachmann and E. Strickle, 'Nylon Gears', Konstruktion, Vol.3, No.18, pp81-94, 1966.
[5] R. Gauvin, P. Girad and H. Yelle, 'Investigation of the Running Temperature on Plastic/Steel Gear Pairs', ASME Paper, 80-C2/DET-108, 1980.
[6] N. Tsukamoto, 'Investigation about Load Capacity of Nylon Gears', JSME, 27, No.229, 1984.
[7] E. Letzelter, M. Guingand, J. Vaujany and P. Schlosser, 'A new experimental approach for measuring thermal behaviour of nylon 6/6 gears', Polymer Testing, 29, pp1041–1051, 2010.
[8] M. Kurokawa, Y. Uchiyama, T. Iwai and S. Nagai, 'Performance of plastic gear made of carbon fiber reinforced polyamide 12', Wear, 254, pp468-473, 2003.
[9] Senthilvelan S and Gnanamoorthy R. Wear characteristics of injection-moulded unfilled and glass-filled nylon 6 spur gears. Proc IMechE, Part J: J Engineering Tribology 2004; 218: 495–502.
[10] Senthilvelan S and Gnanamoorthy R. Fiber reinforcement in injection molded nylon 6/6 spur gears. ApplCompos Mater 2006; 13: 237–248.
[11] K. Friedrich, Z. Zhang, A K. Schlarb, 'Effects of various fillers on the sliding wear of polymer composites', Composites Science and Technology 65 (2005) 2329–2343
[12] N.A. Wright1, S.N. Kukureka, 'Wear testing and measurement techniques for polymer composite gears', pp1567–1578, Wear, 2001.
[13] K D Dearn, T J Hoskins, L Andrei et al. 'Lubrication regimes in high-performance polymer spur gears'. Advanced Tribology, pp 1-9, 2013.
[14] Ir. HGH van Melick and HK van Dijik, 'High temperature testing of Stanyl plastic gears: a comparison with tensile fatigue data', Gear Technology, pp59-65, April 2010.
[15] R. Ramakrishnan, 'An investigation on the injection moulding process and performance of polymer/polymer composite gears', MSc thesis, University of Warwick, 2016
[16] R. Ramakrishnan and K. Mao, 'Minimization of Shrinkage in Injection Moulding Process of Acetal 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] Z. Hu and K. Mao, 'An investigation of misalignment effects on the performance of POM gears', Tribology International, 116, pp 394-402, 2017.
[18] W. Li, A. K. Wood, R. Weidig and K. Mao, 'An Investigation on the Wear Behaviour of Dissimilar Polymer Gear Engagements', Wear, Vol. 271, pp. 2176-2183, 2011.
[19] T. Vale, 'Material Integrity in Moulded Plastic Gears and its Dependence on Moulding Practices', Gear Technology, pp40-47, July, 2008.
[20] K. Friedrich, "Friction and wear of polymer composites (Composite Materials Series, 1)", Elservier Science Publications B V, 1986.