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The effects of cooling rate (mould temperature) on HDPE gears produced through injection moulding

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ABSTRACT

The effects of mould temperature (cooling temperature) on molten HDPE (Hostalen GC 7260) during manufacture, is evaluated in this paper. HDPE gears were produced at varying mould temperatures using Injection Moulding. Optimised injection values for melt temperature, injection volume, hold pressure, and hold time were obtained, and then held constant while the mould temperature was altered.

Analysis on how the mould temperature affected peak melting points and crystallinity were then carried out using differential scanning calorimetry (DSC). These revealed that crystallinity improved as the mould temperature was increased from 22 °C to 65 °C. Gears produced at similar cooling temperatures were then meshed on a gear test rig and run at 1000 rpm, using different torque loadings. Their wear rates, and modes of failure were then analysed, and comparisons were made to ascertain how the differing mould temperatures employed during the injection moulding manufacturing process affected their wear characteristics. Topographical analysis of worn gear teeth was performed using scanning electron microscopy (SEM). It was noted that gear tooth wear and failure was dependent on the mould temperature employed during the manufacturing process. Gears produced at 65 °C showed improved tooth surface wear resistance at lower loads (0.5 Nm and 1 Nm) compared to those produced at 22 °C, but were more likely to fail through tooth fracture at the pitch line due to excessive material removal. Gears produced at lower mould temperatures, on the other hand, exhibited better wear resistance for higher loads (3 Nm and 4 Nm), compared to those produced at higher mould temperatures, and were more likely to fail due to material flow. The results show a correlation between mould temperature, crystallinity, and gear performance. Based on wear rate responses of gears produced at differing mould temperatures to the application of varying torque loadings, a Mould Temperature to Torque Reference Chart for HDPE is presented.

1. Introduction

Polymers and polymer composite materials are emerging as viable front runner alternatives to metallic gears as they offer distinct advantages, such as good weight to strength ratios, the ability to run without external lubrication, less noise when running, and a lower coefficient of friction. Polymer gears undergo complex microstructural changes such as hysteresis, viscous flow, and elastic deformation which affect their performance capabilities to a greater extent compared to those of metallic gears. These differences mean that the failure of these gears differ to those made from metals. They have different characteristics to those made from metals, such as different coefficients of temperature, lower melting points, and lower impact handling capabilities [1].

The wear behaviour and performance of polymetric gears have been studied by several authors [2–7], but to date there has been little focus on understanding the link between the input parameters used during the manufacturing process, and their corresponding physical and performance characteristics. This approach seems peculiar to polymer gears, as metal gears tend to be tested and graded not only by their material type, but also according to their mode of manufacture [8,9]. Of particular importance during the manufacturing process for both metallic and polymetric gears, is the cooling temperature (mould temperature) of the molten material. Techniques such as quenching, annealing, or tempering, are used in metallic gear production to alter the cooling rate, which in turn alters the internal microstructure of the gear. The main objectives in altering the cooling rates in metals is to increase strength, hardness, toughness, machinability, ductility, and to improve elasticity [10]. Unlike in metals, the effects of cooling rates on polymer

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composites are not well understood and documented. The findings presented in this paper constitute an important contribution to the understanding of how input parameters employed in the manufacturing process influence their microstructural construct, and hence, the types and nature of polymer gear failures. These findings were obtained by firstly obtaining optimised input parameters. These parameters were held constant, while the cooling temperature was varied from 22 °C to 65 °C. Pairs of gears produced at the same cooling temperature were then meshed in a uniquely designed gear test rig [11], and differing torque loadings were applied.

Work done by previous researchers has shown that mould temperature (cooling temperature) has a direct influence on physical characteristics of polymer products. Cartledge et al. [12], carried out experimental investigations into the effects of thermal processing on microstructures of glass filled PA6 composites. Results showed that crystallinity increased as the cooling rate was increased from fast to slow. This observation was subsequently collaborated by the work done by Apichartpattanasiri et al. [13], who used different cooling rates of between 30 °C and 90 °C on discs made from PA66, and observed that different cooling rates produced different microstructural formations which led to differences in slip ratios when the discs were slid against each other. Russell et al. [14] carried out a number of studies on injection moulded PA66 discs, and found that an increase in mould temperature increased crystallinity and established a skin-core morphology which increased with mould temperature. This led to an increase in yield strength, but a reduction in toughness. The authors were able to show that the strain-rate within the crystals was responsible for the slight increase in yield strength, but for a significant decrease in toughness. This finding mirrors that of Woodward [15]. Zhuang et al. [16] showed that varying the mould temperature of PEEK during the injection moulding process produced glassy or crystalline parts. In general, cold moulds produce glossy parts, and hot moulds, crystalline parts. Further work carried out by Speke [17] noted that mould temperatures had profound effects on the final properties of different polymers. In amorphous polymers such as acrylonitrile butadiene styrene (ABS), and polycarbonate, higher mould temperatures produced lower levels of moulded-in stress, and consequently better impact resistance, stress-crack resistance, and fatigue performance. Additionally, Speke found that in semi-crystalline materials, the mould temperature was an important factor in determining the degree of crystallinity in the polymer. The degree of crystallinity governs many performance parameters, including creep resistance, fatigue resistance, wear resistance, and dimensional stability at elevated temperatures. The work done by Gupta et al. [18] is of particular importance to this research, as it concluded that contact stress produced in mating gears is one of the most important factors which needs to be considered in gear design. The conclusions reached by the previously highlighted studies were based on rolling discs, where the interactions between surfaces have extended contact areas (conformal contact). In this case, the wear is almost solely caused by friction as the discs slip against each other. However, the interaction between mating gear surfaces is made nominally at a point (tooth), or along a line (non-conformal contact). In this case, Hackmann et al. [19] stated that tooth wear occurs through fatigue (caused by the cyclic flexing of teeth as they come into contact with each other), cracking at the root or pitch circle (mainly as result of impact forces), or through friction. This leads to differences in wear and performance of rolling discs and meshing gears. Consequently, results obtained through conformal tests should not be taken as representative of non-conformal tests.

2. Materials and experimentation

2.1. Materials and equipment

The polymer used is High density polyethylene (HDPE), with a commercial name of Hostalen GC 7260. It is an unfilled, semi-crystalline thermoplastic polymer made from the ethylene monomer, and is widely used in applications such as bottles, containers, water pipes, and a variety of consumer goods. It has a melting temperature of 180 °C, a density of 0.9 g/cm^3, and a melt volume-flow rate of 23 g/10 mins at 190 °C/5 kg.

Table 1
Properties of different polymer materials [2].

	HDPE	PC	POM	PA46	PEEK650
Specific density (g/cm^3)	0.96	1.20	1.42	1.18	1.3
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 (°C)	131	155	178	295	343

Fig. 1. Engel Victory 60T injection moulding machine.

Although polyamides and polyacetals are widely used in gearing applications, other semi-crystalline materials such as polyether ether ketone (PEEK), and high-density polyethylene (HDPE), have shown good surface wear resistance when operating below certain critical loads [2]. HDPE has a relatively low tensile strength, flexural modulus, and melting temperature compared to other semi-crystalline materials, as shown in Table 1, but is advantageous to use in low load applications (below 4.6 Nm), due to its low coefficient of friction and low specific density. The low coefficient of friction property of HDPE gears enables them to have high cycles to failure, while their low specific density gives them a distinct weight to surface wear rate advantage.

The ability for HDPE to be easily recyclable is another important factor as to why it was selected for this study. According to a test carried out by ESE World B.V (Maastricht, Netherlands) [35], HDPE can be recycled up to ten times without adversely altering the material properties. This means gears made from HDPE can be recycled many times, thereby increasing the availability of the material and at the same time reducing waste to the environment.

Despite these advantages, HDPE is not widely used in gearing applications, due in part, to the lack of published research data relating to performance under different environments and load settings. As such, there is hardly any design guidance for those wanting to use these gears.

It was important to use an unfilled polymer as all materials have different responses to variations in temperature, which are dependent on factors such as molecular weight, density, and moisture content. Polymer composites are made up of reinforcement materials, fillers, and other bonding compounds, which have a direct influence on gear characteristics. An investigation into temperature response to a composite material would reveal an aggregate response to all materials within the compound, whereas an unfilled polymer enables a single material response to mould temperature variation to be analysed, thereby giving an accurate determination of how a particular polymer grade is affected by such changes.

The gears were produced using an Engel Victory 60T machine, Fig. 1.

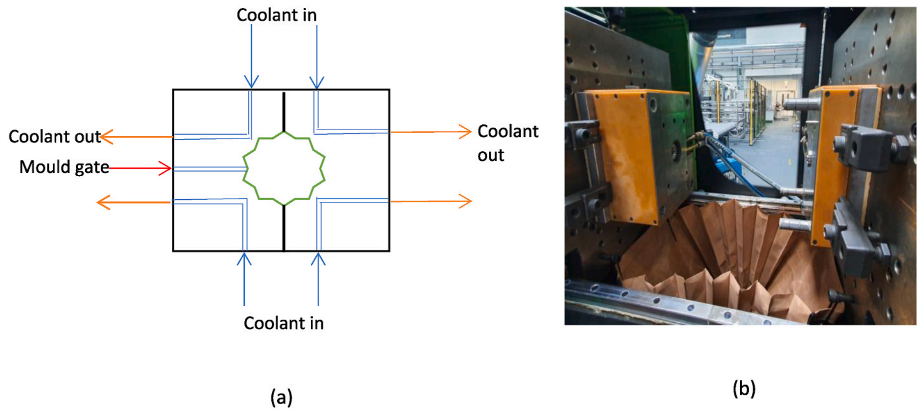

Fig. 2. (a) CAD schematic of the mould design
(b) Angel 60T mould tool in open position.

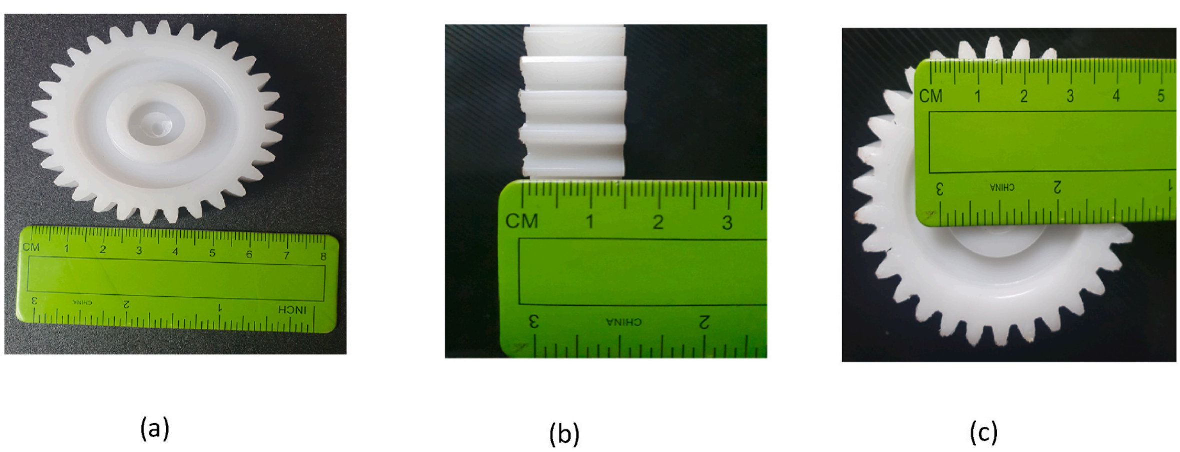

Fig. 3. (a) HDPE gear
(b) Tooth width
(c) Tooth thickness.

It has a maximum clamping force of 60T, a 30 mm screw diameter, and a maximum nozzle continuous pressure of 4T.

2.2. *Gear mould design*

The gear mould used in this experiment is of a 2-half-split design, with a centre gate in one half, through which the melt is injected into the mould, Fig. 2(a). Both halves are cooled by a coolant supplied by external chillers. The gate through which the melt is ejected is centred, and this ensures that the injected melt flows uniformly in all directions of the mould, while allowing good heat transfer to control the cooling process. Uniform flow helps eliminate the influence of differences in material density along the gear. If such differences in density were not mitigated, the characteristics of the produced gears would be affected.

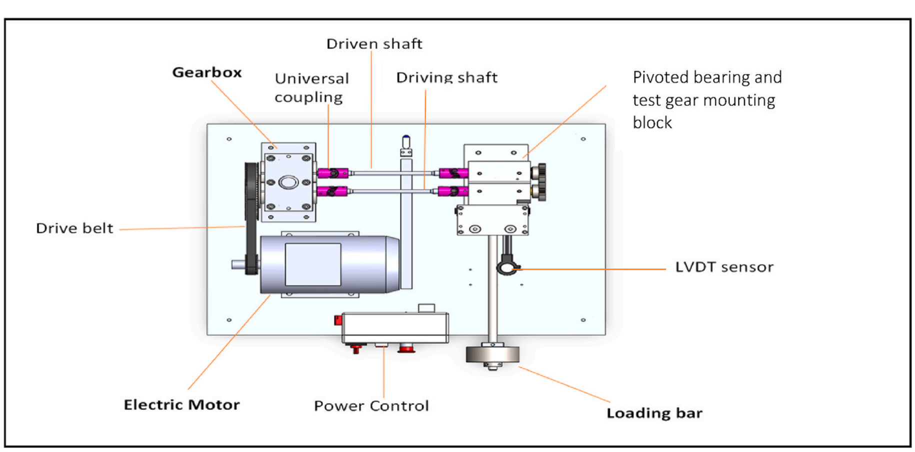

Fig. 4. CAD representation of gear test rig.

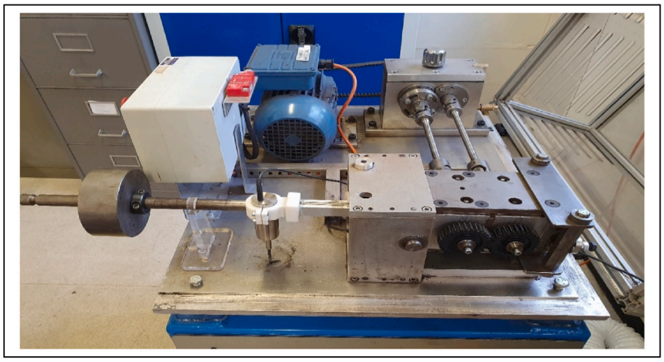

Fig. 5. Non-metallic gear test rig.

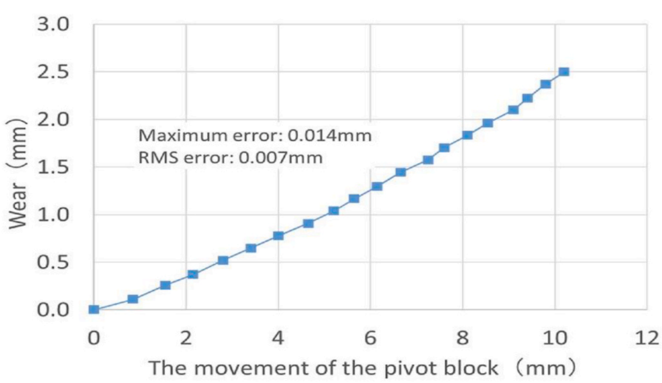

Fig. 6. Movement of the pivot block in response to wear [11].

The other half of the mould constitutes the clamping half. It has 6 ejector pins, which protrude and force the formed gear off the mould, once the mould is retracted, Fig. 2(b).

The mould cavity specifications represent those of the produced gear, and are shown inTable 2. Fig. 3 shows the actual injection moulded HDPE gears.

2.3. *Gear test rig and data logging system*

The gears were tested on a gear test rig with a unique design that allows the application of a load which exacts a continuous torque on meshed gears. The full details of the design have been covered elsewhere [11], and so a brief description is given here. The schematics of the test rig is shown in Fig. 4, and the actual rig is shown in Fig. 5.

The design of the test rig is modelled on a back-to-back, 'four-square' design. It consists of an electric driving motor, gearbox, a pivoted bearing and test gear mounting block, and a loading bar. The loading arm is attached to the block at the pivot arm, and a dead-weight load can be placed along its length. As the gear teeth wear, the arm rotates from the initial equilibrium position, while maintaining a constant torque on the tested gears. Fig. 6 shows movement of the pivot block as wear occurs.

A Linear Vertical Displacement Transformer (LVDT) translates the linear displacement of the loading arm due to wear as an electric signal. This signal is interpreted by LabView software. A flowchart of this arrangement is shown in Fig. 7.

An important characteristic of this new test rig is that the load is not affected by the rotation of the arm as the gears wear. This load stability gives an accurate load to wear rate for the tested gears.

The gears were tested for wear using torque loadings of 0.5 Nm, 1 Nm, 2 Nm, 3 Nm, and 4 Nm, at 1000 rpm. The tests were conducted at a room temperature of 21 °C, and no external gear cooling was employed. Gear failure is defined when there is a big and sudden recording of displacement as the meshed gear teeth jump from their running positions. The gears were run unlubricated to obtain accurate wear characteristics of unfilled HDPE. Several studies [2,5,12,30] have shown that gear surface temperature play an important role in polymer gear wear and failure, and so no external temperature control was used in order to obtain unmitigated response to surface temperature rises associated with friction and hysteresis. These gear surface temperature increases were not measured.

2.4. *Injection moulding process*

To isolate cooling temperatures as the only factor to be varied, all other input values needed to be optimised so that they did not become 'noise', and skew the results. The Taguchi design of experiment [20], was used to obtain optimum values for the melt temperature (A), injection volume (B), hold pressure (C), and the hold time (D). For all other input parameters, the median values of those given in the material datasheet were used, [21]. Each input range is classified as low (representing the lowest value), medium, or high. This makes the experiment a 4-factor, 3-level experiment, as shown in Table 2. Accordingly, a L_{27} orthogonal array (OA) was selected for the experiment, Table 3.

Table 2
Gear mould specifications.

Module (mm)	2
Tooth number	30
Pressure angle ()	20
Tooth face width (mm)	15
Tooth Thickness (mm)	3.14
Contact ratio	1.67

Table 3
Variable factor level.

Factors	Level 1	Level 2	Level 3
Melt temperature, A (°C)	180	200	220
Injection volume, B (cm^3)	38	40	42
Hold pressure, C (MPa)	70	80	90
Hold time, D (s)	5	10	15

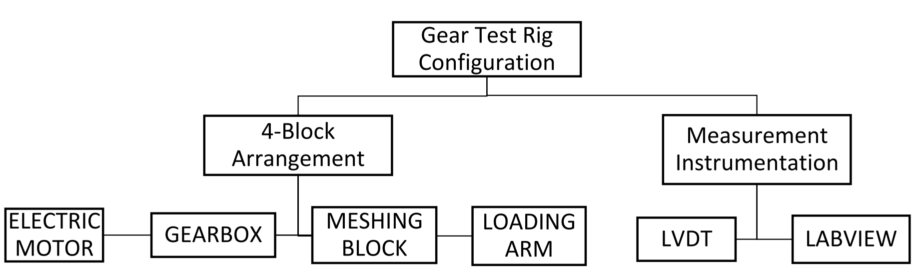

Fig. 7. Gear test rig configuration.

Table 4
Change in Diameter values and S/N ratios for HDPE.

Experiment #	Melt temperature (A)	Injection volume (B)	Hold Pressure (C)	Hold time (D)	Change in Diameter (%)	S/N Ratio (dB)
1	180	38	70	15	2.812	−8.980
2	180	40	80	30	1.995	−5.999
3	180	42	90	45	1.715	−4.685
4	180	38	70	30	2.574	−8.212
5	180	40	80	45	2.383	−7.542
6	180	42	90	15	2.193	−6.821
7	180	38	70	45	2.574	−8.212
8	180	40	80	15	2.24	−7.005
9	180	42	90	30	1.906	−5.602
10	200	40	90	15	2.05	−6.235
11	200	42	70	30	2.478	−7.882
12	200	38	80	45	2.097	−6.432
13	200	40	90	30	1.668	−4.444
14	200	42	70	45	2.002	−6.029
15	200	38	80	15	2.144	−6.624
16	200	40	90	45	1.621	−4.196
17	200	42	70	15	2.765	−8.834
18	200	38	80	30	2.478	−7.882
19	220	42	80	15	1.906	−5.602
20	220	38	90	30	2.002	−6.029
21	220	40	70	45	1.859	−5.386
22	220	42	80	30	1.906	−5.602
23	220	38	90	45	1.525	−3.665
24	220	40	70	15	2.383	−7.542
25	220	42	80	45	1.763	−4.925
26	220	38	90	15	2.002	−6.029
27	220	40	70	30	2.29	−7.197

Table 5
S/N ratio response for HDPE.

	Melt temperature	Injection volume	Hold pressure	Hold time
Level 1	−7.006	−6.896	−7.586	−6.821
Level 2	−6.506	−6.172	−6.401	−7.075
Level 3	−5.775	−6.220	−5.301	−6.539
Difference	−1.231	−0.724	−2.285	−0.536

$$S \Big/ N = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right] \quad (1)$$

For each experimental run, the diameter of each gear was measured using a digital veneer calliper, and the average diameter (D_m) for that temperature group was then calculated. The average mass (M_x) was also measured.

3. Results and discussion

3.1. Injection moulded HDPE gears

The rationale of having a design of experiment (DoE), is to have a systematic method of determining the relationship between factors affecting a process and the output of that process. As each factor is varied, the gear specification will deviate from the target value, as defined by the gear mould. The smaller this deviation is, the better the quality of gear. The S/N ratio was used in this study as an indication of quality. Table 4 represents the response to each input factor.

Table 5 shows the S/N for the different levels. The highest S/N represents the optimum process conditions, and these are: melt temperature of 220 °C, injection volume of 40 cm^3, hold pressure 80 MPa, and hold time of 45 s.

3.2. DSC analysis

Differential scanning calorimetry (DSC) was carried using a Mettler Toledo HP DSC 1 machine (Mettler-Toledo Ltd, Leicester, UK), which uses STARe software, Fig. 8. Samples of between 4 and 6 g were removed from gear teeth surfaces.

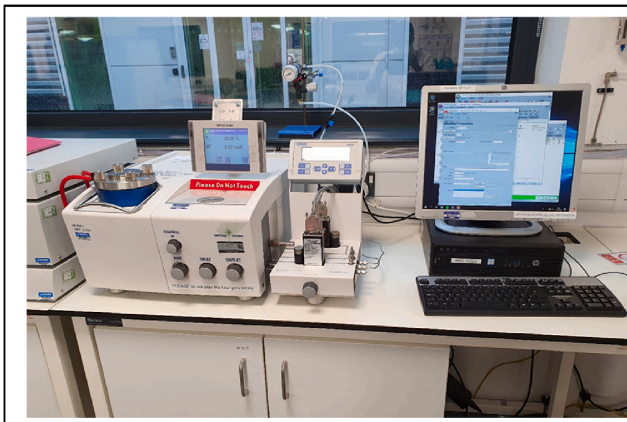

Fig. 8. Mettler toledo HP DSC 1.

To simplify crystallinity calculations, the DSC analysis of gear samples produced at different mould temperatures focused on the shift in the peak melting points. This was based on the fact that a higher crystalline formation of the same amorphous or semi-crystalline material results in a higher melting temperature, as shown by the work done by Ronkay et al. [22]. The exact crystallisation percentages were therefore not calculated, but a higher temperature was taken as an indication of higher crystallinity. A comparison of all temperature group thermograms are shown in Fig. 9.

Results presented in Fig. 9 show that 22 °C mould temperature produced gears had a melting peak of 136.1 °C. This melting temperature increased to 140.7 °C for 34 °C produced gears, 142 °C for the 50 °C group, and 143 °C for the 65 °C gears. The increase in melting points indicate increases in crystallinity as the mould temperatures increased.

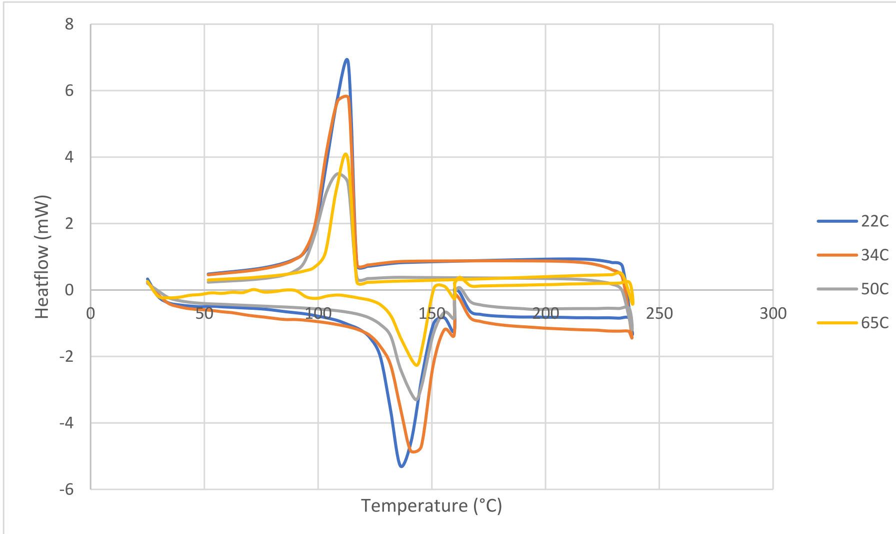

Fig. 9. DSC thermograms for different mould temperatures.

3.3. Wear rate analysis

Meshed gear pairs were subjected to lifetime tests. Lifetime tests, as opposed to step-load tests, were used as these provide more accurate data. Once the load and speed are set, there is no external interference with the test. This allows the tested gears to follow a natural wear path for the set load. The loss of material per minute represents the rate of wear. Various researchers [23–28] have put forward alternative mathematical formulae and methodologies for calculating wear rates.

According to VDI 2736 [29], linear wear characterisation of gear teeth can be expressed as in equation (2).

$$W_m = \frac{T.2.\pi.N_L.H_V.K}{b.z.F} \quad (2)$$

where:

T is the applied torque, N_L is the gear working cycle, H_V is degree of tooth loss, K is the wear coefficient of a polymer/steel gear pairing, b is gear tooth width, z is the number of gear teeth, and F is the meshing length.

The use of the wear coefficient, K, in equation (2) made its use in this presented work inappropriate due to two reasons.

1. It is based on a polymer/steel gear pairing. This is not the case in this study. The work done by Mao et al. [30], and Wood [8], established that gear pairing has a significant bearing on the wear rate.
2. The wear rates of polymer discs have been shown to greatly vary according to the cooling rates employed during the production process [12,13,16,31,32].

It would therefore be more appropriate to use another novel way of calculating both the wear rate and wear coefficient directly from experimental data, without employing equation (2).

Wear rates can be expressed in two main ways: as a function of time (mm/min); or as a function of cycles (mm/cycle).

$$\text{Wear rate (mm / min)} = \frac{\textit{Change in height (wear)}}{\textit{Time taken} \text{ (min)}} \quad (3)$$

$$\text{Wear rate (mm / cycle)} = \frac{\textit{Change in height (wear)}}{\textit{Number of cycles} \text{ (cycles)}} \quad (4)$$

The methodology used to measure wear in this study is based on equation (4), and is proposed in the work done by Mao et al. [11]. It involves meshing gears and applying a constant load on a pivoted arm, as described in section 2.2.

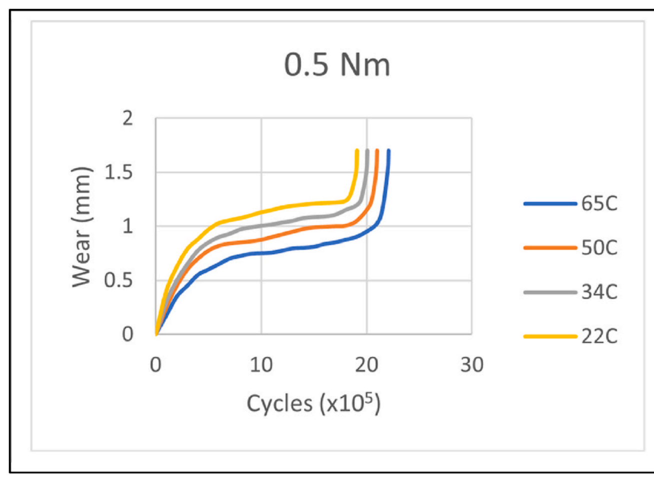

Fig. 10. 0.5 Nm wear curve comparisons for different mould temperatures at 1000 rpm.

3.4. Wear of HDPE gears

3.4.1. Wear curves

As meshed gears wear, the signal from the LDVT sensor is used to plot a wear curve against the number of cycles. Each curve is unique and is dependent on torque applied, and on the mould temperature employed during the injection moulding stage.

Taking into account the geometry of the tested HDPE gears, complete failure of the meshed gears corresponded to a maximum displacement of 1.5 mm of the loaded arm.

The different phases of running-in, linear or steady, and final rapid wear, identified by previous researchers [27,33] are clearly visible on most curves. Some wear curves also display a transition wear phase.

3.4.1.1. 0.5 Nm torque loading at 1000 rpm. As shown in Fig. 10, at 0.5 Nm loading, lower mould temperatures produce higher wear rates. As the mould temperature increase, the wear rates decrease. Based on this observation, wear performance is a direct response to the level of crystallinity of the gears at this torque loading.

The lower mould temperatures cause lower crystallinity as revealed

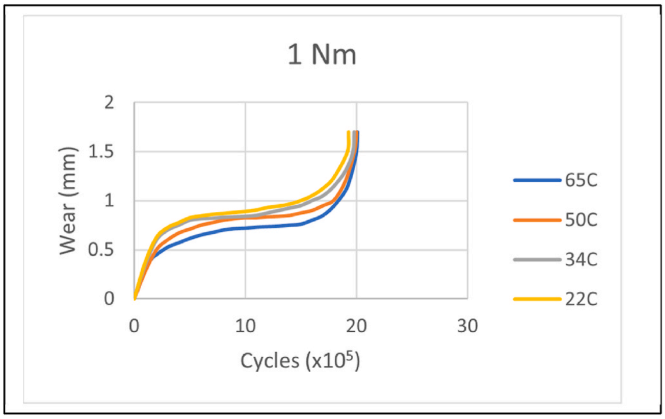

Fig. 11. 1 Nm wear curve comparisons for different mould temperatures at 1000 rpm.

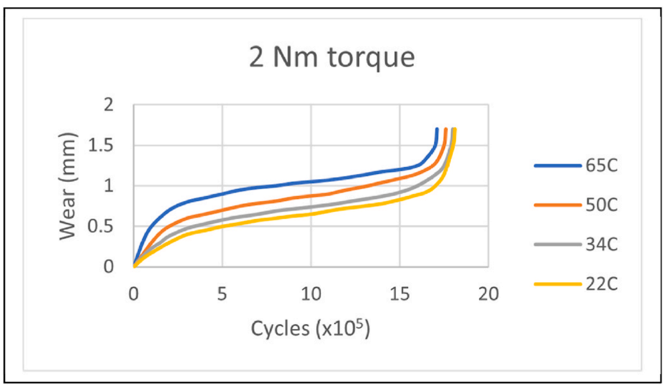

Fig. 12. 2 Nm wear curve comparisons for different mould temperatures at 1000 rpm.

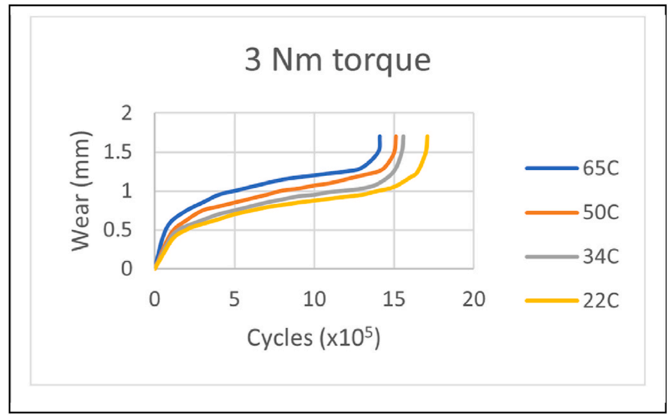

Fig. 13. 3 Nm wear curve comparisons for different mould temperatures at 1000 rpm.

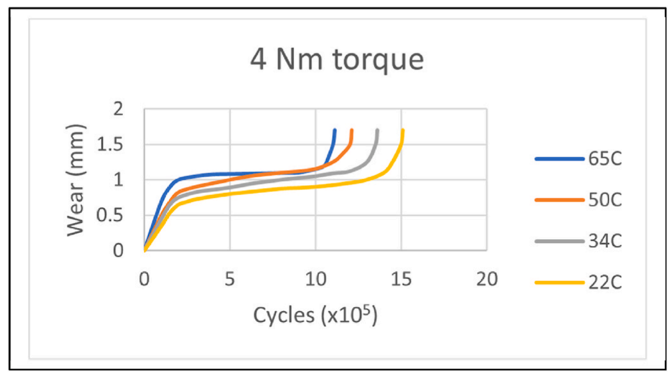

Fig. 14. 4 Nm wear curve comparisons for different mould temperatures at 1000 rpm.

by the thermograms presented in Fig. 9. This results in tooth flank flexing as the driving and driven gears come into mesh. This flexing causes the build-up of heat as a result of hysteresis and frictional forces. The wear curves show that a transition, instead of a linear wear phase, is attained between the running-in and rapid wear phases, indicating elevated wear rates for all mould settings due to continual tooth surface temperature rises, as identified by Mao et al. [34]. Gears produced at 65 °C fail at 2.2×10^6 cycles, while those produced at 50 °C fail at 2.15 $\times\ 10^6$ cycles, those produced at 34 °C at 2.1×10^6, and those produced at 22 °C fail at 2×10^6.

3.4.1.2. 1 Nm torque loading at 1000 rpm. An increase in torque to 1 Nm produced distinct changes in the wear curves of all mould temperature settings compared to those of 0.5 Nm, as can be seen in Fig. 11.

The cycles to failure for the 65 °C temperature setting reduces from 2.2×10^6 to 2×10^6, while those for 50 °C decrease from 2.15 to 1.98 $\times\ 10^6$ cycles. The 34 °C gears show a decrease from 2.1×10^6 to 1.95×10^6 cycles, while those of 22 °C decrease from 2×10^6 to 1.92×10^6 cycles.

At this torque setting, there is very little difference in cycles to failure between the different mould temperature settings.

All three wear phases for the 22 °C and 34 °C gears show a similar trajectory. The 50 °C wear curve shares similarities with that of the 65 °C: they both have a transition phase before moving into a steady wear phase.

3.4.1.3. 2 Nm torque loading at 1000 rpm. An increase from 1 Nm to 2 Nm represents the most significant changes in the wear curves for all mould temperature settings, Fig. 12. The biggest variations are shown by the 22 °C and 65 °C curves. The cycles to failure for 65 °C decreases from 2×10^6 cycles to 1.7×10^6 cycles, signifying a 15% decrease, while those of 22 °C gears decrease from 1.92×10^6 to 1.82×10^6, signifying a 10% decrease. The 34 °C temperature setting gears decrease from 1.95 to 1.8×10^6 while those of 50 °C decrease from 1.98×10^6 to 1.75×10^6, representing a decrease of 7.7% and 11.6% respectively.

As the wear curve gradient is a measure of the average wear rate, the main changes in wear rates at 2 Nm are for those of 65 °C and 22 °C. The wear rate for 22 °C decreases, while those for 65 °C increase. This is an indication that the wear rate of HDPE gears is not only dependent on the level of crystallinity, but also on the torque loading imposed on the gears. It can be seen from these wear curves that there is a torque setting between 1 Nm and 2 Nm at which mould temperatures have no bearing on the wear performance of the gears. At this torque, the morphological formations imposed on HDPE gears by mould temperature, become insignificant to gear performance.

3.4.1.4. 3 Nm torque loading at 1000 rpm. The wear curves for all mould temperature settings continue to display a similar three wear phase pattern, with similar gradients during the running-in and transition stages, Fig. 13. While the 22 °C, 34 °C, and 50 °C curves continue to display rapid, but gradual gradients, that of the 65 °C is now displaying a much steeper and shorter duration, indicating a more accelerated wear rate than previously experienced in the lower torque loadings.

Of particular interest at this loading is the distinct separation of cycles to failure between the different mould settings. Gears produced at 65 °C failed at 1.4×10^6 cycles, while those produced at 22 °C failed at 1.7×10^6, which represents a 21% improvement on performance through the reduction of mould temperature from 65 °C to 22 °C.

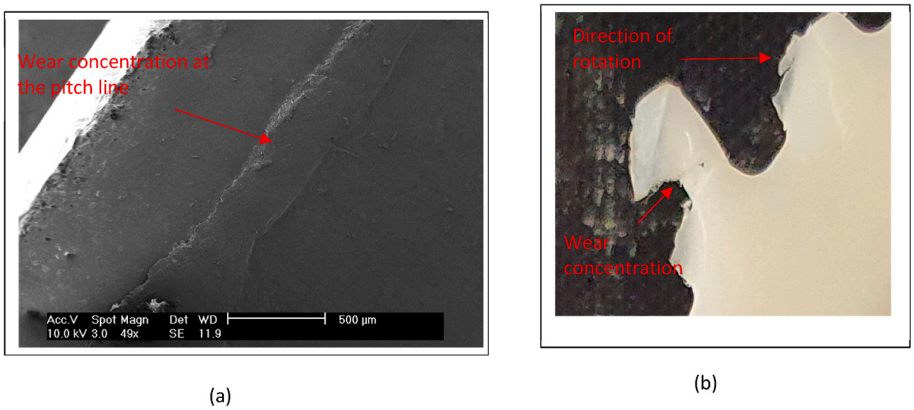

Fig. 15. (a) SEM image showing material removal starting at the pitch line for 65 °C produced gear.
(b) Physical appearance of gear teeth showing wear concentration at the pitch line.

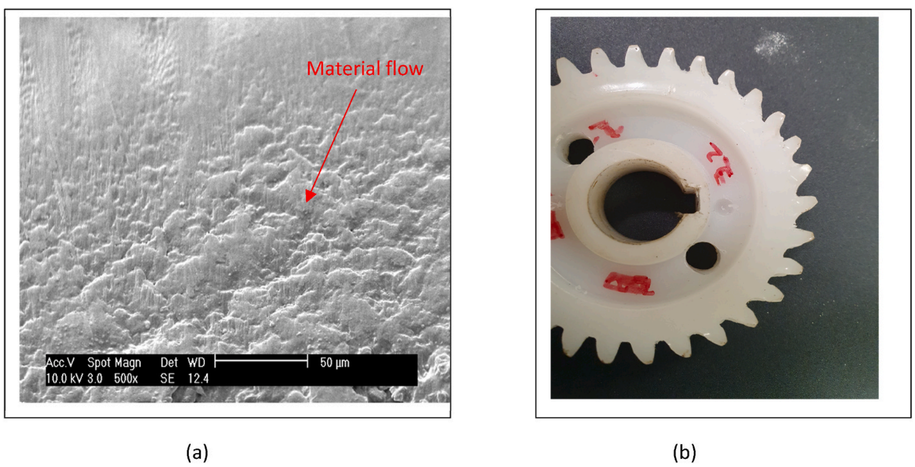

Fig. 16. (a) Wear caused by material flow for 22 °C produced gear.
(b) Physical appearance of gear teeth.

3.4.1.5. 4 Nm torque loading at 1000 rpm. At 4 Nm, the wear curves for the 22 °C, 34 °C, and 50 °C mould temperature setting show similar characteristics for all phases, Fig. 14. What is interesting at this torque setting, however, is that after the initial running-in phase, the wear curve gradients for the transition wear phases are much less than those seen at lower torques, indicating lower wear rates. The final rapid wear phase exhibit exponential wear, as seen at 3 Nm.

The 65 °C wear curve follows a unique path. The running-in phase duration lasts to around 0.2×10^6 cycles and is much steeper than at any other torque. Unlike the other wear curves, a state of linear wear is attained soon after. This lasts up to around 1.05×10^6 cycles. During this linear wear, the wear rate of the 65 °C gears and that of the 50 °C are equal between 0.75×10^6 cycles and 1.05×10^6 cycles.

During the last wear phase, 65 °C gears experience sudden failure as a result of tooth fracture at 1.1×10^6 cycles.

Failure for 50 °C gears occur at 1.2×10^6 cycles, for 34 °C gears at 1.34×10^6, and for 22 °C at 1.5×10^6.

3.4.2. SEM analysis of worn HDPE gears

To determine the mode of failure for the different mould temperature groups, scanning electron microscopy was conducted using a Mettler Toledo HP DSC 1 machine (Mettler-Toledo Ltd, Leicester, UK). The analysis revealed that there are differences between the wear mechanism for the different mould temperature groups.

3.4.2.1. 0.5 Nm mode of failure. SEM images for 65 °C produced gears show wear is concentrated at the pitch line, and is caused by the detachment of material, as shown in Fig. 15(a) and Fig. 15(b).

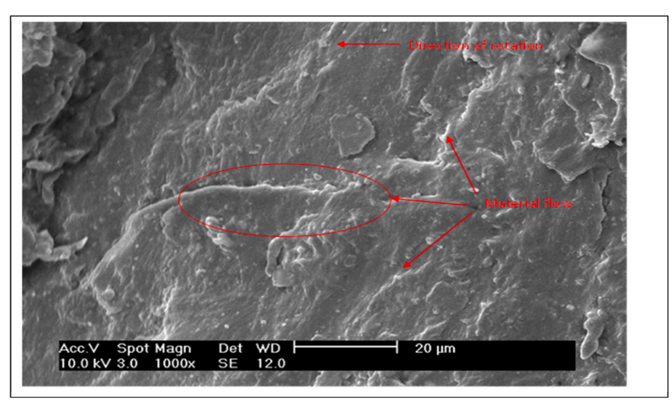

Fig. 17. Slight increase in material flow for 22 °C gears.

22 °C produced gears show wear as resulting from the gradual flow of material starting at the pitch line, as shown by the SEM image in Fig. 16 (a) and Fig. 16(b), at a resolution of 50x. Fig. 17 shows the same gear surface at 500x resolution.

3.4.2.2. 1 Nm mode of failure. SEM analysis shows a slight increase in material flow in the direction of rotation for the driven gear, and the

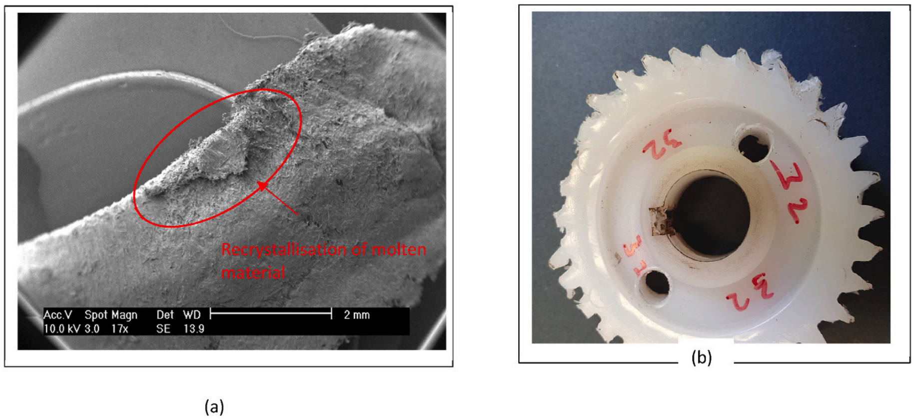

Fig. 18. (a) SEM image showing recrystallisation of molten material for a 22 °C produced gear.
(b) Physical appearance of gear showing broken teeth.

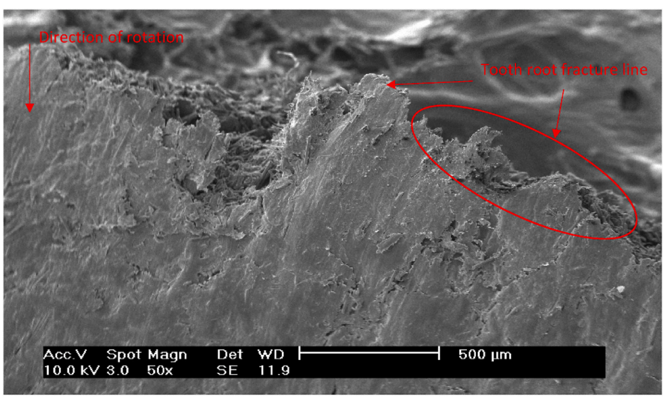

Fig. 19. 65 °C produced showing tooth fracture at root for driven gear.

Fig. 20. Fine debris produced by 65 °C produced gears at 0.5 Nm.

opposite direction of rotation for the driving gear, for the 22 °C mould setting. The 34 °C, 50 °C, and 65 °C gears do not show any significant changes in the wear mechanism in comparison to those of 0.5 Nm.

3.4.2.3. 4 Nm mode of failure. Topological examination of 22 °C produced gears showed less material flow than that seen at lower torques. This was not expected, as earlier increases in torque tended to increase

Fig. 21. Mixed debris produced by 65 °C produced gear at 4 Nm.

material flow. Upon further analysis, it was clear that there was significant recrystallisation of melted material, Fig. 18.

Higher mould temperature gear teeth show failure as result of material separation as the teeth fracture at the pitch line. Fig. 19.

Fig. 22. Coarse debris produced by 22 °C gears at 0.5 Nm.

Fig. 23. Coarse debris produced by 22 °C gears at 4 Nm.

Table 6
Cycles to failure according to cooling temperature.

Cooling Temperature	Load Nm	Cycles to failure @500 rpm (x10^6)	Cycles to failure @1000 rpm (x10^6)
22 °C	0.5	3.2	2.1
	1	3.0	2.0
	2	2.71	1.7
	3	2.5	1.4
	4	2.2	1.11
34 °C	0.5	3.1	2.15
	1	2.97	1.98
	2	2.75	1.75
	3	2.58	1.5
	4	2.3	1.2
50 °C	0.5	3.02	2.1
	1	2.91	1.75
	2	2.8	1.8
	3	2.7	1.57
	4	2.4	1.34
65 °C	0.5	3.0	2.0
	1	2.9	1.92
	2	2.89	1.82
	3	2.8	1.7
	4	2.7	1.5

3.4.3. Debris formation

As the gears wear, they produce material debris, which accumulates just below the running pair. It was observed that the rate at which debris accumulated at the base of the meshed gears, was dependent on the wear phase in which the gears were going through. More debris was produced during the running-in and rapid wear phases, than the linear or transition phases. Analysis of the debris showed a variation in debris size and texture. 65 °C gears produced two distinct debris types. At loadings of 0.5 Nm and 1 Nm, fine powdery debris was dominant, Fig. 20. 3 Nm and 4 Nm torque loadings produced less, but bigger debris. Broken gear teeth were also present, Fig. 21, and there was a consist shiny appearance regardless of torque loading.

The 22 °C produced gears produced coarser debris, which was dull in colour across the different loadings, Fig. 22, and Fig. 23.

3.4.4. Wear coefficient for different mould temperatures

Table 6 shows the cycles to failure for the different mould temperature gears for each torque setting.

Using Table 6, the wear coefficient for a torque loading for each mould temperature group can be calculated using equation (5), and Fig. 22 shows the differing wear coefficients.

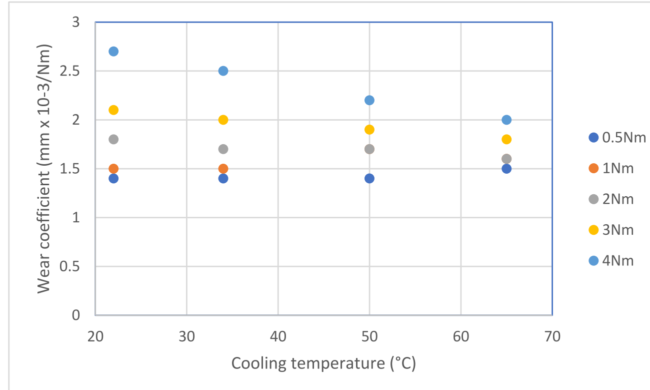

Fig. 24. Wear Coefficient at different mould temperatures.

$$\text{Wear coefficient} = \frac{\text{Wear}}{\text{number of cycles}} \quad (5)$$

Fig. 24 shows that each mould temperature group has its own unique response to different torque loadings. Based on these unique responses, a mould temperature to torque wear rate reference chart for HDPE is shown in Fig. 25.

From Fig. 25, it can be seen that.

- At 0.5 Nm and 1 Nm, the wear rates decrease as mould temperature is increased
- At 2 Nm, 3 Nm, and 4 Nm, the wear rates increase with mould temperature

The rate of increase of wear rates increases at greater rates each time there is an increase in torque loading beyond 1 Nm.

4. Conclusions

HDPE gears were produced using optimised input values for melt temperature, injection volume, hold pressure, and hold time. These values were then held constant while the mould temperature was varied. DSC, SEM, and gear wear tests results have shown a clear link between mould temperature, crystallinity, performance, and mode of failure. The data shows that the selection of mould temperature should be based on the torque loadings which the HDPE gears are to be subjected to. High mould temperatures are ideal for applications where low loads of below 1 Nm are to be experienced. Low mould temperatures are ideal for applications where loads of 2 Nm to 4 Nm are applied. Wear is concentrated at the pitch line, regardless of any other fact examined. This is due to contact fatigue as identified by Hackmann et al. [19]. Lower mould temperature produced gears, fail through tooth surface material flow. For the tested torque range, there were no tooth breakages observed for the 22 °C, 34 °C, and 50 °C gears. The debris produced tended to be bigger in size, but less in amount. It also had a dull appearance.

Gears produced at 65 °C mould temperature failed through tooth surface wear at lower torque loadings. The driving gear tooth flank tips were rounded, while those of the driven gear were more pointed. The debris produced had a very fine texture, and was shiny in appearance. At 3 Nm and 4 Nm, failure was through tooth fracture at the pitch line.

While the findings of this study agree with the work of Apichartpattanasiri et al. [13], and Russel et al. [14], who both carried out investigations into mould temperature effects on PA66, it seems to contradict the conclusions of Speke [17], whose work on amorphous polymers such as acrylonitrile butadiene styrene (ABS) and polycarbonate, found that higher mould temperatures produced better impact resistance and fatigue performance as a result of lower moulded-in stress. The most likely explanation to this apparent

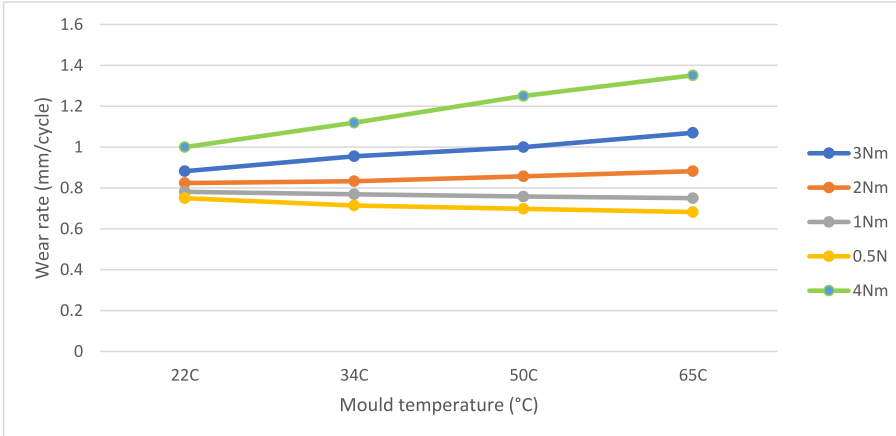

Fig. 25. Mould temperature to torque reference chart for HDPE

difference is the fact that Speke used high mould temperatures in combination with lower melt temperatures. The optimisation process during the injection moulding process of HDPE conducted in this study identified a high melt temperature in conjunction with a high mould temperature.

The higher cycles to failure at low torques shown by HDPE gears produced at higher mould temperatures indicate good wear resistance as a result of higher crystallisation rates. This performance advantage is lost at higher torques, where the higher mould-in stresses and brittleness identified by Speke come into play.

Based on these results, a Mould Temperature to Torque Reference Chart for HDPE was developed. This reference chart is of great importance to both gear manufacturers and those who match gear qualities with application use.

5. Future work

The production of HDPE gears using injection moulding and the subsequent changes in performance has revealed some interesting new data and understanding of the link between manufacture and performance. This information is important as the focus on more energy efficient gearing increases in efforts to reduce the carbon footprint. However, there's still a lot more work to be done to gain an even greater depth of understanding. This requires time, finance, and more focus. The authors intend to carry out further studies on composite polymer materials.

Authorship statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they haveparticipated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the Hong Kong Journal of Occupational Therapy. Authorship contributions Please indicate the specific contributions made by each author (list the authors' initials followed by their surnames, e.g., Y.L. Cheung). The name of each author must appear at least once in each of the three categories below.

Category 1Conception and design of study: P Zengeya; K Mao; V Goodshipacquisition of data: P Zengeya; K Mao, V Goodshipanalysis and/or interpretation of data: P Zengeya; K Mao, V Goodship.

Category 2Drafting the manuscript: P Zengeya; K Mao, V Goodshiprevising the manuscript critically for important intellectual content: P Zengeya; K Mao, V Goodship.

Category 3 Approval of the version of the manuscript to be published (the names of all authors must be listed): P Zengeya; K Mao, V Goodship.

All persons who have made substantial contributions to the work reported in the manuscript (e.g., technical help, writing and editing assistance, general support), but who do not meet the criteria for authorship, are named in the Acknowledgements and have given us their written permission to be named. If we have not included an Acknowledgements, then that indicates that we have not received substantial contributions fromnon-authors. This statement is signed by all the authors (a photocopy of this form may be used if there are more than 10 authors).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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