A physical investigation of wear and thermal characteristics of 3D printed nylon spur gears.

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Abstract: The use of 3D printing to manufacture nylon polymer gears is evaluated in this paper. More specifically, Nylon spur gears were 3D printed using Nylon 618, Nylon 645, alloy 910 filaments, together with Onyx and Markforged nylon proprietary materials, with wear rate tests performed on a custom-built gear wear test rig. The results showed that Nylon 618 provided the best wear performance among the 5 different 3D printing materials tested. It is hypothesised that the different mechanical performance between nylon filaments was caused by differences in crystallinity and uniqueness of the Fused Deposition Modelling (FDM) process. SEM (Scanning Electron Microscopy) revealed dramatically different wear behaviour for the 3D printed gears when compared to literature reports of injection moulded gears. Monitoring with a thermal camera during wear tests was used to analyse the thermal performance of gears during wear tests and together with SEM was used to analyse gear failure mechanisms. The performance results showed that gears 3D printed using Nylon 618 actually performed better than injection moulded nylon 66 gears when low to medium torque was applied.

Keywords: 3D Printing; Nylon; Gears; Wear; Polymer Gears; FDM

1. Introduction

For particular applications such as automotive and aerospace engineering, polymer gears have unique advantages over metal gears, such as: low cost and weight; high efficiency; quietness of operation; functioning without external lubrication; etc. The characteristics of wear and thermal behaviour of injection moulded gears have previously been studied [1], however, additive manufacturing (AM) and 3D printing processes have become increasingly popular for production of polymer components. It is generally understood that 3D printing is cost effective if production volumes are below 1000 units in comparison with plastic injection moulding [2]. The technology has been applied in wide range of industries, including the automotive, aerospace, medical and architectural industries [3]. The nature of 3D printing means that the process is inherently linked to the materials used and each 3D printing technology has a subset of materials that it is compatible with. For Fused Deposition Modelling (FDM) for instance there are many different materials available on the market including polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), nylon and many others [4]. Due to the increased interest in 3D printing there is an increasing amount of research regarding the direct mechanical properties and thermal properties of 3D printed materials and their modification. Leigh et al [5] introduced a low-cost conductive composite material for 3D printing of electronic sensosr. Christ et al [6] increased the elastic strain of polyurethane through addition of multi wall carbon nanotubes. Blok, et al [7] claimed that adding continuous fibers could further increasing the tensile strength compared with carbon fibre nylon composites. Kalin et al. [8] Claimed that gear performance and durability could be affected by thermal properties with the result showing an increase in operating temperature could decreasing the life cycle of the gear. Hu and Mao. [9] investigated misalignment effects on acetal gears together with wear behaviour, with the results demonstrating that acetal gears were most sensitive to pitch misalignment.

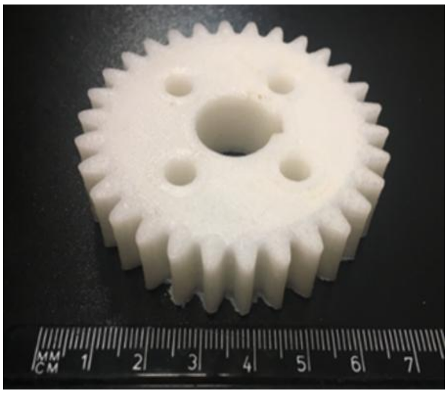
ABS FDM filaments have for instance been reinforced by Montmorillonite (OMMT) with the mechanical properties and thermal properties such as tensile stress, elastic modulus and thermal expansion increasing as the percentage of composite loading is increased, [10]. Torrado et al. [11] evaluated the mechanical properties of eight different ABS-based polymer matrix composite with different build orientations. The results showed the anisotropy in mechanical properties and variation in the mechanical properties across the range of different ABS materials. Moreover, ABS: UHMWPE: SEBSA composites showed a reduction in anisotropy. Gupta et al [12] introduced a numerical method to evaluate the mechanical properties of a carbon nanotube (CNT) reinforced PEEK matrix. Moreover, the reaction stress between the host polymer and carbon nanotubes was simulated, with the results stating that CNTs could directly affect the mechanical properties of PEEK. Singha et al [13], state the current issues in additive manufacturing with more focuss on the rigidity of 3D printed parts. There was also some further investigation regarding the increase in mechanical performance by adding carbon fibres into filaments and showing dramatic increases in rigidity [14, 15]. Tavcar et al. [16] investigated life time tests for several types of material and reinforced materials including Nylon, 6 Nylon 66, POM and PPS, with the results showing reinforced materials could survive more cycles if lubrication was applied.

In the above published studies, static forces applied to test samples can provide relatively accurate static mechanical properties, however other methods are required to evaluate more complex dynamic contact problems as might be encountered in components such as polymer gears. For 3D printed gears it is important to understand gear performance under set load conditions, their complex thermal mechanical behaviour their hyper elastic and visco elastic behaviour. Conventionally, polymer gears are produced using injection moulding but surprisingly to date there are have been very few studies published on the topic of 3D printing of polymer gears, perhaps due to mistrust or preconceptions about their potential mechanical performance. In this paper we report the manufacture of spur gears using a range of 3D printable nylon and nylon composite materials using FDM, characterise their performance under load and compare the results to gears produced using injection moulding.

2. METHODS and EXPERIMENTS.

2.1 Gear Design

The first stage in 3D printing of a polymer spur gear was to design the gear itself. The gear design selected was similar to the injection moulded gears used in a previous study [1]. The gear tooth face width was reduced by 2mm due to test rig specifications. The specifications of the final gear are given in figure 1.



(a)

Module	2mm
Tooth number	30
Pressure angle	20°
Face width	15mm
Nominal backlash	0.18mm
Tooth thickness	3.14mm
Contact ratio	1.65

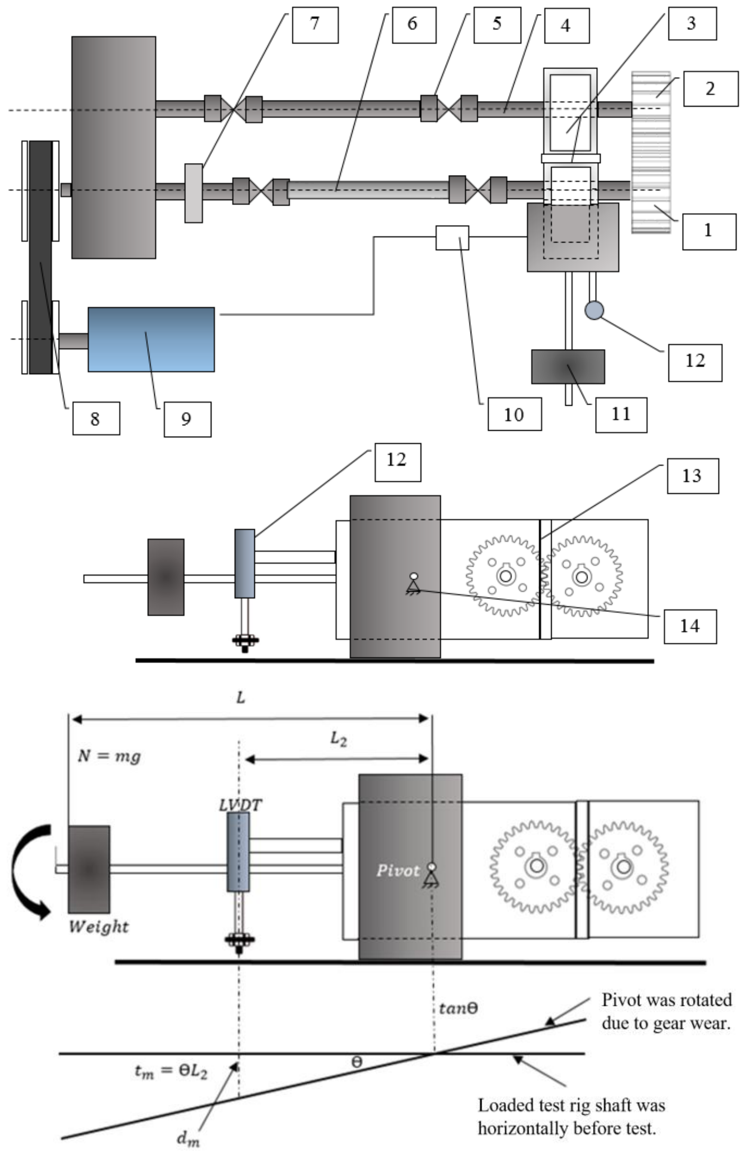
(b)

Figure.1. (a) 3D printed Nylon gear in simplified 3D, (b) specifications of gears.

Five different 3D printed nylon materials were tested and compared with injection moulded nylon gears including nylon 618, nylon 645, alloy 910, Onyx, and Markforged nylon. The different materials were printed using two different types of 3D printer. Nylon 618, Nylon 645 and Alloy 910 were printed using an Ultimaker 2 and the proprietary Onyx and Markforged nylons were printed using a Markforged X7 system. Gear inspection has carried out by KLINGENBERG ZPK 260 gear inspection machine, and the result showed the quality of the gear was DIN 12. All 3D printing parameters were set as default and printed with manufacturer recommended temperature and speed apart from infill percentage, which was set to 60% for both printer systems. Printer settings were matched between the Ultimaker 2 and Markforged systems where possible. Gear wear tests were conducted with a pair of 3D printed gears with the same geometry and printed using the same settings, with both the driven and driver gear manufactured in same material. Between and during printing, all materials were stored in a dry chamber.

2.2 Gear Testing Rig

The gear test rig is designed to test the gear wear whilst the gears are meshed and running. The specific details of the test rig have been published previously. 3D printed gears can be tested in much the same way as injection moulded gears, using a back to back test configuration where the gears are loaded by winding in the torque to a prescribed level [1]. The schematic of the test rig is presented in figure 2. In this instance torque was applied to the gear at the different levels of 5 Nm, 7 Nm, 10 Nm 12 Nm and 15 Nm. Gear fatigue tests were performed with nylon 618, nylon 645, alloy 910, Onyx, and Markforged nylon gears. The test rig motor drives the gears with externally applied torque. The reaction force between gear teeth is equivalent to the bearing block and loading arm. This loading method permitted large amounts of wear without significantly affecting the applied torque. In order to increase the sensitivity of the displacement sensor on the test rig, the displacement sensor was relocated from the pivot block to the weight to create a large reading of the displacement sensor. Gear failure was defined as when a large deformation was recorded by the test rig and the meshed gear tooth jumped out from its original running position.



Θ: Rotation angle of the pivot.

t_m: Signal of wear to being magnified

d_m: Displacement measured by LVDT (Linear Variable Differential Transformer)

L and L_2: Distance of pivot between LVDT and weight.

1. Driver gear	2. Driven gear	3. Pivot block assembly.	4. Driven shaft	5. Universal couplings.	6. Driving shaft	7. Conical clutch
8. Pulley	9. Motor	10. Motor controller	11. Weight	12. LVDT	13. Centre spacer	14. Pivot

Figure. 2. Schematic of test rig for polymer gears.

2.3 Gear surface temperature

There are three temperature components contributing to the gear surface temperature: the ambient, bulk and flash temperatures [1]. The ambient temperature was between 20 ℃ and 30 ℃ for the different tests. The bulk and flash temperatures were measured during running using a thermal camera. In order to check that the wear transition, thermal behaviour and mechanical behaviour actually corresponded to the maximum surface temperature during operation reaching the melting point of Nylon (approximately 256 ℃), a number of incremental tests were carried out at elevated surface temperatures.

An investigation into the gear surface temperature during wear tests was carried out, with the aim of investigating the gear surface temperature under different loading criteria. A FLIR E4 thermal camera was used and set 10 cm above the testing gears. Surface temperature tests were carried out on Nylon 618 and Onyx gears. The duration of each test was 15 minutes and in the first 10 seconds of each test, an image was captured every 2 seconds due to rapid temperature rise and after the first 10 seconds the thermal image captured every 10 seconds until surface temperature settled with a range stable range. The wear can be divided into three phases, a “running-in” period, a linear wear period and a final rapid wear period [1]. The linear wear period is most representative of the operational conditions and should reveal the operational temperature of a gear [17].

2.4. Differential Scanning Calorimetry (DSC) Analysis.

In order to understand the thermal behaviour of the nylon materials being used and assess if the thermal behaviour of 3D printed filament changed after printing, differential scanning calorimetry (DSC) was performed using a Mettler Toledo DSC 3. The results showed that materials had relatively stable thermal behaviour and high repeatability of heating and cooling after being printed. Due to relatively poor performance in wear tests, alloy 910 and Markforged Nylon were not included in the DSC test. Nylon 66 (as used in the literature study of injection moulded gears) was included in the tests as a comparison material. The other aim of DSC tests was to measure the glass transition temperature, crystallinity of the materials and enthalpy change during heating. Tests were performed with two cooling cycles and two heating cycles to analyse the repeatability of each heating and cooling cycle. The temperature range of the test was set at -150 °C to 320 °C, with a heating rate of 10.00 K/min. An initial test was carried out with a maximum temperature of 420°C, however, the materials decomposed after first heating cycle, and hence the heating temperature was limited to 320°C.

3. RESULTS AND DISCUSSION

3.1 Wear of 3D Printed Gears

During the test, a set of gears were produced in each of the material variants and tested to a maximum of 2.4 million cycles or until gear failure (whichever came first). If a gear survived for greater that 0.5 million cycles, another gear in the same material was tested at an increased load. When taken with the properties presented in Table 1, [1] [18-21], it is immediately evident that the moduli of the materials is not necessarily directly correlated with the performance of the resultant gear. For example, from a visual inspection it appeared that the majority of gear failures were due to the thermal bending of the gear teeth. Interestingly, a high proportion of the Nylon 618 gear failures appeared to be due to failure at the root of the gear teeth.

Table.1. material properties of five different materials provided by manufactures.

Material/ Properties	Nylon 66[1]	Nylon 618[18]	Nylon 645[19]	Alloy 910[20]	Onyx [21]	Markforged Nylon [21]
Specific gravity (g/cm^3)	1.41	N/A	N/A	N/A	1.18	1.10
Tensile strength (MPa)	62	31.5	35.7	55.8	36	31
Flexural modulus (MPa)	2600	152.9	212.7	502.8	2900	840
Glass transition temperature (℃)	51	48	52	82	N/A	N/A
Melting temperature (℃)	256	218	217	210	N/A	N/A

N/A: Data was not provided by manufacture

The results of the wear tests are presented in Table 2. The Nylon 66 results of the injection moulded gear performance test are from a literature report and nylon 618, nylon 645, Alloy 910, Markforged Nylon and Onyx values are resultant from the tests on the 3D printed gears. For the 3D printed gears, both Nylon 618 and Onyx gears were relatively stable below 10 Nm, however Onyx gears failed instantly after any load beyond 10 Nm due to dramatic thermal bending and wear. There were two regimes of debris observed, strip-like debris occurred after operation of Nylon 645, Alloy 910, Onyx and MF Nylon. Strip-like debris was also associated with relatively high operation noise and relatively high wear rate. Snowflake-like wear debris occurred in Nylon 618. The operation noise of Nylon 618 was significantly lower compared with the other 3D printed materials tested. As shown in table 2, several tests were undertaken on the gears. When a gear failed after less than 1 hour at 5 Nm torque no further tests were carried out, which was the case for MF nylon, nylon 645 and alloy 910. MF nylon gears operated for around 0.018 Million cycles, Nylon 645 gears operated for 0.014 Million cycles and Alloy 910 failed just after 0.0078 Million cycles. Perhaps most importantly, as a comparison, 3D printed Nylon 618 gears performed better than the literature values for an injection moulded Nylon 66 gears in the region below 10 Nm. Nylon 66 gave relatively better performance when torque was applied beyond 12 Nm. It is often incorrectly assumed that 3D printed parts have inferior performance when compared to conventionally produced counterparts, however this result showed that the 3D printed gear performed better than a ‘conventionally’ produced gear in this low to medium torque regime. In order to further understand the performance of Nylon 618 printed gears, further tests were carried out. The results of the wear tests are presented in Table 2

Table.2. Wear test rig results

Material/ Load	**Nylon 66** (Injection mould)[1]	**Nylon 618**	**Onyx**	**MF nylon**	**Nylon 645**	**Alloy 910**
5Nm	2.4 Million cycles	2.4 Million cycles	2.4 Million cycles	0.018 Million cycles	0.014 Million cycles	0.0078 Million cycles
7Nm	2.4 Million cycles	2.4 Million cycles	0.96 Million cycles	N/A*	N/A*	N/A*
10Nm	1 Million cycles	1.5 Million cycles	0.006 Million cycles	N/A*	N/A*	N/A*
12Nm	Tested 0.504 Million cycles	0.78 Million cycles	N/A*	N/A*	N/A*	N/A*
15Nm	0.08 Million cycles	0.012 Million cycles	N/A*	N/A*	N/A*	N/A*

3.2 Comparison of 3D Printed Nylon 618 Gears to Injection Moulded Nylon 66 Gears

The wear in a gear is defined as the material lost from gear tooth contact surface during gear operation. As detailed previously, the wear can be divided into three distinct phases, a “running-in” period, a linear wear period and a final rapid wear period. In the low torque stage, there was only a small amount of wear observed with minimal wear debris generated during both the running-in and linear wear stages. In the final rapid wear period, the wear rate increased dramatically and subsequently the appearance of debris was accompanied by a marked increase in operational noise. For the majority of the printed gears, the gear failure appeared to resultant from thermal bending. After gross wear (nearly 40% of tooth thickness), the gears failed in thermal bending and the teeth jumped out from meshing position. Notably, after the gear was left to cool, the teeth formed back to their original shape. For loads greater than 12 Nm there was no run-in period observed with gears going straight into a linear wear period. Large amounts of wear debris were recorded at the outset of gear operation at loads in excess of 12 Nm. The results obtained can be compared to literature results of injection moulded Nylon 66 gears, where under 5 and 7 Nm loads, the gears were operational for in-excess of 1.2 million cycles, however, wear increased from 0.2 mm to 0.5 with the same wear rate. Under 10 Nm load, the test duration of injection moulded gears was decreased to 0.9 million cycles. When the load applied was increased to 15 Nm, the gear survived up to 0.08 million cycles [1]. Hence, when compared to literature for injection moulded nylon gears, Nylon 618 3D printed gears provide better performance when load is applied below 12 Nm. Figure 3 shows the results of a wear test carried out on a pair of printed nylon 618 gears.

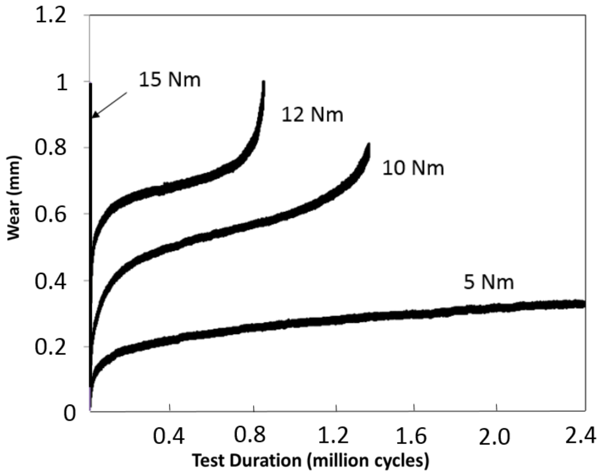
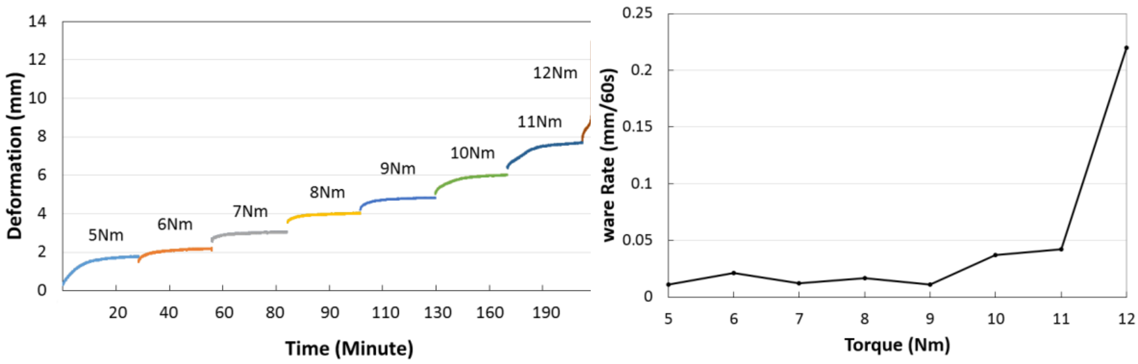


Figure.3. Result of Nylon 618 wear tests.

3.3 Wear rate analysis.

In order to ascertain the wear rate of 3D printed gears, a step load test was carried out. Nylon 618 gears were operated at 1000 rpm from 5 Nm and step load was increased by 1 Nm each step until the gear failure. The results are shown in figure 4 (a).



(a) (b)

Figure.4 (a) Step load test of Nylon 618 (b) Wear rate against load for nylon 618 gears.

The nylon 618 test results in figure 4 (a) can be used to calculate wear rate, where the wear rate represents the material loss against torque per minute. Where t_v is the wear of the gear tooth, $d_p$is the pitch circle diameter of test gears, α is the pressure angle of gear, d_m is reading from LVDT, $L_2$is the distance between pivot and load apply to the gear.

According to the Friedrich et al. [23], the wear volume V_w is:

$$V_w = kFs \tag{1}$$

Where is k is the specific wear rate, F the normal force, and s the sliding distance. If this equation is revised for tooth profiles, the specific wear rate for gear can be expressed as:

$$Qbd = k\frac{T}{r}d \times n \tag{2}$$

Rearrange equation:

$$k = \frac{Qbr}{Tn} \tag{3}$$

Where Q represents wear depth, b represents tooth face width, d is tooth depth, r is gear pitch circle radius and n is the number of cycles corresponding to the wear Q. Associated with the test of Nylon 618, at 5 Nm the wear rate was around 0.0113mm per 1 minute, and hence after calculating each step load test, the wear rate against torque was plotted as figure 4 (b).

As figure 4 (b) shows, the wear rate from 5 Nm to 9 Nm was very low. Each step load test was carried out for 30 minutes, hence, the operation time of each step load was not considered in this test. For loading above 9 Nm, the wear rate increased dramatically, believed to be mainly due to two factors: gear tooth bending force reaching the limitation of material yield stress, and gear failure due to thermal softening. As Lancaster et al. [24] described, when the gear surface temperature exceeds the material melting point, including ambient, bulk and flash temperatures, the wear rate will increase sharply. In order to fully characterise the wear behaviour of the 3D printed gears they were examined using microscopy.

3.4 Scanning Electron Microscopy (SEM) Analysis.

Injection moulded gears have previously been examined for signs of wear using SEM. In acetal and Nylon 6 gears, the material has been observed to be torn away at both sides of the pitch line. [25, 26] Notably however, in the 3D printed gears tested here, there appears to be more material torn away at the addendum of the tooth flank. This contrast to literature behaviour may due to higher tensile strength of Nylon 6 compared to Nylon 618 in the 3D printed gear. The lower tensile strength in the resultant gears potentially causes increased bending deformation of teeth causing a change in meshing position.

Figure 5 shows the failed tooth surface of nylon 618 3D printed gear. It is evident under x100 magnification that there is significant wear and bending at the addendum of the tooth, with that region of the tooth surface appearing to be melted. Moreover, SEM revealed that there was no material

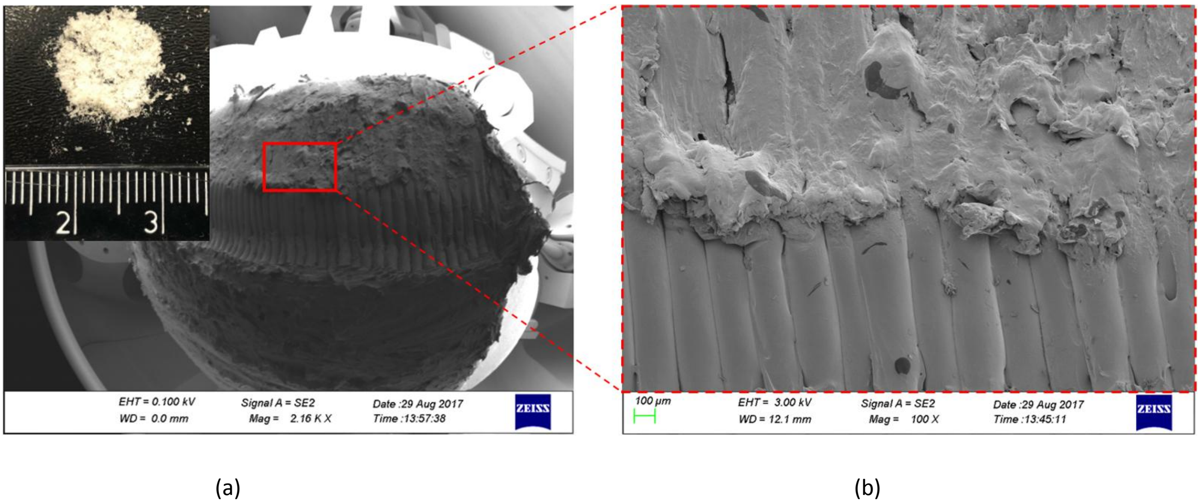
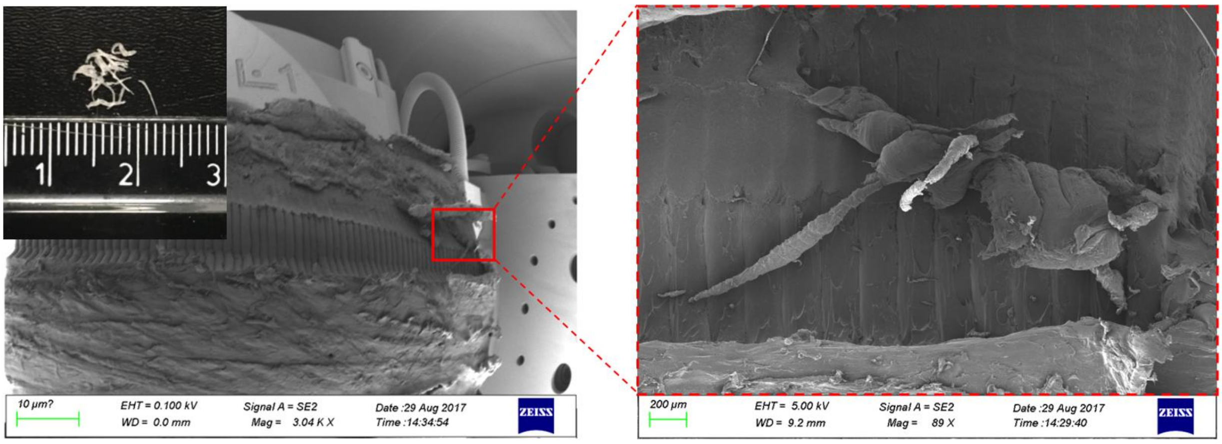


Figure.5 (a) Fish eye SEM image over view of failed 618 tooth surface and debris. (b) Surface wear debris (×100))

peeled off from the tooth (as might be expected with a 3D printed gear), showing there was strong bonding between each layer deposited during the 3D printing process. From visual inspection, the color of the printed material on the contact surface changed from white to yellow and the pitch line on the tooth face remained parallel to the addendum.

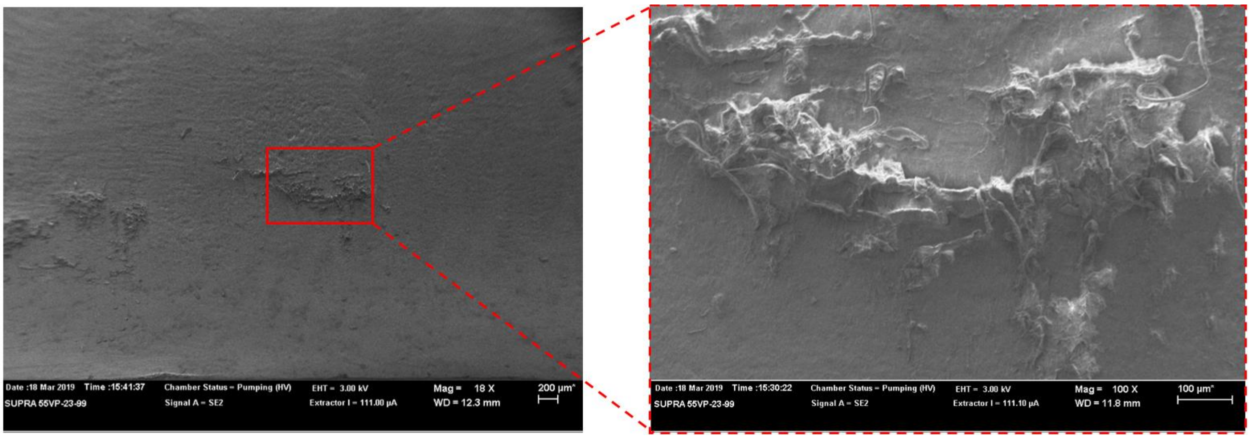
In order to draw a comparison between the Nylon 618 printed gears and one of the other printed gears, SEM was carried out on a Nylon 645 gear. As presented in figure 6, the SEM showed significant wear and bending at addendum of the tooth and the addendum part of the tooth surface appears to be melted. Moreover, the SEM also showed that material had peeled off from the tooth (Fig 6(b)), which shows there was relatively weak bonding between each layer during the 3D printing process. As with the Nylon 618, the colour of the material changed on the contact surface from white to yellow and the pitch line on the tooth face did not remain parallel to the addendum cycle (Fig 6 (a)).



(a) (b)

Figure 6. (a) Fish eye over view of failed 645 tooth surface and debris. (b) Gear surface wear debris (×100)

The results show dramatically different wear behaviour compared to injection molded gears. Examination of the tooth flank below the pitch line of the driver showed evidence of the material being torn away as the teeth roll against the direction of sliding and the tooth surface showed relatively low surface roughness with no material peeled off from tooth surface [9, 25].



(a) (b)

Figure 7. (a) Nylon 66 injection mould gear (x 18). (b) Gear surface wear debris of Nylon 66 injection mould gear (×100)

Moreover, as shown in figure 7, there is evidence of the onset of melting on the gear tooth surface, with the gear tooth shown relatively smoother compare with 3D printed gear. Several studies have mentioned that during FDM process, changes in temperature of the layer-by-layer polymer FDM process causes dramatically different cohesion strength of the layers and, the strength of the part.

Greater differences in temperature during printing will weaken the bonding between each layers hence, this is one of the reasons causing different wear behaviour of 3D printed gear [27].

Polymer sintering effects affecting bond formation between layers, as shown in figure.7 [28, 29]. Parameter y represents the ratio of half the width of sintered bond, and d relates to filament radius. Hence y/d represents the bond formation of filaments and temperature difference in each layer could significantly affect the sintering process during FDM process.

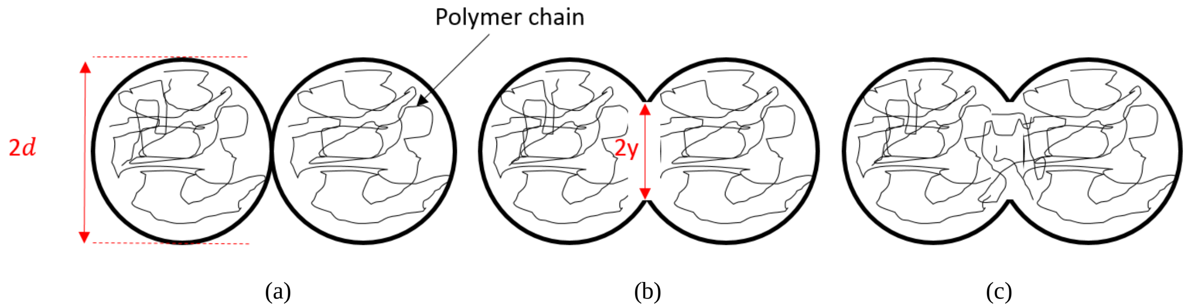


Figure 8. Process of polymer sintering between layers. (a) Represent filament instantaneously after deposition (b) Represent the neck growth, and (c) Represent sintering effect due to the movement of polymer chains.

This view of inter-layer bonding in 3D printed part (as shown in figure 8) could go some way to explain the difference formation in wear surface between Nylon 618 and Nylon 645, because nylon 618 has better polymer sintering behaviour compared with nylon 645 when printed using the manufacturers recommended parameters.

3.5 Differential Scanning Calorimetry (DSC) analysis.

In order to understand the thermal behaviour of the materials being used for 3D printing and assess if the thermal behaviour of 3D printed filament changed after printing, DSC was performed. DSC tests were carried out at three different stages, the first test was carried out before printing, the second test carried out after the nylon filaments were 3D printed and the third test carried out after the nylon gear step load test. It was found that the crystallinity of the filament before printing was slightly lower compared with the material after printing and material from gear tooth surface after testing. For example, the crystallinity of the Nylon 618 filament before printing was 43% and after printing was measured at 48%. Nylon 645 exhibited similar behaviour. Materials from a gear tooth surface after testing showed a crystallinity of 47.4%. DSC test results of glass transition temperatures and melting temperature showed that they remained relatively stable across the different stages with high repeatability of heating and cooling after being printed. Due to relatively poor performance in wear tests, alloy 910 and Markforged Nylon were not included in the DSC test. Nylon 66 (as used in the literature study of injection moulded gears) was included in the tests as a comparison material.

Tests were performed with two cooling cycles and two heating cycles to analyse the repeatability of each heating and cooling cycle. The temperature range of the test was set at -150 °C to 320 °C, with a heating rate of 10.00 K/min. An initial test was carried out with a maximum temperature of 420°C, however the materials decomposed after first heating cycle, and hence the heating temperature was limited to 320°C. As table 3 shows the DSC tests of the different materials. Crystallinity was calculated using standard method based on a constant standard ΔH=196 J/g [30].

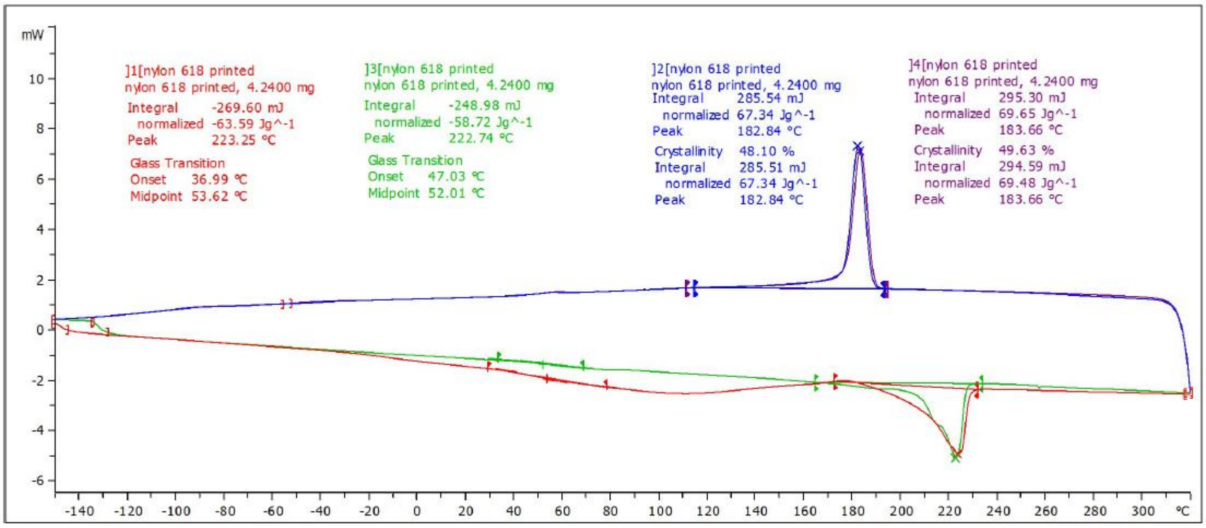


Figure 9. DSC test result of Nylon 66

As table 3 shows, the glass transition temperature of Nylon 66, Nylon 618, Onyx and Nylon 645, were measured as 54℃, 48℃, 47℃ and 43.5℃ respectively. The glass transition temperature of Nylon 618 was the same as the manufacturer's quoted value of 48℃. However, the test result of Nylon 645 was

Table.3.DSC test results

Measured Material / Thermal spec	Nylon 66	Nylon 618	Onyx	Nylon 645
Glass transition temperature	54°C	48°C	47°C	43°C
Melting temperature	260°C	225°C	200°C	210°C
Crystallinity	56%	48%	23%	31%
Normalised energy consumption	84J/g	60J/g	34J/g	45J/g

around 16% different to the value provided by manufacturer. The measured melting temperatures were similar compared with the data provided. However, pure Nylon 66 had a higher melting temperature than the manufacturer quoted value. The crystallinities of Nylon 66, Nylon 618, Onyx and Nylon 645 were 56.51%, 48%, 23.5%, and 31% respectively. Normalised energy consumption showed the energy consumed during the heating and cooling cycling.

Based on the result of DSC test, it is believed that in the dynamic contact scenario found in polymer gears, thermal behaviour of polymer affects the wear rate and hence the performance of the polymer gear. Santos et al. [31] established that higher crystallinity could increase elasticity when polymers are heated up beyond glass transition temperature. Moreover, higher crystallinity is coupled with stronger intermolecular forces which makes the polymer harder but more brittle but with amorphous regions within polymer providing plasticity and impact resistance [32].

From the test rig result, Nylon 618 filament had higher wear resistance compared with injection moulded gears at low applied torque. This may due to the unique process of the FDM, with the gear tooth extrusions following the path of the gear tooth [33]. Moreover, the 3D printing process could provide a benefit to molecular alignment in crystalline polymers such as Nylon [34]. Shear stress distributed during the printing process can potentially cause the polymer to be aligned in the plane of the printed layers [35]. Intramolecular bonding in 3D printing process often occurs as covalent bonding, which is stronger than van der Waals forces. Hence the mechanical properties could increase with suitable intramolecular bonding, which could further help explain why 3D printed gears can perform better than injection moulded gears in certain operating scenarios [36].

3.6 Gear tooth surface temperature.

The thermal performance of the Nylon 618 gears and Onyx gears is shown in figure 10 (c) and 10 (d) respectively via different torque at a constant rotational speed of 1000 rpm. The initial reading from the camera is plotted in doted light grey, and the dark solid line represents the 6th order polynomial trend line in order to simplify the temperature analysis. Thermal test will be carried out by wear test which the torque applied to nylon618 with 5Nm, 7Nm, 10Nm and 12Nm. Torque applied for thermal test for Onyx with 5Nm, 7Nm and 10Nm.

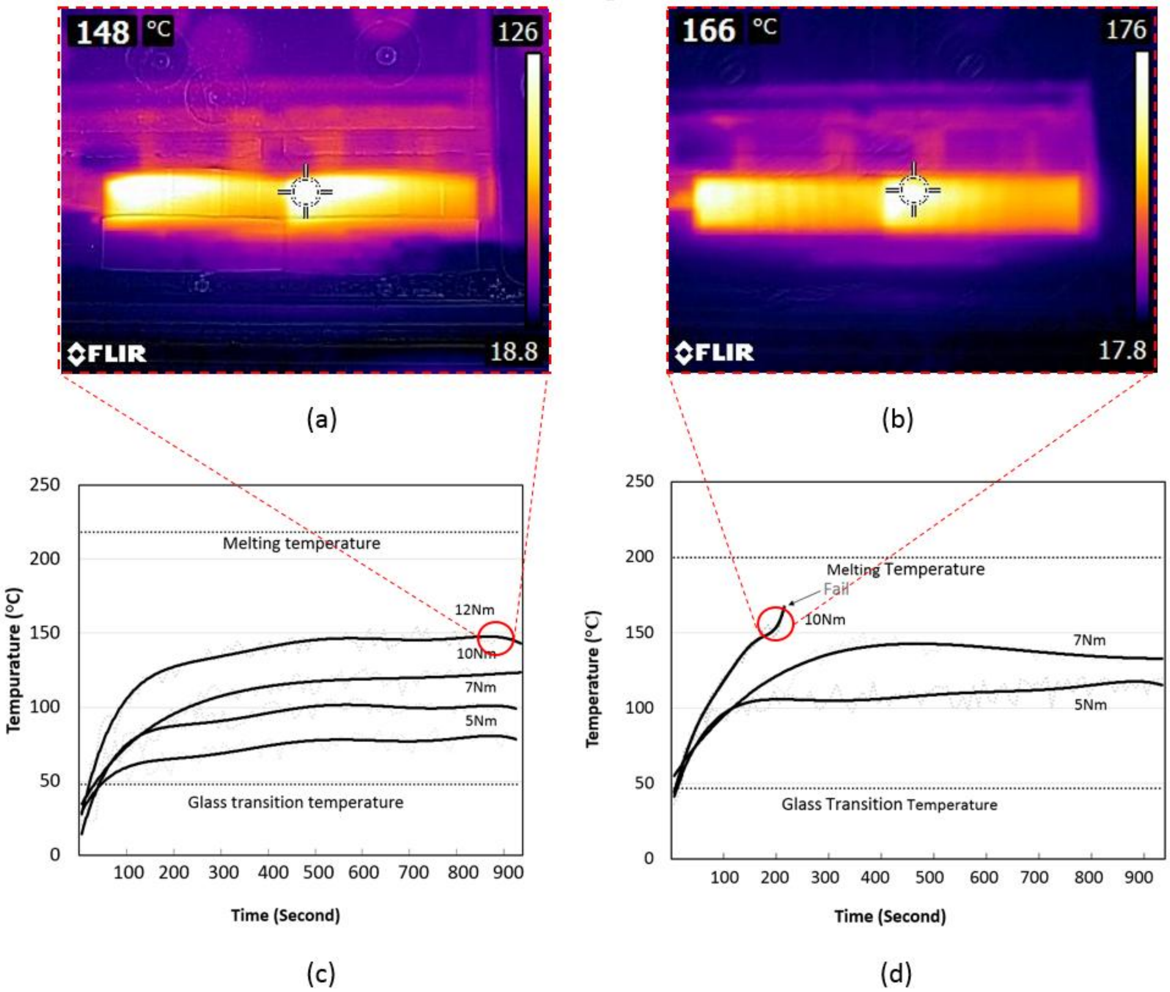


Figure 10. (a) Thermal image of Nylon 618 gear with 12Nm torque at 890 s. (b) Thermal image of Onyx gear with 10Nm torque at 200 s. (c) Thermal behaviour of Nylon 618 gears at 1000 rpm. (d) Thermal behaviour of Onyx gears at 1000 rpm

It was observed that for both materials, the surface temperature of the gears during operation was above the glass transition temperature. The analysis shows that there is a linear increase in temperature with increasing load in both materials. When the applied torque was 5 Nm, the surface temperature of the nylon 618 gears was steady around 80℃. There was a 20% increase in temperature when the torque was increased to 7 Nm, with a 30% increase in the surface temperature between 7 Nm and 10 Nm. Furthermore, there was around a 20% increase in temperature between 10 Nm and 12 Nm.

When 5 Nm torque was applied to Onyx 3D printed gears, the gear surface temperature stabilised around 110℃, increasing by 27% (140℃) when the torque was increased to 7 Nm from 110℃. However, when the applied torque was increased to 10 Nm, the gear failed after just over 180 seconds with a surface temperature of 170 °C, 30 degrees below the melting temperature.

Comparing the thermal behaviour of Nylon 618 and Onyx, there was a 37% difference (from 80℃ to 110℃) in surface temperature when both gears were subjected to the same torque of 5 Nm. There was around a 40% difference in surface temperature between Nylon 618 gears and Onyx gears at an applied torque of 7 Nm.

3.7. 3D printed gear failure mechanism.

Increasing the torque applied to 3D printed gears could lead to three main effects: an increase in contact stress, bending stress, and flash temperature of contact surface [37]. According to the equation (4) (5) below:

$$\sigma = W^t K_0 K_v K_s \frac{P_d}{F} \frac{K_m K_b}{J} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

σ : Gear bending stress.

W^t: Tangential transmitted load (N).

K_0 : Over load factor.

K_v : Dynamic factor.

K_s : Size factor.

P_d : Transverse diametral pitch.

F : Face width of the narrower member (mm).

K_m : Load-distribution factor.

K_b : Rim thickness factor.

J : Geometry factor for bending strength.

Increasing the torque will lead to a greater value of W^t hence, bending stress acting on the gear tooth will accordingly increase. Gear tooth contact stress shown as equation below.

$$\sigma_c = C_p(W^t K_0 K_v K_s \frac{K_m}{d_p F} \frac{C_f}{I})^{\frac{1}{2}} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (5)$$

C_p : Elastic coefficient (N/mm^2).

C_f : Surface condition factor.

d_p : Pitch diameter of pinion. (mm).

I : Geometry factor for pitting resistance.

As shown in equation 5, increasing of the load applied to the gear will give rise to a raise in gear contact stress. Moreover, increasing the torque will cause a temperature accumulation in the gear body [38]. An expression for the gear body temperature is shown as equation (6) below.

$$\theta_b = \frac{3.927\mu T}{c\rho Z b(r_a^2 - r^2)} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots . (6)$$

Where θ_b is the body temperature of gears, T represents the transmitted torque, ρ is specific gravity, c refers to specific heat.r_a, r and b are outside radius, reference radius and tooth face width respectively. Z represents tooth number. From this equation it can be seen that torque and gear body temperature are positively correlated. The flash temperature can be expressed as in equation (7) below.

$$T_f = 1.11\mu F \frac{(V_1^{0.5} - V_2^{0.5})}{b\sqrt{2k\rho ca}} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots . . (7)$$

Where T_f is the flash temperature of the gear, a is half contact width, V represents sliding velocity of each gear, F represents the transmitted torque.

As figure 11 below shows, there were three different types of failure that occurred in the wear tests of nylon 618 gears. When low torque was applied, the gears could sustain dramatically longer life cycles compared with higher torque being applied. According to figure 11 (c), the gears failed due to material loss from the pitch line of the gear tooth when 10 Nm of torque was applied. Once wear from the gear tooth reached a certain depth, size factor $K_s$could dramatically increase lead bending stress in equation 4 excised the limitation of the gear tooth causing gear failure. When 12 Nm torque were applied, the life cycles were decreased from 1.5 million cycles to 0.78 million cycles with gear teeth failing due to root fracture (figure 11 b). With less life cycles, material loss was not the main cause for the gear tooth fail where in fact failure was due to lack of sintering affect between layers at the root of a gear tooth. Moreover, increasing load from 10 Nm to 12 Nm could rise the beading stress causing gear root fracture. With a higher toque of 15 Nm applied (figure 11a), due to higher contact stress could lead to higher operational temperature (equation 6.7), teeth failed due to thermal bending.

For other types of nylon filaments, failure was mainly due to the lack of bonding between each layer of gear tooth, leading to dramatically higher rates of material loss from wear tests. Moreover, other nylon filaments are easier to heat up according to DSC tests, and hence operational temperature easily reached the melting temperature of the material. Those combined effects caused the rest of the nylon filaments to exhibit a much reduced lifetime compared with Nylon 618 gears.

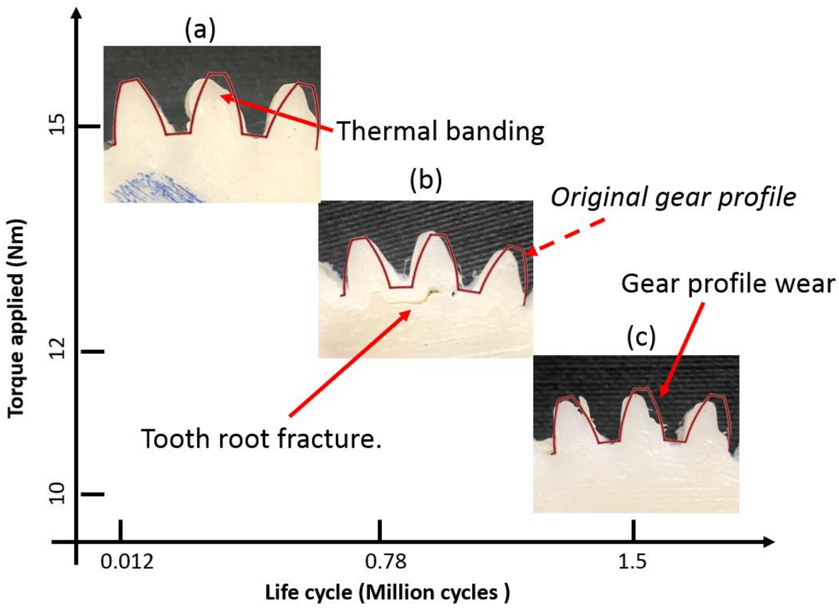


Figure.11. Failure mechanism of nylon 618 during wear test.

4. Conclusion

In this report, there were five different 3D printed materials tested, including Nylon 618, Nylon 645, alloy 910, Onyx and Markforged nylon. Comparisons between literature values for injection moulded nylon 66 gears and the five 3D printed gear types have been carried out. Nylon 618 provided better results when low to medium torque was applied compared with injection moulded gears. Different wear behaviour and wear patterns on the gear tooth were recorded by SEM. Interestingly, wear only occurred on the pitch line of 3D printed gear and for the Nylon 618 printed gears, parts of the gear tooth surface were melted but no materials were peeled off from the tooth, while the other four printed materials exhibited peeling of material from the gear tooth. In DSC tests, Nylon 66 and Nylon 618 showed relatively better thermal behaviour in terms of higher glass transition temperatures, higher melting temperatures and higher crystallinity when compared to the other materials tested. It is thus hypothesized that the superior Nylon 618 friction and wear performance (when compared to the other printed materials) is mainly dependent on the thermal behaviour and the level of sintering effect between each layers.

5. Limitations and future scope

The main limitation of this study is the lack of conventional materials information provided by the filament manufacturers. Both 3D printing filament manufacturers claim that the materials are based on Nylon 66 or a Nylon mixture, however no other compositional information is provided. It is noted that this area of 3D printed gears is certainly an area requiring future study. Firstly, further material analysis of available printing materials is required to give a better understanding of the key factors that influence the wear behaviour. Secondly, an investigation into optimasation methods for 3D printing parameters to enhance the performance of 3D printed gears is required. Thirdly, a much wider analysis and comparison of the characteristics of polymer gears manufactured by different manufacturing processes including injection moulding, machine cutting and 3D printing is required.

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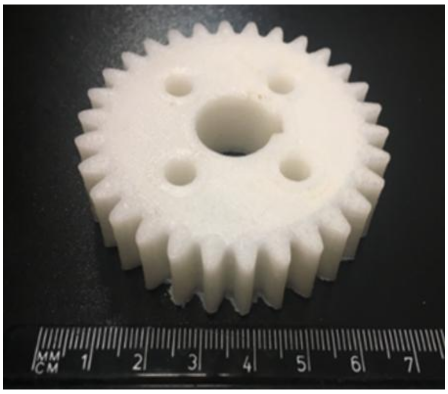
Figure(s)

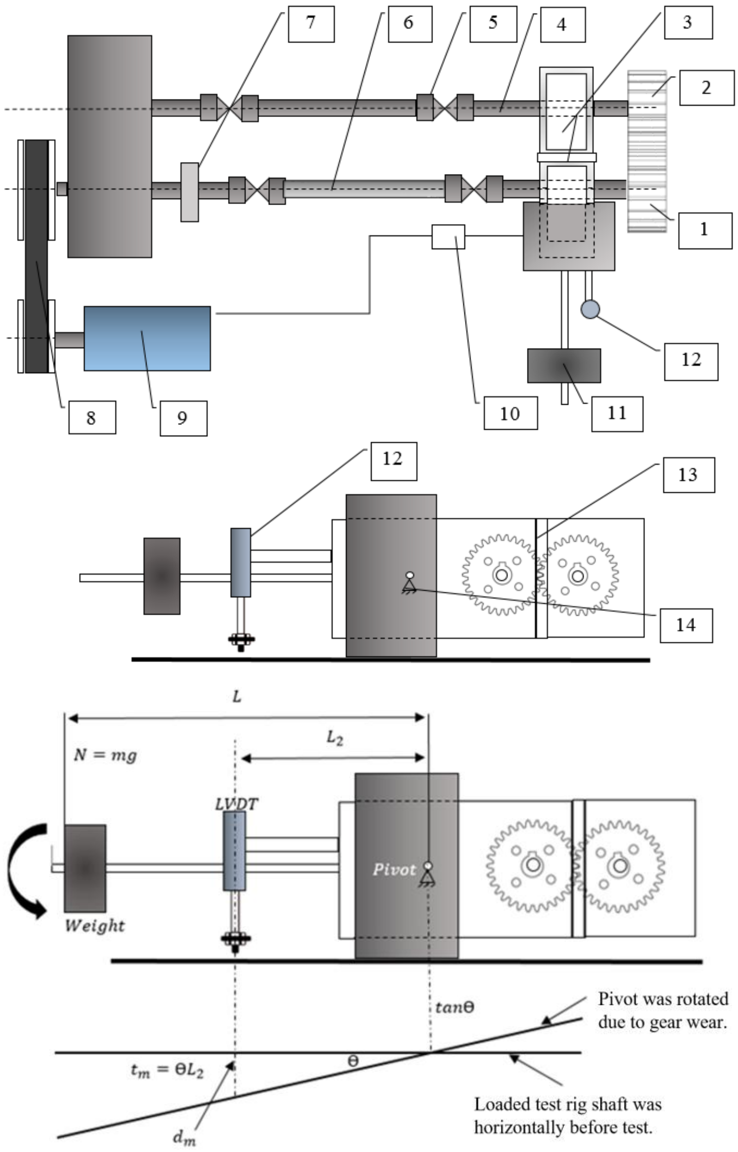


(a)

Module	2mm
Tooth number	30
Pressure angle	20°
Face width	15mm
Nominal backlash	0.18mm
Tooth thickness	3.14mm
Contact ratio	1.65

(b)

Figure.1. (a) 3D printed Nylon gear in simplified 3D, (b) specifications of gears.



Θ: Rotation angle of the pivot.

t_m: Signal of wear to being magnified

d_m: Displacement measured by LVDT (Linear Variable Differential Transformer)

L and L_2: Distance of pivot between LVDT and weight.

1. Driver gear	2. Driven gear	3. Pivot block assembly.	4. Driven shaft	5. Universal couplings.	6. Driving shaft	7. Conical clutch
8. Pulley	9. Motor	10. Motor controller	11. Weight	12. LVDT	13. Centre spacer	14. Pivot

Figure. 2. Schematic of test rig for polymer gears.

Table.1. material properties of five different materials provided by manufactures.

Material/ Properties	Nylon 66[1]	Nylon 618[18]	Nylon 645[19]	Alloy 910[20]	Onyx [21]	Markforged Nylon [21]
Specific gravity (g/cm^3)	1.41	N/A	N/A	N/A	1.18	1.10
Tensile strength (MPa)	62	31.5	35.7	55.8	36	31
Flexural modulus (MPa)	2600	152.9	212.7	502.8	2900	840
Glass transition temperature (℃)	51	48	52	82	N/A	N/A
Melting temperature (℃)	256	218	217	210	N/A	N/A

N/A: Data was not provided by manufacture

Table.2. Wear test rig results

Material/ Load	**Nylon 66** (Injection mould)[1]	**Nylon 618**	**Onyx**	**MF nylon**	**Nylon 645**	**Alloy 910**
5Nm	2.4 Million cycles	2.4 Million cycles	2.4 Million cycles	0.018 Million cycles	0.014 Million cycles	0.0078 Million cycles
7Nm	2.4 Million cycles	2.4 Million cycles	0.96 Million cycles	N/A*	N/A*	N/A*
10Nm	1 Million cycles	1.5 Million cycles	0.006 Million cycles	N/A*	N/A*	N/A*
12Nm	Tested 0.504 Million cycles	0.78 Million cycles	N/A*	N/A*	N/A*	N/A*
15Nm	0.08 Million cycles	0.012 Million cycles	N/A*	N/A*	N/A*	N/A*

*When gear tested for less than 1 million cycles no further test were done.

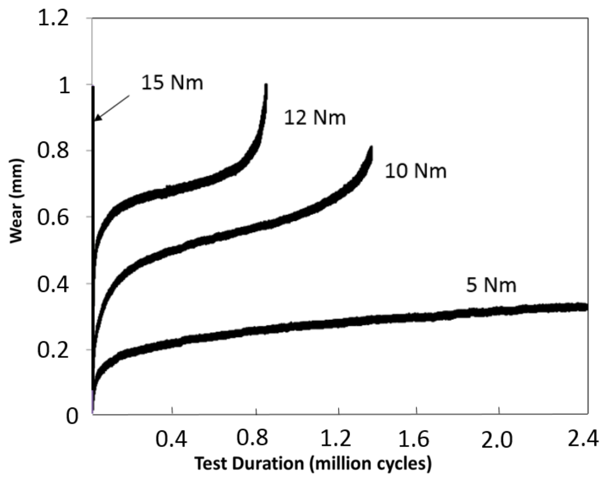
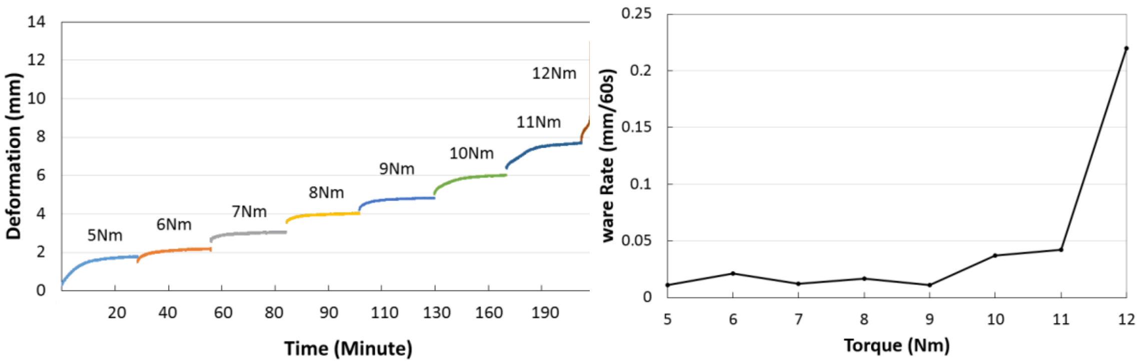
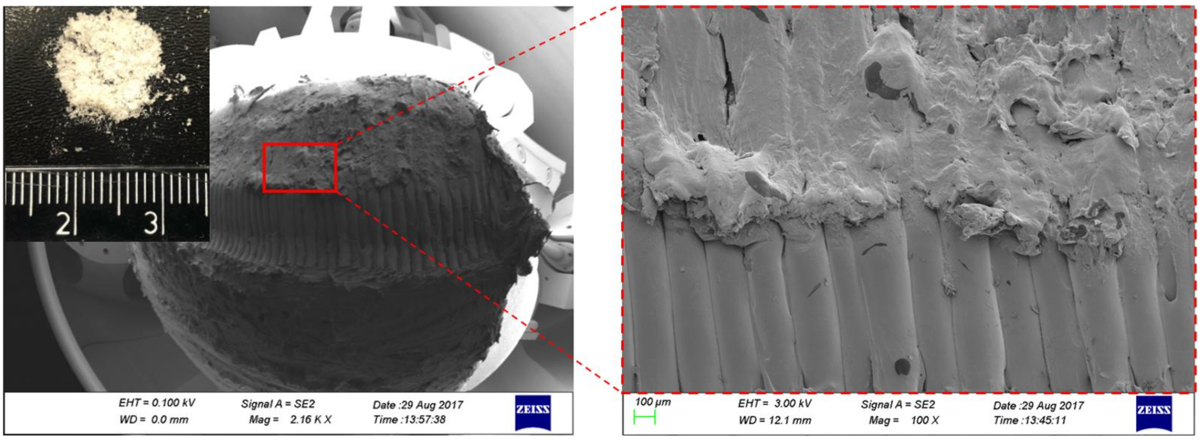


Figure.3. Result of Nylon 618 wear tests.



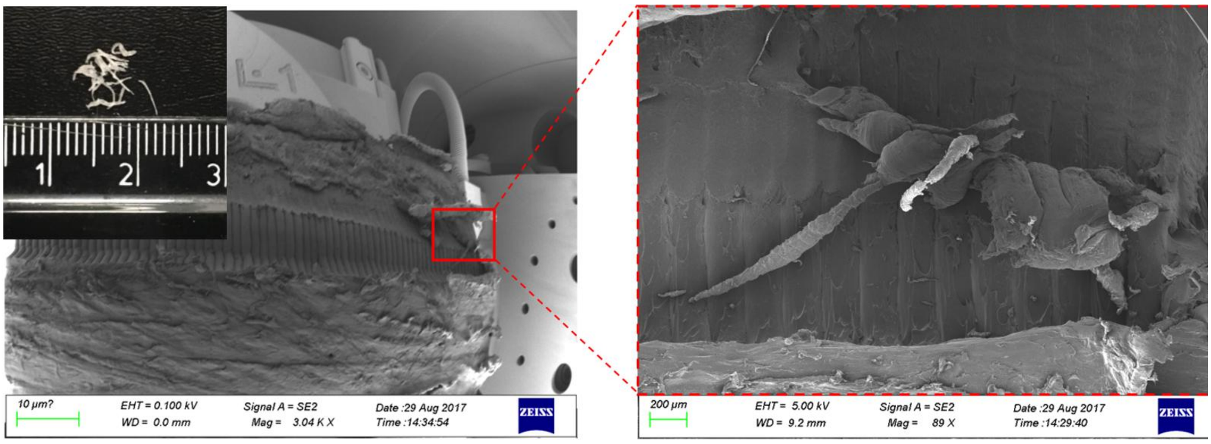
(a) (b)

Figure.4 (a) Step load test of Nylon 618 (b) Wear rate against load for nylon 618 gears.



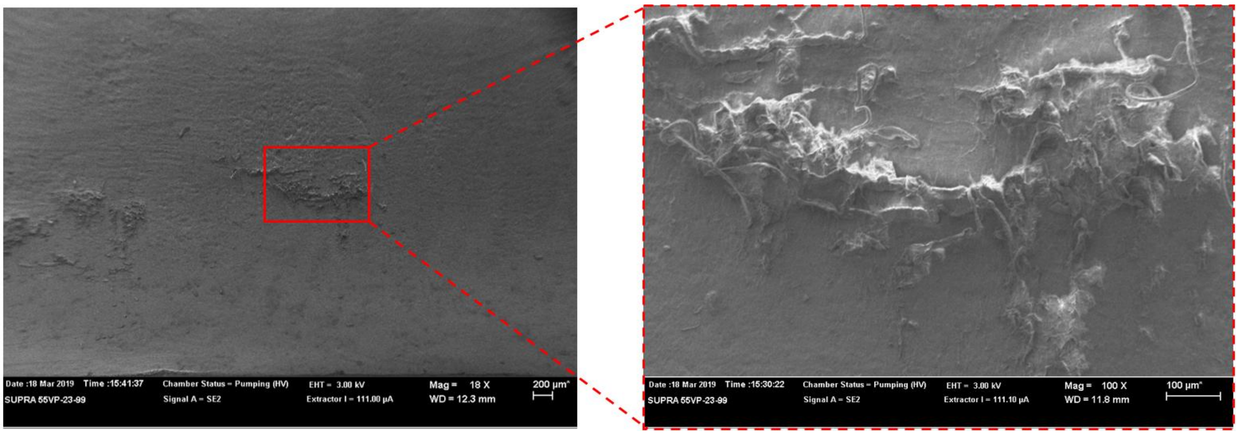
(a) (b)

Figure.5 (a) Fish eye SEM image over view of failed 618 tooth surface and debris. (b) Surface wear debris (×100))



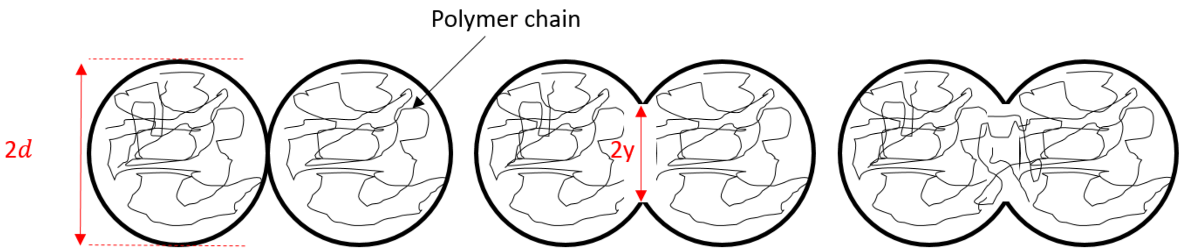
(a) (b)

Figure 6. (a) Fish eye over view of failed 645 tooth surface and debris. (b) Gear surface wear debris (×100)



(a) (b)

Figure 7. (a) Nylon 66 injection mould gear (x 18). (b) Gear surface wear debris of Nylon 66 injection mould gear (×100)



(a) (b) (c)

Figure 8. Process of polymer sintering between layers. (a) Represent filament instantaneously after deposition (b) Represent the neck growth, and (c) Represent sintering effect due to the movement of polymer chains.

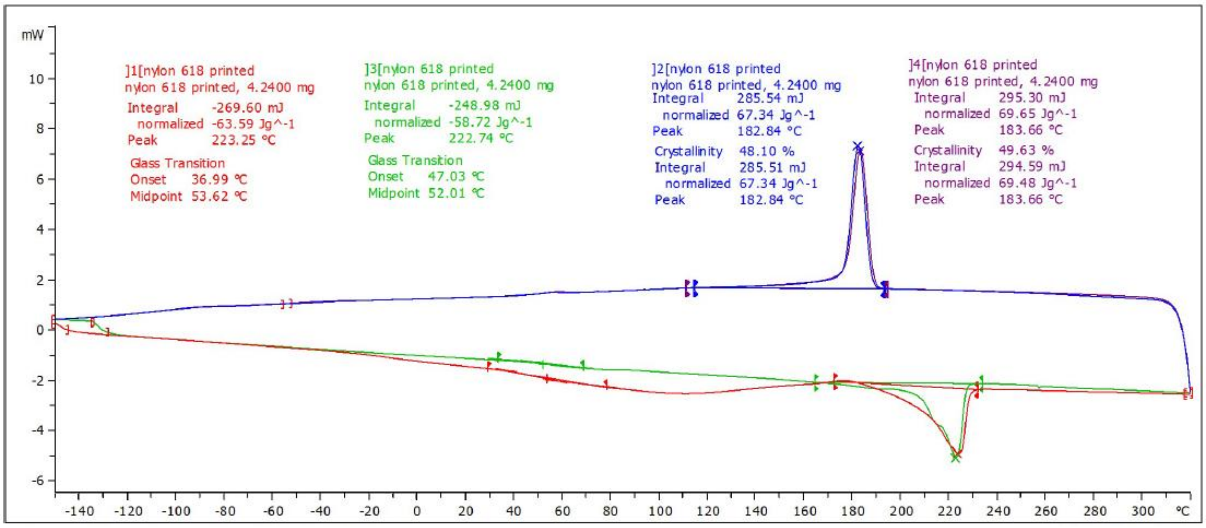


Figure 9. DSC test result of Nylon 66

Table.3.DSC test results

Measured Material / Thermal spec	Nylon 66	Nylon 618	Onyx	Nylon 645
Glass transition temperature	54℃	48℃	47℃	43℃
Melting temperature	260℃	225℃	200℃	210℃
Crystallinity	56%	48%	23%	31%
Normalised energy consumption	84J/g	60J/g	34J/g	45J/g

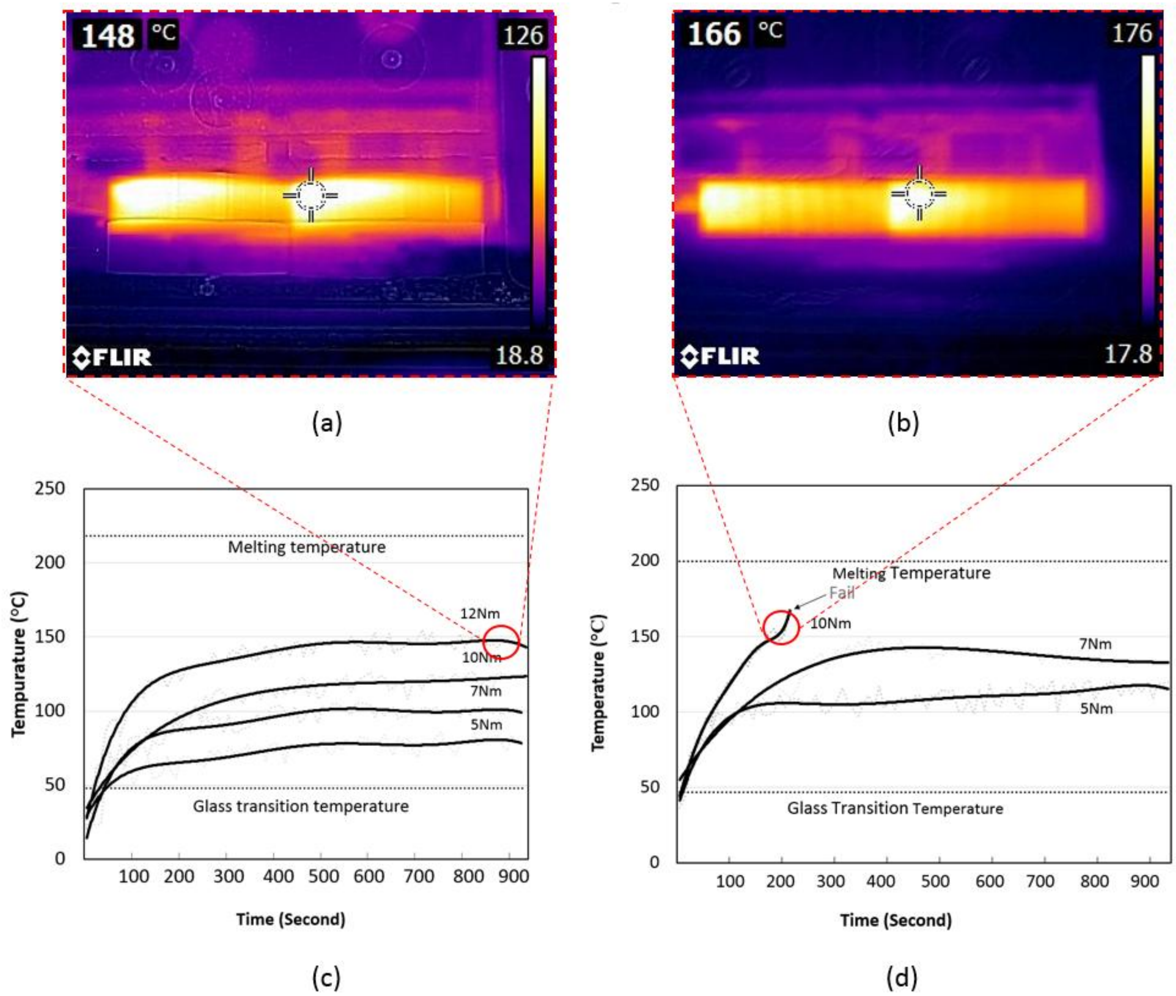


Figure 10. (a) Thermal image of Nylon 618 gear with 12Nm torque at 890 s. (b) Thermal image of Onyx gear with 10Nm torque at 200 s. (c) Thermal behaviour of Nylon 618 gears at 1000 rpm. (d) Thermal behaviour of Onyx gears at 1000 rpm

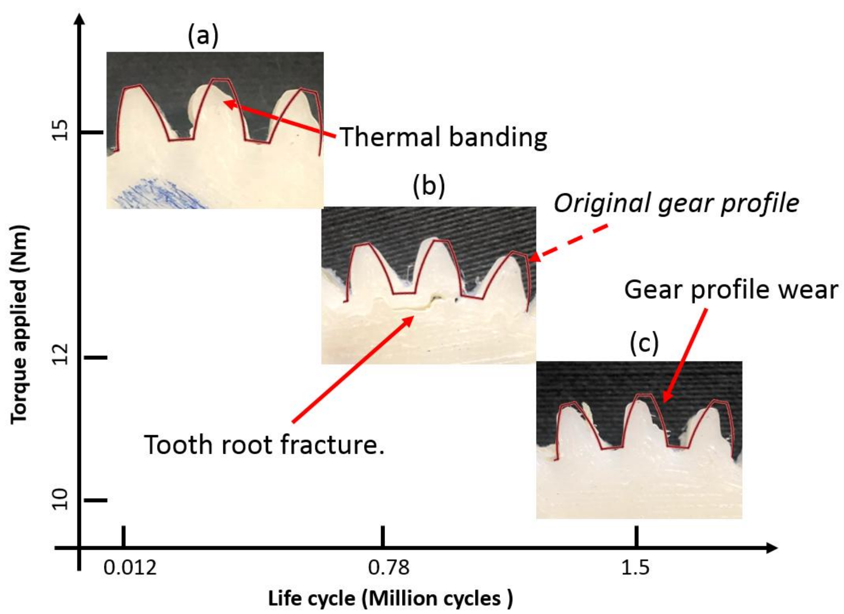


Figure.11. Failure mechanism of nylon 618 during wear test.