MATERIALE PLASTICE
https://revmaterialeplastice.ro
https://doi.org/10.37358/Mat.Plast.1964

Surface Durability Study of 3D Printed Gears Using Two Different Materials

CHENXIAO LI, CHUL-HEE LEE*
Inha University, Department of Mechanical Engineering, Advanced Vehicle Design & Control LAB, Incheon 22212, South Korea

Abstract: *This study evaluated surface durability use of manufacture 3D printed gears. Polymer gears were 3D printed using PLA, Tough-PLA, and TPU materials, Through different combinations of materials,three gears of the same size were manufactured: the PLA gear, the PLA plus TUP gear and the Tought PLA plus TPU gear. The surface wear test of the 3d-printed gears were on a self-designed test bench. The differences in mechanical performance between the polymer filaments were attributed to differences in crystallinity and the uniqueness of the fused deposition modeling (FDM) process, but by combining two materials with different features, it is possible to change the mechanical properties of 3D printed gears.In this study , from the changes of torque data during the whole experiment also showed the difference of transmission efficiency of three different gears.Scanning electron microscopy (SEM) revealed the different surface wear of three different gears under the same test conditions. During the gear surface wear test, a thermal camera was used to recorded the surface temperature changes of the gears, and SEM was used to analyze the wear of the gear surface. The test results showed Tough-PLA Plus TPU gear showed the best wear performance among the three different 3D printing gears tested.*

Keywords: *3D printing, 3D printing materials,gear design, wear*

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 behaviors of injection molded 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 molding [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. Some researchers [5] introduced a design and optimization of prosthetic foot by using polylactic acid. The other researchers [6] introduced friction and wear of textured surfaces produced by 3D printing. In some research [7] claimed that adding continuous fibers could further increasing the tensile strength compared with carbon fiber nylon composites. Some research [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. Some researchers [9] investigated misalignment effects on acetal gears together with wear behavior, 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

---

**email: chulhee @inha.ac.kr*

[10]. Some researchers [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 [12]. 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 behaviors their hyper elastic and visco elastic behaviors. Conventionally, polymer gears are produced using injection moldings but surprisingly to date there are being 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 T-PLA and TPU composite materials using FDM, characterize their performance under load and compare the results to gears produced using TPA material by 3D printing.
Conventionally, polymer

2. Materials and methods

2.1. Gear design

In The first stage in 3D printing of a polymer spur gear was to design the gear itself. The gear tooth face width was reduced by 2 mm due to test rig specifications. The specifications of the final gear are given in Table 1. A combined 3D printing method used two materials as shown in Figure 1.

Table 1. Detailed parameters of the gear

Parameter	Value
Module	5
Tooth number	26
Pressure angle	20°
Face width	8mm
Tooth thickness	15mm

Three different 3D printed materials were tested and compared with injection moulded nylon gears including TPA, Tough-PLA and TPU. The different materials were printed using same types of 3D printer. They were printed using an Ultimaker system. 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.

Figure 1. Example of a figure caption

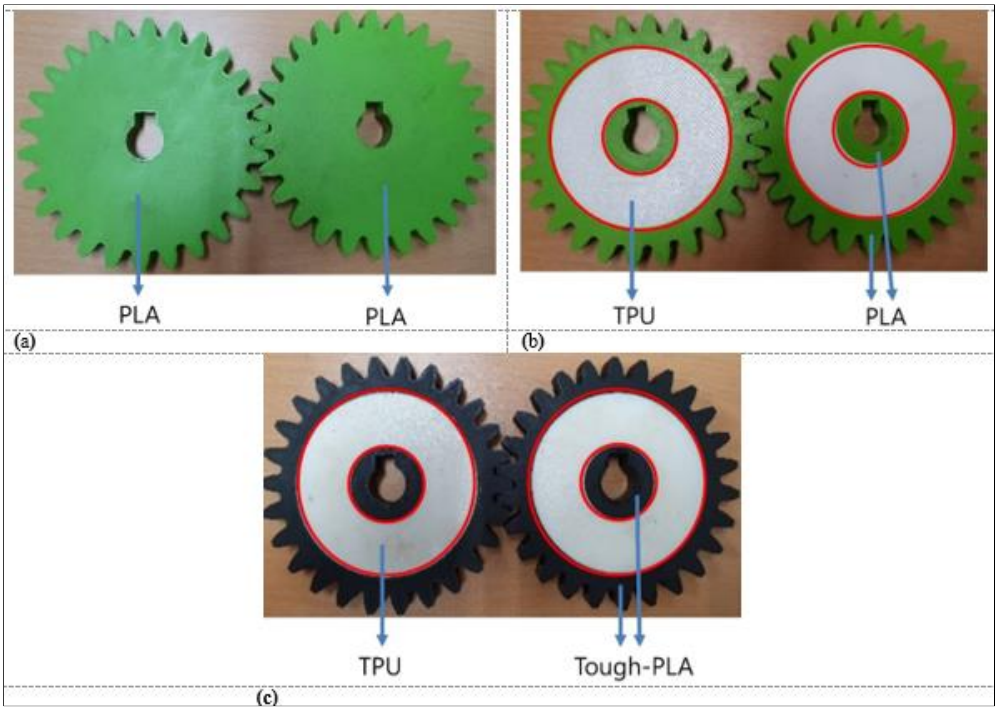


Figure 2. Three types of printing gear. a. PLA+PLA gears;
b. PLA+TPU gears; c. Tough PLA+PLA gears

The 3D printing process is shown in Figure 2. 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. 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. The schematic of the test rig is presented in Figure 3.

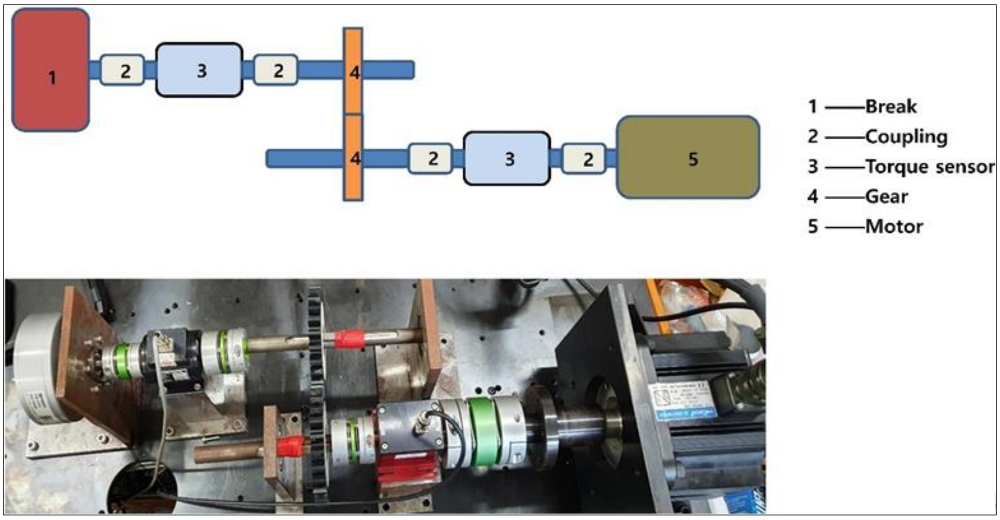


Figure 3. Schematic of the test rig for 3D printed gears

In this instance torque was applied to the gear at the different levels of 0.5 Nm, 1 Nm, 1.5 Nm, 2 Nm, 2.5 Nm, 3 Nm, 3.5 Nm and 4 Nm. Gear fatigue tests were performed with TPA, Tough-PLA and TPU 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.

2.3. Gear surface temperature

There are three temperature components contributing to the gear surface temperature: the ambient, bulk and flash temperatures. The ambient temperature was between 20°C and 30°C 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 behaviors and mechanical behaviors actually corresponded to the maximum surface temperature during operation reaching the melting point of TPA, a number of incremental tests were carried out at elevated surface temperatures. The temperature in the experiment was measured using a OLIR C5 Thermal imaging camera.

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 temperature detector was used and set 10 cm above the testing gears. Surface temperature tests were carried out on PLA and Tough-PLA gears. The duration of each test was 15 min and in the first 10 s of each test, an image was captured every 2 s due to rapid temperature rise and after the first 10 s the thermal image captured every 10 s 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. The linear wear period is most representative of the operational conditions and should reveal the operational temperature of a gear.

3. Results and discussions

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 0.4 million cycles or until gear failure (whichever came first). For a greater number of cycle than 0.3 million cycles, another gear in the same material was tested at an increased load. When taken with the properties presented in Table 2, 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 3D printing gears failures appeared to be due to failure at the root of the gear teeth.

Table 2. Gear design parameters

Material/Properties	T-PLA	PLA	TPU
Tensile modulus (MPa)	1820.0	2346.5	26.0
Tensile stress at yield (MPa)	37.0	49.5	8.6
Tensile stress at break (MPa)	37.0	45.6	39
Elongation at yield	3.1%	3.3%	55%
Elongation at break	3.1%	5.2%	580%
Flexural strength	78.0	103.0	4.3
Flexural modulus	249.0	3150.0	78.7
Hardness (Shore D)	79	83	46

3.2. Comparison results of input torque and output torque

In this experiment, two torque sensors of the same specification were used to record the values of input torque and output torque. The difference between the input torque and the output torque can reflect the operating state and power changes of the gear during the operation of the gear, and at the same time has a certain degree of influence on the wear of the gear. The efficiency of torque conversion can be obtained by the difference between the output torque and the input torque. Since, in gear transmission, there is no loss of speed, the efficiency of the gear transmission is the percentage of the ratio of output power to input power. The efficiency results of different gears are shown in Tables 3, Tables 4, Tables 5 and Tables 6.

Table 3. Transmission efficiency of the three gears at 60 rpm

Torque (Nm)	**Transmission Efficiency (%)**		
	PLA+PLA	PLA+TPU	T-PLA+TPU
0.5	96.1	96.5	96.6
1.0	91.5	93.7	96.1
1.5	90.3	92.7	93.4
2.0	89.6	92.1	92.2
2.5	89.2	92.1	91.5
3.0	89	91.9	91.2
3.5	88.7	91.8	91.0
4.0	88.6	91.7	90.8

Table 4. Transmission efficiency of the three gears at 120 rpm

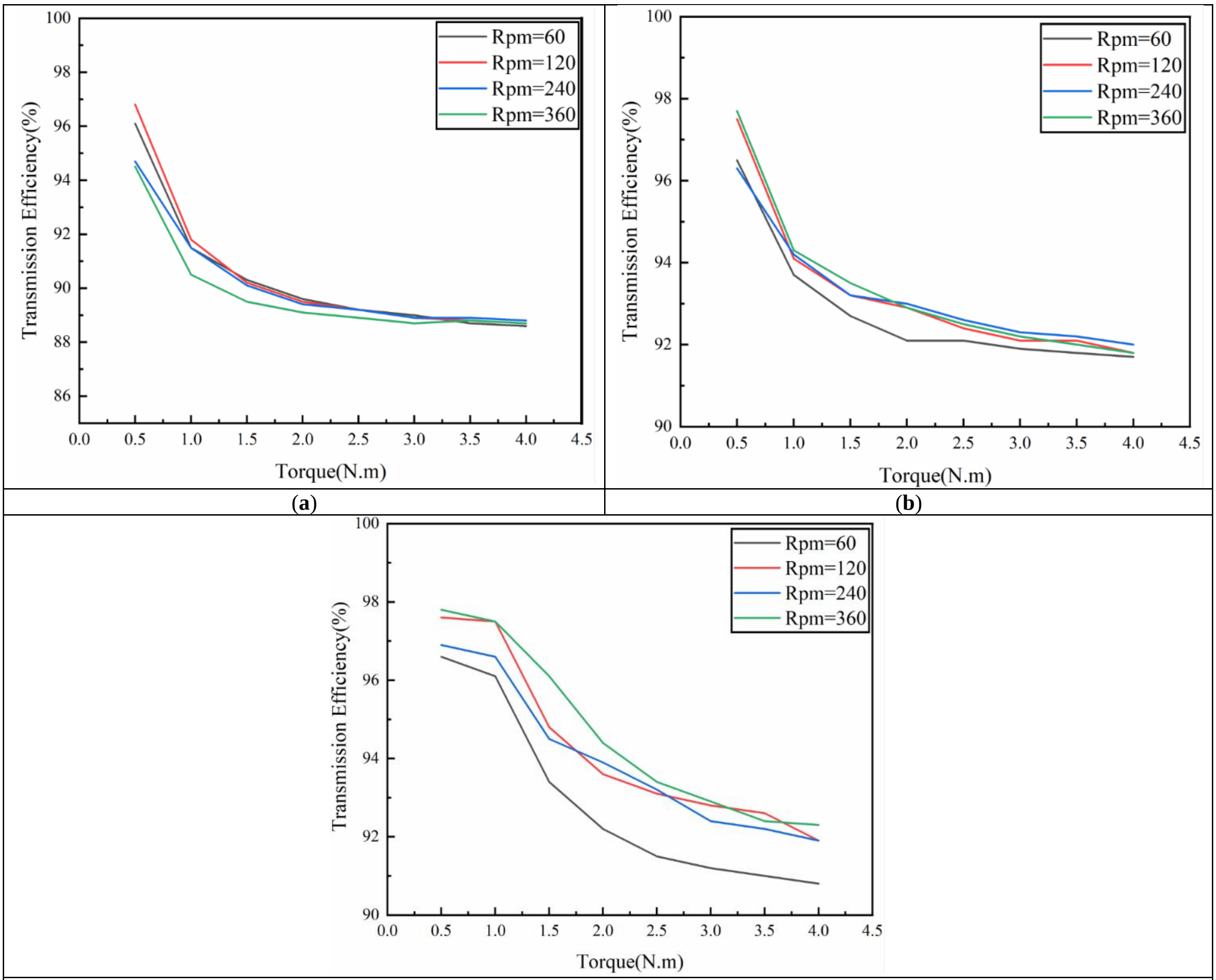
Torque (Nm)	**Transmission Efficiency (%)**		
	PLA+PLA	PLA+TPU	T-PLA+TPU
0.5	96.8	97.5	97.6
1.0	91.8	94.1	97.5
1.5	90.3	93.2	94.8
2.0	89.5	92.9	93.6
2.5	89.2	92.4	93.1
3.0	88.9	92.1	92.8
3.5	88.8	92.1	92.6
4.0	88.7	91.8	91.9

Table 5. Transmission efficiency of the three gears at 240 rpm

Torque (Nm)	**Transmission Efficiency (%)**		
	PLA+PLA	PLA+TPU	T-PLA+TPU
0.5	94.7	96.3	96.9
1.0	91.5	94.2	96.6
1.5	90.1	93.2	94.5
2.0	89.4	93.0	93.9
2.5	89.2	92.6	93.2
3.0	88.9	92.3	92.4
3.5	88.9	92.2	92.2
4.0	88.8	92.0	91.9

Table 6. Transmission efficiency of the three gears at 360 rpm

Torque (Nm)	**Transmission Efficiency (%)**		
	PLA+PLA	PLA+TPU	T-PLA+TPU
0.5	94.5	97.7	97.8
1.0	90.5	94.3	97.5
1.5	89.5	93.5	96.1
2.0	89.1	92.9	94.4
2.5	88.9	92.5	93.4
3.0	88.7	92.2	92.9
3.5	88.8	92.0	92.4
4.0	88.7	91.8	92.3



(a) (b)

(c)

Figure 4. Variation in the efficiency of different gears a. Efficiency of PLA+PLA gear at different rpm; b. Efficiency of PLA+TPU gear at different rpm; c. Efficiency of tough-PLA+PLA gear at different rpm

Figure 4 shows the variation in the transmission efficiency of each gear at four different speeds. In Figure 4a, the transmission efficiency of PLA+PLA gear has various changes at different speeds. However, with increasing load, the transmission efficiency has the same downward trend, and the final transmission efficiency approaches an approximate value. A comparison of Figure 4b with Figure 4c showed, that the transmission efficiency is obviously at the lowest value at 60 rpm. With increasing rpm, the transmission efficiency of the two combined 3D-printed gears was significantly higher at high speed than that at low speed.

3.4. Scanning electron microscopy (SEM)

After the experiment, SEM was used to observe and analyze the wear of the gear surface. In the case of using the same multiple, the surface of the three kinds of gear has different degrees of wear.

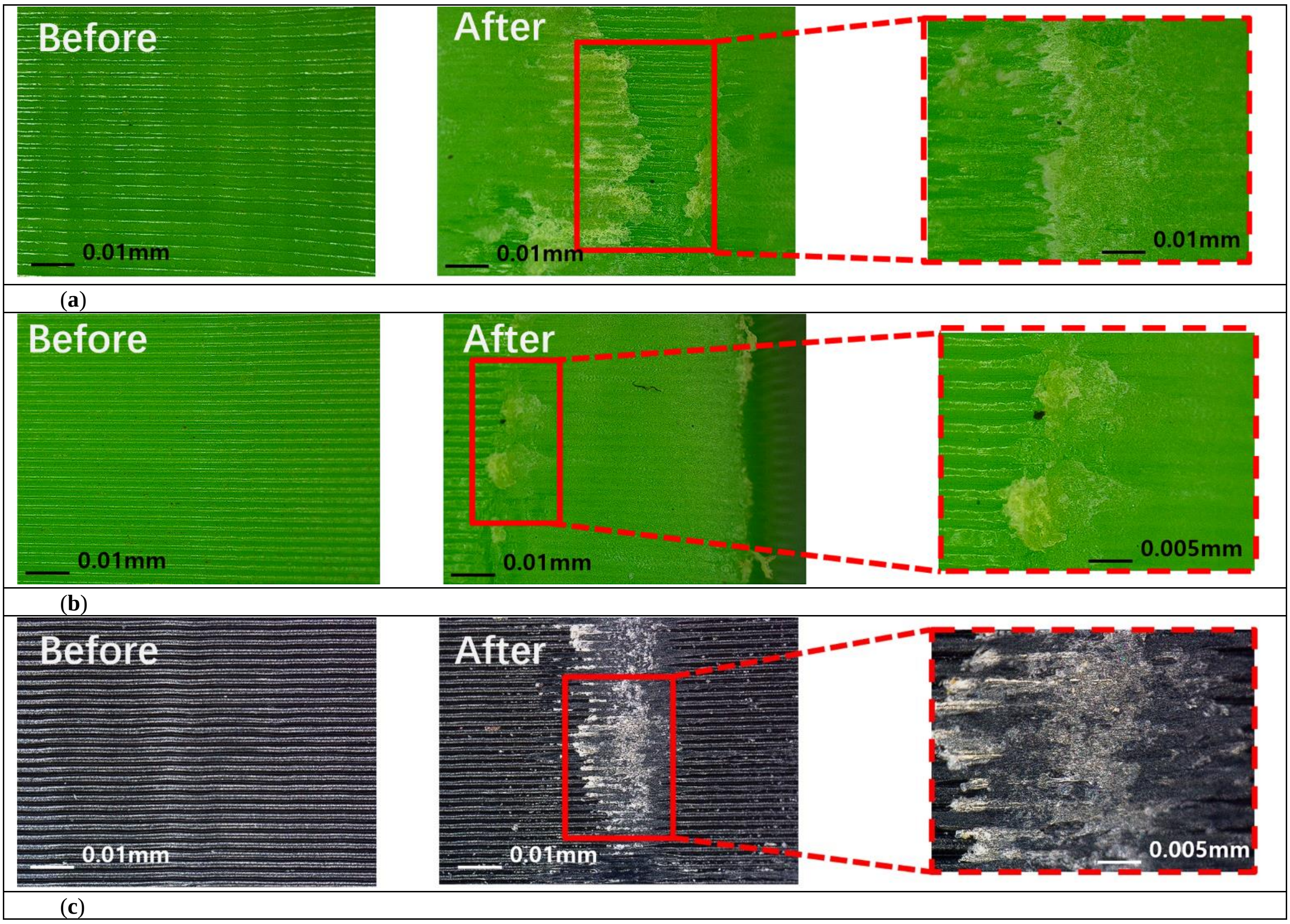


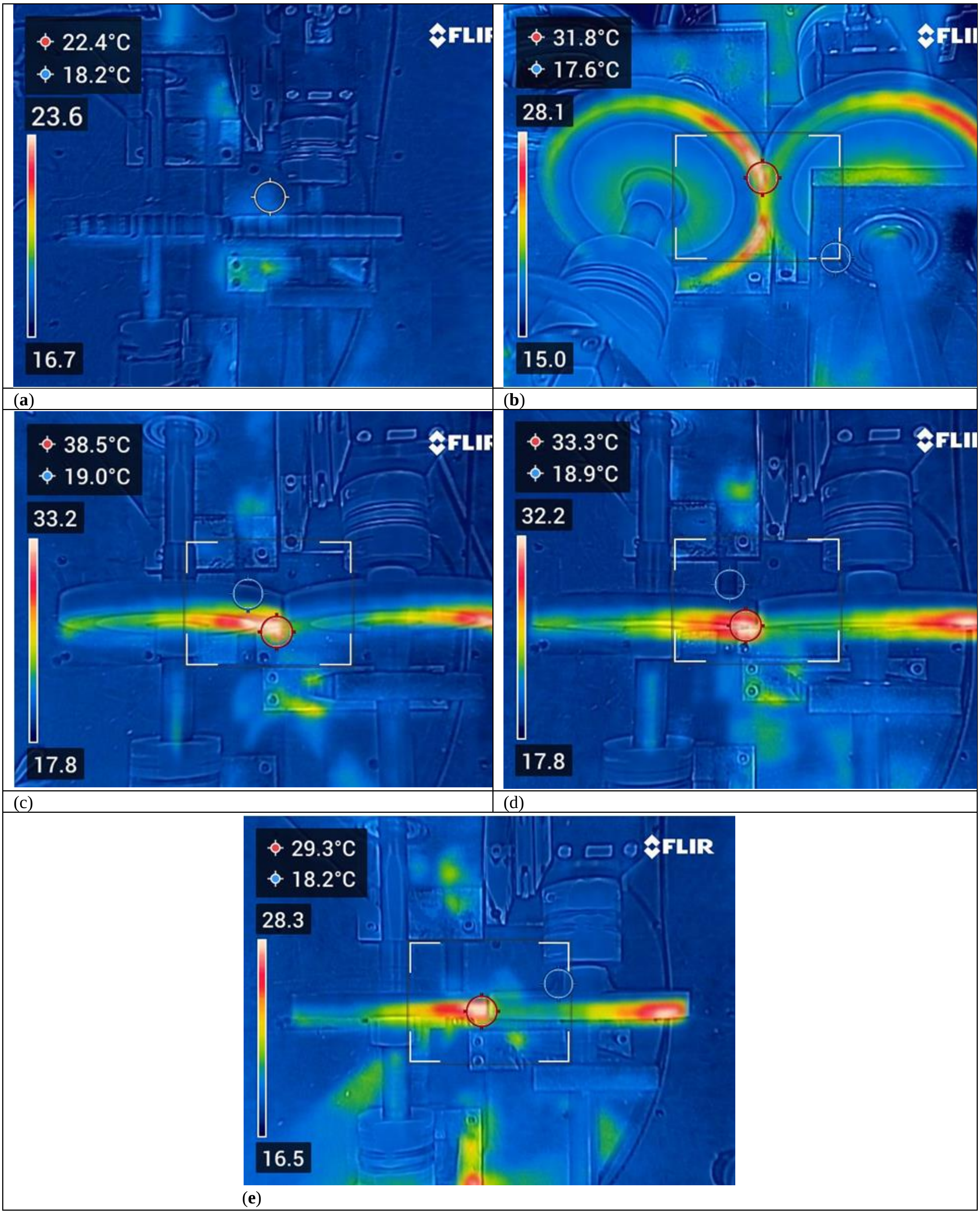
Figure 5. Surface wear of three gears a. PLA+PLA gears surface; b. PLA+TPU gears surface; c. Tough-PLA+PLA gears surface

Figure 5a shows the failed tooth surface of printed gear. It is evident under x200 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 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 green to white and the pitch line on the tooth face remained parallel to the addendum. In Figure 5b the microphotograph of the surface wear of the gear printed by the two materials of PLA+TPU. It can be seen that a large number of wear marks appear on the surface of the gear. In Figure 5c gears printed from a combination of Tough-PLA and TPU materials exhibit different wear properties. It can be seen that the surface wear properties of Tough-PLA are mainly due to the indentation generated during gear meshing. While the gears are meshing, the 3D-printed surface texture is deformed due to the pressure, resulting in slight wear on the surface.

On the whole, in the three-gear manufacturing material selection schemes, the wear resistance of Tough-PLA material is the best, followed by PLA+TPU material, and the wear resistance of PLA material is the same as that of its own material.

3.5. Gear tooth surface temperature

The gear surface temperature has an important influence on the durability and wear of the gear, so the infrared camera is used in the experiment to measure the gear surface temperature. The temperature changes under different torques and rotational speeds were measured. The infrared camera model used for the test is FLI C5. By comparing the temperature difference before and after the test, the energy loss during gear operation can be determined.



(a) **(b)** (c) (d) **(e)**

Figure 6. Gear surface temperature a. Temperature before the experiment begins; b. Temperature in the experiment; c. Thermal image of PLA+PLA gear with 2.5Nm torque at 1800s; d. Thermal image of PLA+TPU gear with 2.5Nm torque at 1800s; e. Thermal image of Tough-PLA+TPU gear with 2.5Nm torque at 1800s

In Figure 6a shows the measurement of gear and ambient temperature at the be-ginning of the experiment. At this time, the ambient temperature is 18.2 degrees, the gear surface temperature is 22.4 degrees, the experimental torque is set at 2.5Nm, and the rotational speed is 300. Figure 6b shows the measurement of gear and ambient temperature in the experiment. Figure 6c shows the temperature of PLA+PLA material when the experiment time is 1800 s. Figure 6d shows the measured temperature of PLA+TPU material when the experiment time is 1800 s. Figure 6e shows the measured temperature of Tough PLA+PLA during the experiment time of 1800s under the same experimental conditions, the gear combination of PLA+PLA material is obviously at the same time, the gear surface temperature is higher, which means that more heat is generated in the process of gear operation, but also produces greater wear. The test results of gear surface temperature under other conditions are shown in Table 7.

Table 7. Changes in the surface temperature of the gears

Test torque (Nm) / Temperature difference (℃)	**PLA+PLA**	**PLA +TPU**	**T-PLA+TPU**
0.5	7.1	6.9	6.8
1.0	9.8	9.1	9.0
1.5	11.2	10.2	9.9
2.0	14.3	11.7	11.1
2.5	16.1	13.9	13.5
3.0	17.4	16.3	15.5
3.5	19.8	18.5	17.6
4.0	22.4	19.6	18.5

4. Conclusions

In this study, there were three different 3D printed materials tested, including TPA, Tough-PLA and TPU. Comparisons between literature values for the three 3D printed gear types have been carried out. Tough-PLA plus TPU provided better results when low to medium torque was applied compared with injection molded gears. Different wear behavior 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 Tough-PLA printed gears, parts of the gear tooth surface were melted but no materials were peeled off from the tooth, while the other printed materials exhibited peeling of material from the gear tooth. It is thus hypothesized that the superior Tough-PLA friction and wear performance (when compared to the other printed materials) is mainly dependent on the thermal behavior and the level of sintering effect between each layer.

Among the gears made of PLA, TPU and Tough-PLA, the gear Tough-PLA of the combined material has the best surface wear resistance and shows the least surface wear under the same conditions. At the same time, because of the combination of the two materials to print the gears, Through the analysis of the experimental results, it is found that the power transmission efficiency of the 3D-printed gears made of T-PLA+TPU gears and PLA+TPU gears is higher than that of the traditional 3D-printed single material. The improvement of transmission efficiency is related to the performance of TPU, a flexible material, because during the operation of the gear, there will be some vibration, which leads to the loss of energy, and the vibration will also aggravate the wear of the surface material of the gear, thereby reducing the speed of the gear. transmission efficiency. When using TPU material for combined printing, TPU, as a flexible material, can reduce the vibration of the gear itself during the operation of the gear, thereby reducing the wear of the gear surface. At the same time, when the two materials are combined for 3D printing, the tooth surface part of the gear uses a material with higher hardness to enhance the surface wear resistance of the gear and reduce surface wear.

Acknowledgment: This work was supported by INHA UNIVERSITY Research Grant.

References

1. K. MAO, W. LI, C.J. HOOKE, D. WALTON, Friction and wear behaviour of acetal and nylon gears. *Wear*, **267**, 2009, 639-645, https://doi.org/10.1016/j.wear.2008.10.005

2. BARRY BERMAN, 3D printing: the new industrial revolution. *Business Horizons*, **55**, 2012, 155-162, https://doi.org/10.1016/j.bushor.2011.11.003

3. WOHLERS T., *Additive manufacturing and 3D printing state of the industry*, Wohlers Associates, Fort Collins, 2013, 269-375

4. K.V. WONG, A. HERNANDEZ, A review of additive manufacturing, *International Scholarly Research Notices*, **2012**, 2012, 1-10, https://doi.org/10.5402/2012/208760

5. S.J. LEIGH, R.J. BRADLEY, C.P. PURSSELL, D.R. BILLSON, D.A. HUTCHINS, A simple low-cost conductive composite material for 3D printing of electronic sensors. *PLOS One*, **7**, 2012 https://doi.org/10.1371/journal.pone.0049365

6. HONG, Y., ZHANG, P., LEE, K. H., LEE, C. H, Friction and wear of textured surfaces produced by 3D printing. *Science China Technological Sciences*, **60**, 2017,1400-1406 https://doi.org/10.1007/s11431-016-9066-0

7. J.F. CHRIST, N. ALIHEIDARI, A. AMELI, 3D printed highly elastic strain sensors of multiwalled carbon nanotube/thermoplastic polyurethane nanocomposites, *Materials & Design*, **131**, 2017, 94-401 https://doi.org/10.1016/j.matdes.2017.06.011

8. L.G. BLOCK, LONGANA, M.Y. HANA, B.K.S. WOODS, An investigation into 3D printing of fibre reinforced thermoplastic composites, *Additive Manufacturing*, **22**, 2018, 176-186 https://doi.org/10.1016/j.addma.2018.04.039

9. M. KALIN, A. KUPEC, The dominant effect of temperature on the fatigue behavior of polymer gears, *Wear*, **376-377**, 2012, 1339-1346, https://doi.org/10.1016/j.wear.2017.02.003

10. Z. HU, K. MAO, An investigation of misalignment effects on the performance of acetal gears, *Tribology International*, **116**, 2012, 394-402, https://doi.org/10.1016/j.triboint.2017.07.029

11.Z. WENG, J. WANG, T. SENTHIL, L. WU, Mechanical and thermal properties of ABS / montmorillonite nanocomposites for fused deposition modeling 3D printing, *Materials & Design*, **102**, 2016, 276-283, https://doi.org/10.1016/j.matdes.2016.04.045

12.A.R. TORRADO, C.M. SHEMELYA, J.D. ENGLISH, Y. LIN, R.B. WICKER, D.A. ROBERSON, Characterizing the effect of additives to ABS on the mechanical property anisotropy of specimens fabricated by material extrusion 3D printing, *Additive Manufacturing*, **6**, 2015, 16-29 https://doi.org/10.1016/j.addma.2015.02.001

Manuscript received: 20.11.2022