The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2024

Volume 31, Pages 52-63

ICATI 2024: International Conference on Advances in Technology and Innovation

Experimental Investigation of the Wear of Some Polymer Gear Wheels Produced by Three-Dimensional Printer on the Variation of Fill Percentage and Shell Thickness

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Abstract: FDM additive manufacturing method has recently been widely used because it is very attractive in terms of cost and material loss compared to traditional manufacturing methods such as molding and milling. In previous studies, many researches have been carried out on the engineering strength of plastic gears produced by conventional methods, but with the discovery of new plastic forms by material science and the practical application of new production methods, researchers continue the researches on additive manufacturing gears. So far, many studies have investigated the wear variation, rotational speed and torque variation with variations in gear wheels produced with three-dimensional printers. In this study, using the ability of FDM technology to produce in layers, gear wheels with several variations in outer shell thicknesses and internal filling ratios were produced. The wear behaviors of these gear wheels produced with different variations were investigated. On the other hand, PETG and ABS polymers were also produced under the same conditions in order to provide material diversity in addition to PLA polymer, which has been used so far in many studies due to its low melting temperature and good printability. Then wear behaviors were observed under the same conditions using the FZG (Forschungsstelle fur Zahnrader und Getriebebebau) test setup. Thanks to additive manufacturing technology, polymer gear types were produced with fill ratios of 100% and 50% and outer shell thicknesses of 0.4 mm and 0.8 mm. The test specimens were operated against the steel gear at a torque of 1.5 Nm and a rotational speed of 900 rpm and the mass losses as a result of wear were compared. Thus, a comparison was made about the strength of polymer types with the variation of outer shell thickness and filling percentage.

Keywords: Wear, 3D printing, Plastic spur gear

Introduction

While the light weight of plastic gears and their use without lubrication make them attractive in cases where high strength is not required, the low melting points and glass transition points of plastics have caused low heat resistance. Since abrasion brings with it heat generation, heating has been one of the biggest handicaps of plastics. On the other hand, with FDM technology, one of the additive manufacturing methods, it is a great convenience for the user to know the total production time thanks to the printer program. However, compared to the mold production method, this method is more cost-effective in prototype production, but the production time is quite long.

In the previous studies, the relationship between the rotational speed and torque change affecting the wear, heat and material losses as a result of wear were calculated and the microstructure changes occurring in the microscope were observed. The increase in layer thickness caused deterioration in surface quality and reduction in the wear coefficient. When the layer thickness was increased from 0.1 mm to 0.3 mm, it was observed that

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

the bending and tensile strength decreased by about 30%. Increasing the nozzle temperature can reduce the wear rate when the polyamide gear is produced by FDM method. (Wang et al.,2024)

The tensile strength of PLA polymer was investigated by producing filling percentages of 25%, 50%, 75% and 100%. It has been shown that the hardness, impact strength and tensile strength of the samples increase in proportion to the filling ratio. (Gunasekaran et al.,2020). The wear resistance of PLA, ABS, PP and PA polymers were compared by scanning the flank area of two teeth of the polymers. When the deviation amounts were examined, it was seen that PLA polymer had the best wear resistance behavior. (Ciobanu et al.,2024). PA6 polymer was produced using a 3D printer and glass fiber reinforcement was made to provide material diversity, and the effects of thermal softening were taken into account and wear resistance and hardness properties were investigated using an electron microscope. (Bolat & Ergene,2024)

Since the production parameters of the three-dimensional printer directly affect the properties of the final product, an algorithm has been produced for the change of printing speed, printing temperature, printer bed temperature and filler percentage from printer parameters. In the study carried out by using GA based ANN model of Nylon material with three-dimensional printer, writing temperature 250 C^o, writing speed 70 mm/bed temperature 25 C^o and filling percentage 80% were suggested (Zhang et al.,2020).

In another study, PLA and ABS polymers were produced by three-dimensional printer with three variations of printing lattice angle as 0^0, 45^0 and 90^0, layer thicknesses as 0.127, 0.254 and 0.33 mm and Pin-on disc test setup was used to investigate the wear resistance. It was stated that the increase in layer thickness provided a decrease in friction force and wear, the best lattice pattern was 45^0 and ABS polymer showed better wear resistance than PLA (Amirruddin & Ismail, 2021).

In a study examining the variation of wear characteristics with filler density, numerous variations were used in experiments by selecting 20%, 40% and 60% as filling ratio and rotational speed as 500, 1000, 1500 rpm. It was stated that extreme wear conditions were observed in the sample with 1000 rpm rotation speed and 40% filling rate, and excessive temperature increase occurred at 1500 rpm rotation speed at 60% filling rate. When the rotation speed was 500 rpm, thermal analysis and microstructure showed high temperature increase and wear caused by friction (Nafiz et al., 2023).

Using three different polymers, PLA, Tok-PLA and TPU filaments, spur gear wheels were produced with a three-dimensional printer and their surface strengths were examined. Thanks to the experimental setup, the effects of 0.5-4 Nm torque changes on the wear behavior were observed by electron microscope scanning at the end of the experiment. In the study where the temperature change on the tooth was observed with a thermal camera, it was determined that the polymer with the best wear resistance under the same conditions was Tok-PLA. It is concluded that the combination of two materials may be useful in terms of increasing wear resistance. (Chenxiao & Lee, 2023)

In this study, ABS, PLA and annealed PLA filaments were produced with a three-dimensional printer. As a result, it was determined that ABS has superior wear resistance compared to PLA by using surface punctuation technique and Minitab19 program (Portoaca et al.,2024). In order to examine the service life with the change of the infill density rate, PLA polymer was produced by additive manufacturing method and fatigue life was examined at 2.5 Nm torque and 1200 rpm rotational speed. Gear wheels were produced with fill percentages of 20%, 40%-60%, 80% and 100%. At the same time, the change in the number of rotations with the increase in torque was examined. In the 20% filled sample, fracture occurred in the tooth root and body, while sample with a filling density of 60%, fracture occurred in the tooth root and melting was observed on the tooth surface. With a filling density of 100%, PLA polymer showed a service life of over 300,000 rotations (Muminović et al.,2023).

Glass fiber reinforced ABS composite gears were produced with a three-dimensional printer and their hardness values were investigated with the change in fiber content. Polymer gears with 100% fill rate were lubricated and unlubricated to reduce wear and weight losses were compared. In the study, it was concluded that with the increase of glass fiber reinforcement, the glass transition temperature increased and better bonding between the layers was obtained, but the hardness decreased due to fiber aggregation. In addition, the highest weight loss was measured in the gear wheel without glass fiber reinforcement, designated as G0, under non-lubricated conditions (Bodaghi et al.,2023). With the decrease in the layer thickness of the gear wheels from 0.28 to 0.12, more than doubled time loss occurred, and deviations in tooth size accuracy with the change of helix angle were examined (Korka, 2022).

Acetal, Nylon 66, and PEEK polymers gear wheels were produced by molding method from granule form. Maximum contact pressures were calculated using finite element analysis. The test was varied by using a steel gear to investigate the wear behavior. In the finite element analysis, it is stated that the contact force is higher at the beginning of the mesh, which causes wear at the top end of the driven gear and in the root region of the driven gear. (Li et al.,2011)

The wear behaviors of HDPE, ABS and POM thermoplastics in granular form produced by molding method were investigated by obtaining different variations under the conditions of 0.8, 1.2, 1.6, 2.0 Nm torque and 600, 800, 1000, 1200 rpm rotational speed. The surface temperature increase, which is a result of wear at all torque values at the tooth roots, was observed mostly in POM plastic and least in HDPE plastic. The highest amount of specific wear rate was observed in ABS and the lowest in POM material. In the service life analysis, the POM gear showed the best performance with 2 million turns. (Singh,2018)

For POM and reinforced GFR-POM polymer gear wheels produced by injection molding method, the torque threshold value, which causes the wear to increase abruptly, was obtained by stepwise load increase method. It was observed that thermal damage rapidly increases the amount of unit wear while the strengthening process provides up to 50% improvement in strength. (Mao et al.,2018)

In the investigation of friction and wear of Acetal and Nylon gear wheels, it was determined that tooth surface temperature and load capacity are the major factors affecting wear. Under high load, the temperature rise approaching the melting point leads to deterioration of wear resistance. The wear development of the nylon gear is completely different from that of the acetal gear wheel in that it occurs at the tooth root and in the rolling circle region instead of on the surface. (Mao et al.,2019)

Materials and Methods

Geometry and Manufacturing of Polymer Gear Wheels

The gear wheels were designed using Solidworks@2013 in the geometry detailed in the Table.1. Three types of polymer materials, PLA, PETG and ABS filaments were used to provide material diversity in the study.

Table1. Dimensions of polymer gear wheels used in the experiments

	Driver (Polymer)	Driven (Steel)
Number of teeth	17	22
Pitch Diamater (mm)	102	132
Base Diamater (mm)	87	117
Outside Diamater(mm)	114	144
Module (mm)	6	6
Face width (mm)	10	10
Pressure Angle (degree)	20^o	20^o
Pitch (mm)	18.85	18.85

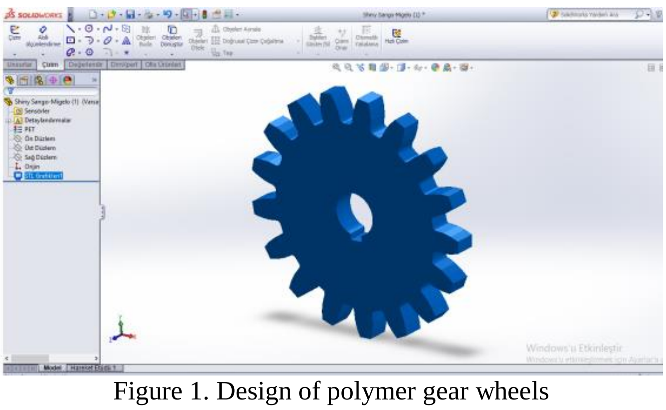

Figure 1. Design of polymer gear wheels

Colourfabb brand filaments with a diameter of 1.75 mm were used for the production of the designed polymer gears. For the wear of the driven (pinion) gear wheels, a gear wheel made of St-32 steel was used as abrasive. By using a steel gear wheel, it is aimed to obtain the accurate service life and the sufficient time for wear and also prevent from forming cohesion between polymer gears. The amount of wear of the steel gear wheel against the plastic gear wheels is negligible. Polymer gear wheels were drawn in the design program and then transferred to the running program that control the printer. Since each polymer type has different characteristics, different parameters are saved for printing before starting production for each polymer type. These parameters are given in Table 2.

Table 2. Printer parameters for each polymer

Printer Settings	PLA	ABS	PETG
Nozzle Diameter	0.4 mm	0.4 mm	0.4 mm
Filament Diameter	1.75 mm	1.75 mm	1.75 mm
Heated Bed Temperature	60 C^{o}	85 C^{o}	70 C^{o}
Extruder Temperature	210 C^{o}	245 C^{o}	245 C^{o}
Nozzle Diameter	0,40 mm	0,40 mm	0,40 mm
Infill pattern	Rectilinear	Rectilinear	Rectilinear
Infill percentage (%)	100/50	100/50	100/50
Shell Thickness (mm)	0.8/0.4	0.8/0.4	0.8/0.4
Printing Speed (mm/s)	3600	3600	3600

In the test setup, BCN3D Sigma R19 ® brand printer was used for the production of polymer gears whose wear rates will be investigated. Since this new model has two extruders compared to the old version, it provides the advantage of producing geometrically identical products simultaneously and halving the total production time.

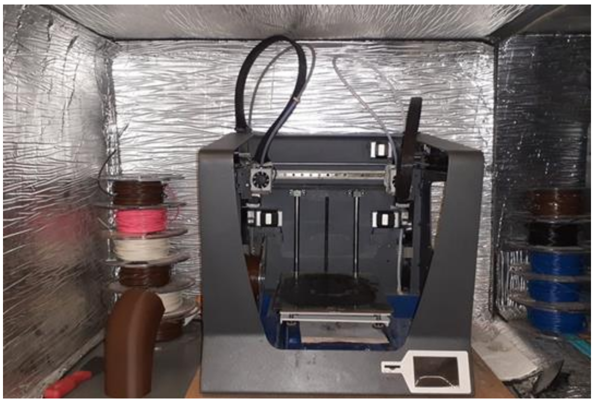

Figure 2. Printer used for the production of polymer gear wheels

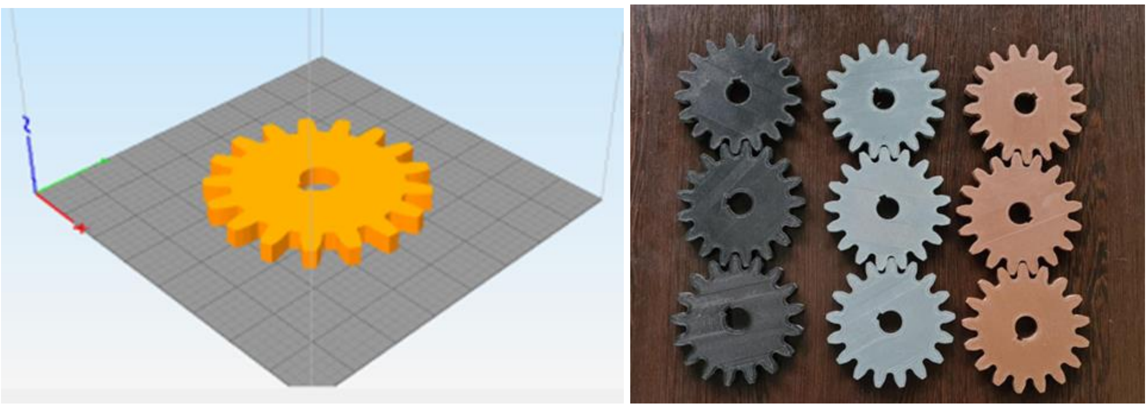

Figure 3. a) Slicing of polymers in the printer program b) PLA, PETG, ABS samples

One of the difficulties encountered in the study is the warpage caused by rapid cooling. The polymer material, which melts above 200 C^{o} during production, starts to cool down with the ambient temperature. Due to this rapid temperature drop, cooling occurs faster in thin section areas as a rule of heat transfer. For this reason, warping occur at the tooth ends as cooling occurs faster. Since the ambient temperature is lower especially in winter season, environment need to be heated or the printing machine can be insulated. Thus, it is aimed to slow down the cooling rate. Figure 2. shows that the three-dimensional printing device is in an isolated environment. On the other hand, in order to prevent the warping problem, a special solution was applied to the surface of the printer platform to stabilize the base of the product during printing. In this way, the tooth tips, which are normally expected to cool faster, are stabilized on the table. The Figure 4. clearly shows the stabilizing solution applied to the platform.

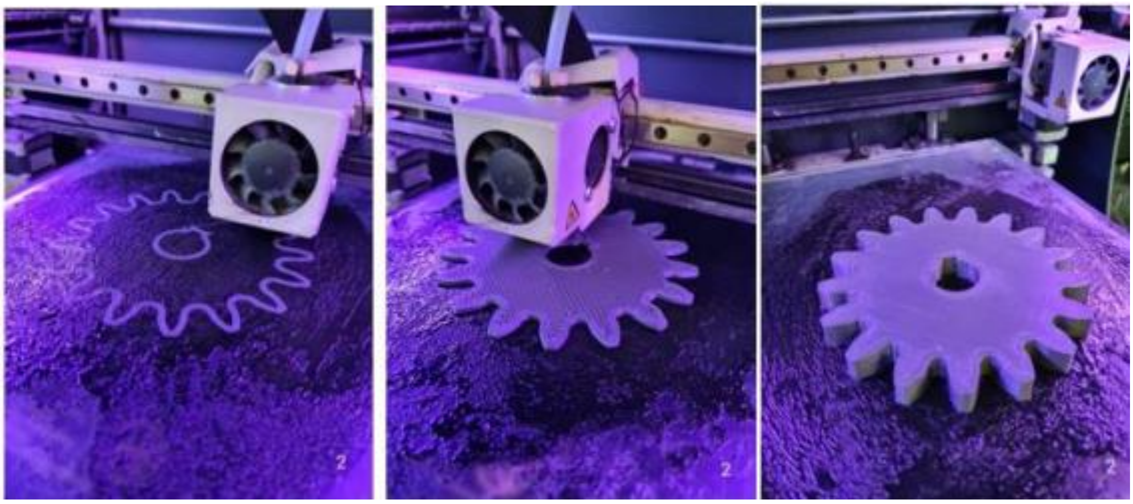

Figure 4. Production stages of PETG spur gear

Investigation of the Variation of the Outer Wall Thickness

Wear can be defined as the removal of chips from the surface of a softer material and it starts from the outer wall of the worn gear wheel. As can be seen in Figure 5, the development of wear on the tooth profile starts from the outer shell of the tooth and progresses by forming a profile towards the center. Therefore, the effect of outer shell thickness variation on wear was investigated in this study.

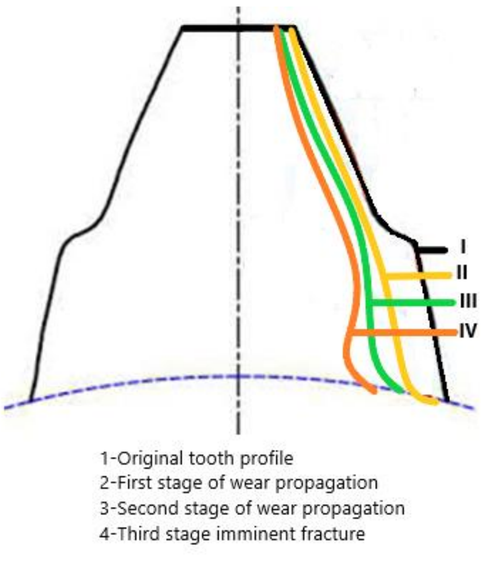

Figure 5. Wear progress from outer shell to center

On the other hand, one of the advantages of the additive manufacturing method is capability of controlling of the number of layers. Thus, the outer wall thickness of the gear can be intervened thanks to FDM technology. While the impact load resistance can be improved by increasing the material density on the outer surface of the tooth, weight and cost can be saved by obtaining a hollow structure in other regions.

Due to the fact that the wear of the gear wheels starts from the outer wall and the ability of the FDM method to make the desired number of walls, the wear rates of the gear wheels with different outer wall numbers are investigated in this section. For this reason, ABS, PLA and PETG spur plastic gear wheels with 50% filling rate from each material type were produced in two groups with outer walls of 0.4 mm and 0.8 mm. In this way, the effect of doubling the outer wall thickness on the wear resistance of the gear wheels was tested by applying certain loads with the help of a test rig.

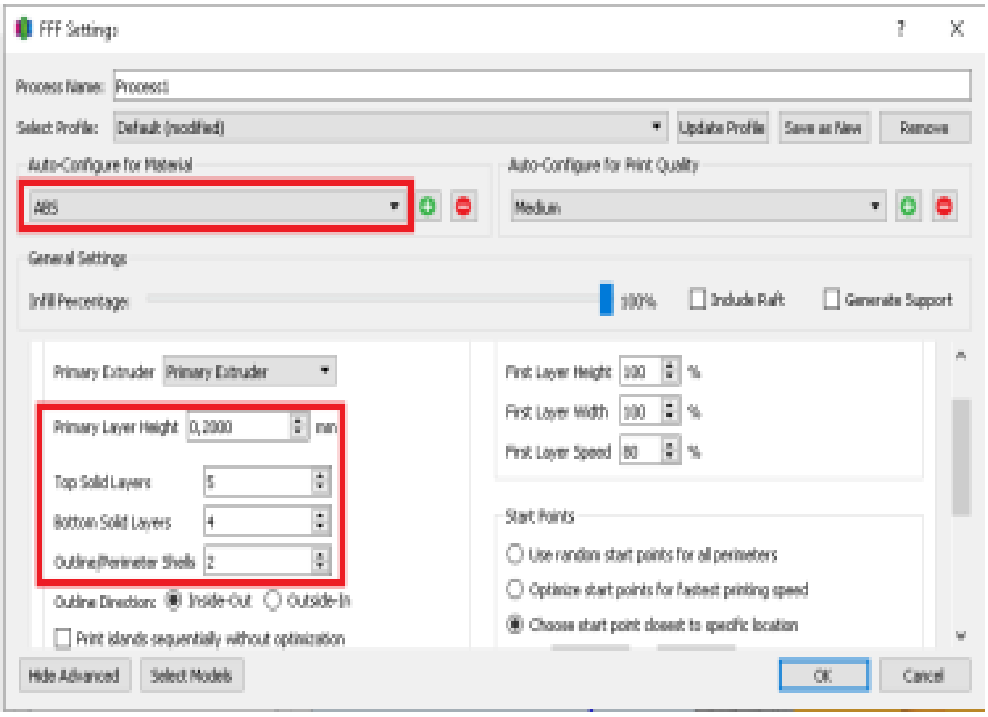

Figure 6.-Setting the outer wall thickness as 0.4 mm

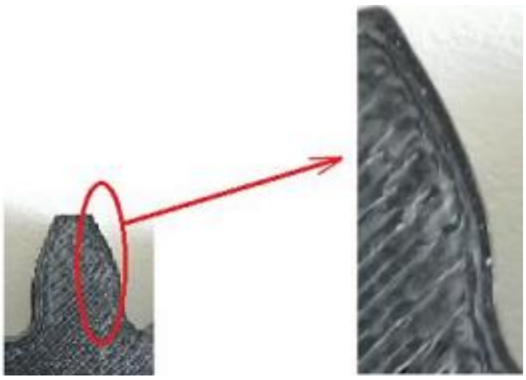

Figure 7. Specimen with wall thickness as 0.4 mm

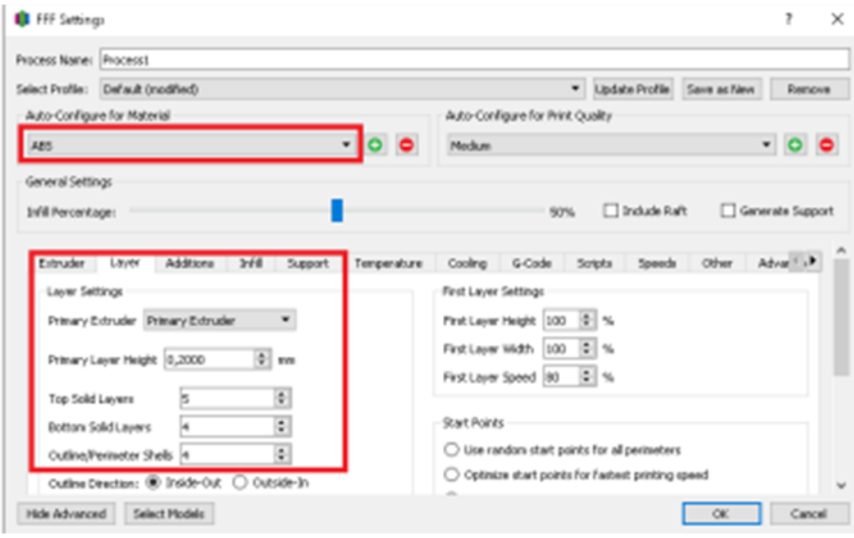

Figure 8. Setting the outer wall thickness to 0.8 mm

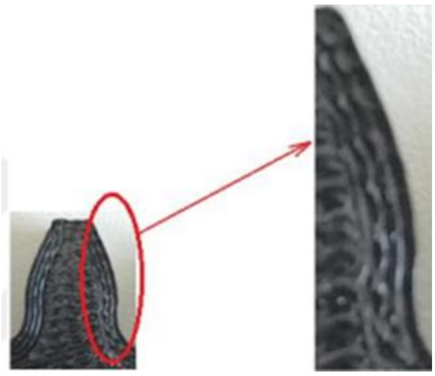

Figure 9. Production of outer wall thickness as 0.8 mm

Influence of Infill Density on Wear

One of the biggest advantages of FDM technology compared to traditional manufacturing methods is that the filling density of the product can be adjusted during production. (Nafiz,2023). It was examined the effect of filler density on strength in previous studies and stated that the minimum filler value can be 10-20% in order to maintain strength of body (Muminović,2023). One of the advantages of controlling the infill density is to reduce the total production time. In this section, the filling ratio of polymer spur gears is halved, less material consumption is aimed and the change in production time is analyzed. For this reason, two groups of spur gear wheels were produced from PLA, ABS and PETG filament materials with fill percentages of 100% and 50%. The produced samples were rotated 10^5 turns with the help of the test rig with 900 rpm rotation speed and 1.5 Nm torque load.

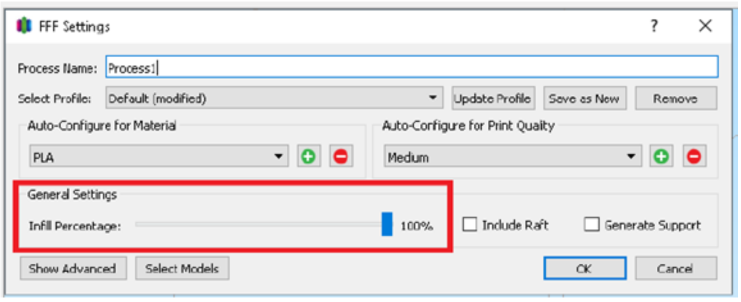

Figure 10. Setting the percentage of internal filling to 100%

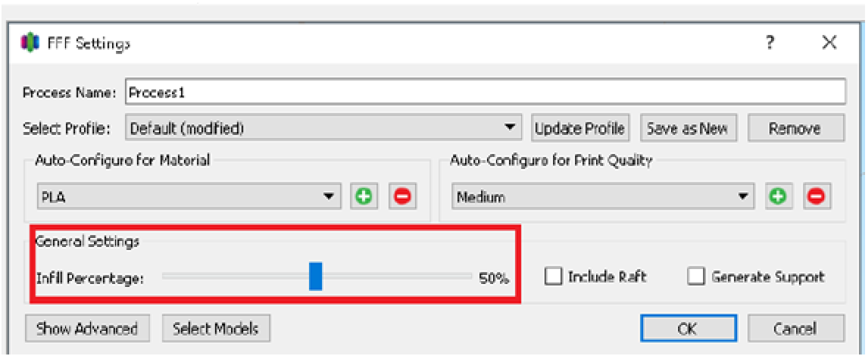

Figure 11. Setting the percentage of internal filling to 50%

Test Procedure

In the study, the FZG (Forschungsstelle fur Zahnrader und Getriebebebau) closed circuit test rig, which has been previously experienced in the literature, was used to determine wear and the service life of the gears. This test rig has been used many times to compare gear wear, corrosion, lubrication efficiency and oil classes by temperature control. (Lacey,1997)

In the test set-up, an electric motor with a power of 0.75 kW gives the first movement to the pinion gear via coupling connection. The electric motor can provide speeds of 300, 600 and 900 rpm. The components of the test rig are numbered in Figure 12.

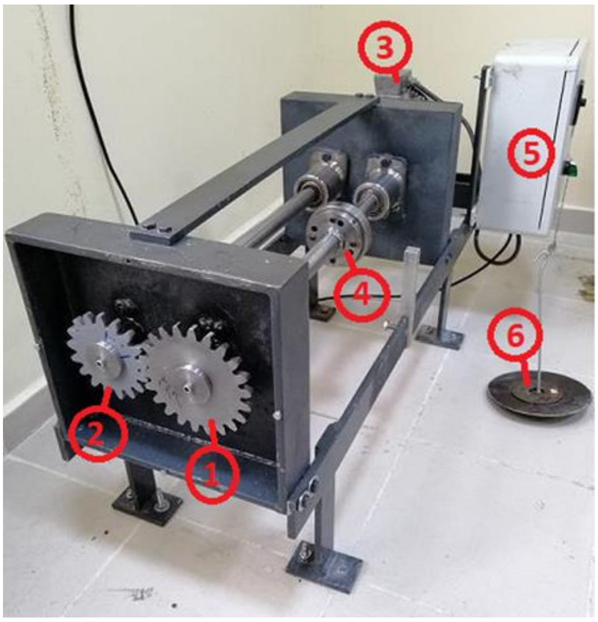

Figure 12. Test setup and components

Table 3. Illustration of test rig components

Test Rig Components	
1	Driven Gear (Steel)
2	Driver Gear (Polymer)
3	Motor Drive
4	Flange Coupling
5	Switch board
6	Scale pan

Relationship between Filling Percentage and Production Time

As mentioned earlier, one of the biggest handicaps of FDM technology is the long printing time. One of the advantages of the printing software is that the printing time can be seen before the process starts. Thus, the user can control the production more effectively and provide raw material supply. The production duration of the polymer gear wheels to be used in the study with the change of the infill rate are shown in Figure13.

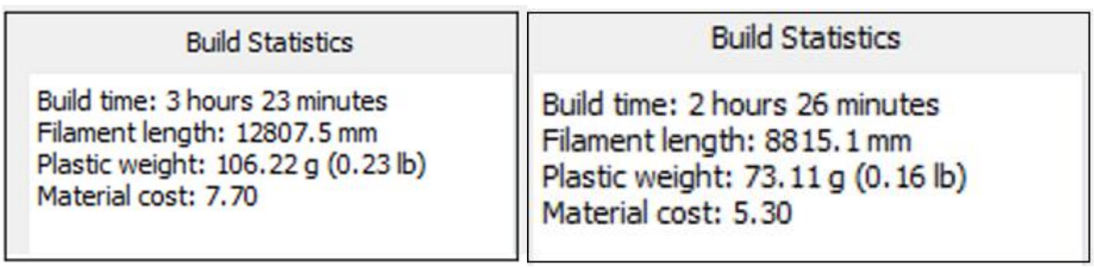

Figure 13. a) 100% filled polymer gear b) 50% filled polymer gear

Looking at the required printing time data obtained through the printer interface, 203 minutes are needed for a polymer gear to be produced as 100% full, while 146 minutes are needed for a polymer gear wheel to be produced as 50% full. This means that the reduced filler rate provides the user with a saving of approximately 25% in terms of time, energy and maintenance costs. When the effect of the reduction of the infill percentage in terms of material consumption is examined, 106.22 g of filament is required for a 100% full polymer gear wheel, while 73.11 g of filament is required with a 50% infill percentage. It can be noted here that although the filling percentage is reduced by 50% through the program, the weight is reduced by approximately 31%. The reason why the weight does not decrease in the same way as the fill percentage is that the printing machine saves filament more intensively in the center of the product in order to ensure product strength by producing a thinner pattern.

Investigation of Wear with Change in Filler Percentage

In this section, the effect of filler density, which is one of the advantages of additive manufacturing, on wear is analyzed. The obtained ABS, PLA and PETG gear wheels with 50% and 100% filler percentages were rotated at 900 rpm with the load placed on the scale pan (number 6) with a torque of 1.5 Nm and the rotation speed shown was adjusted from the selection panel (number 5) shown in Figure 12. REDWAG brand, seen Figure 14, analytical weighing scale was used to calculate the material loss. Each polymer was weighed electronically before the experiment and again after being subjected to abrasion with a steel gear at 100.000 cycles.

Figure 14. Analytical weight scale

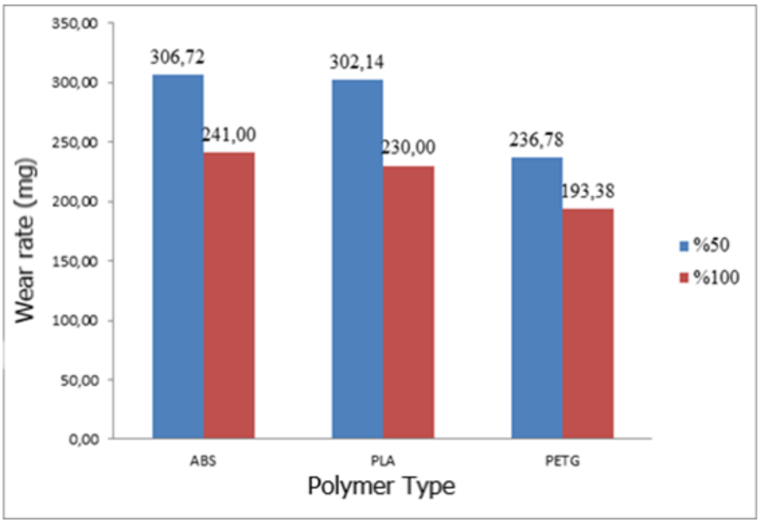

Figure 15. Change in infill percentage versus loss material due to abrasion

Effect of Outer Shell Thickness on Gear Wear

It was previously stated that wear develops in a profile starting from the outer shell towards the center. Therefore, in this section, the effect of the variation of the tooth shell thickness on the wear is investigated by measuring the mass losses. ABS, PLA and PETG polymer gear wheels with a 0.4 mm and 0.8 mm shell thickness were rotated 100,000 revolutions with a rotational speed of 900 rpm against a steel gear wheel and weighed with an electronic scale to measure the mass losses.

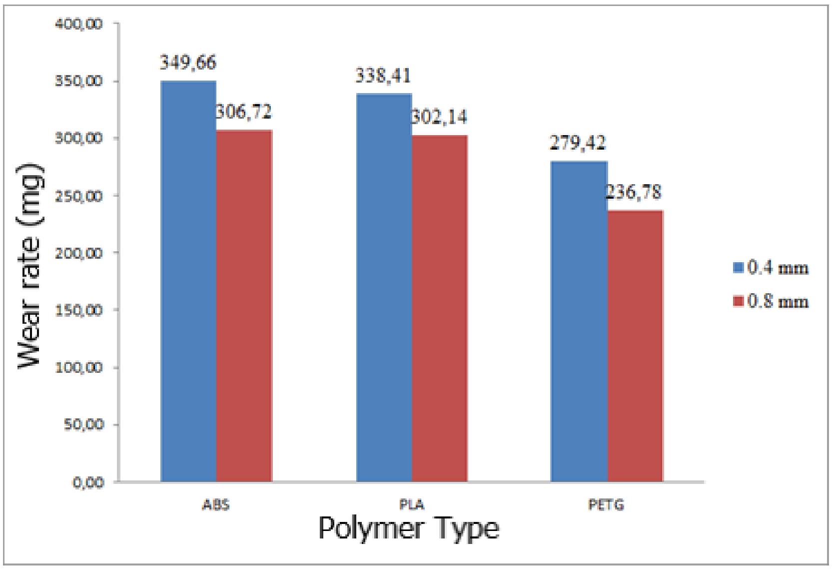

Figure 16. Material loss with the change of shell thickness

Results and Discussion

In the study, ABS, PLA and PETG gear wheels with identical geometry produced with FDM technology. Polymer spur gears were subjected to wear by operating with a steel gear using a test setup in which the rotational speed and torque can be controlled. In the study, the plastic gears were tested under the same conditions and the innovations of the additive manufacturing method were utilized as well as understanding which polymer type has higher wear resistance.

One of the benefits of FDM technology is the ability to intervene in the fill percentage as the printer working. In this way, by reducing the fill percentage in conditions where the strength conditions are not demanding, production time is reduced and labor and energy savings are achieved. For this reason, wear tests were carried out in this study using 100% and 50% samples. When filler rates were halved, wear rates showed growth; it was observed that 31.4% for PLA polymer ,27.2% for ABS polymer, 22.4% for PETG polymer respectively. In other words, PLA was the most affected polymer type when the filling percentage was halved. In general, in case 50% drop in the filling percentage cause an increase of approximately 30% in the amount of abrasion.

Another result obtained in the experiments was that the strengths of the polymers were PETG, PLA and ABS, respectively, even though the filling percentage changed. It was previously stated that wear starts from the outer wall of the gear wheel and that this thickness affects the gear wheel strength. As a result of the experiments, it was seen that the wear change with increasing the outer shell thickness from 0.4 mm to 0.8 mm is calculated as 10.71% for PLA polymer, 12.28% for ABS polymer and 15.26% for PETG polymer. It can be said that the increase in outer shell thickness equally for all polymers, the highest durability and lowest wear were observed for PETG, ABS and PLA respectively. When the effect of increasing the outer shell thickness on the strength is considered in general, it caused an average improvement of 12% for all polymers.

Conclusion

FDM technology firstly melts filament and molten material forms the desired geometry. Then polymer starts to solidify on the platform. The key point is here obtaining a progressive cooling rate, because the cooling rate is vital for making vigorous bonds among the layers. That is why printing machines can be insulated to control cooling rates instead of running in an exposed atmosphere. Table 2 shows the amount of bed temperature for each polymer type. According to the table, because PLA has a minimum bed temperature, as 60C^{o}, it can be assumed that it has the ability to print better than the other polymers. Conversely, the highest energy is needed to print for ABS polymer that has a bed temperature of 85 C^{o}.

Recommendations

As plastics have poor thermal conductivity, they tend to emit heat energy. This energy gives rise to become softer and subsequently lose their toughness. Because of this drawback of plastics, Researchers faced distortion problems at the tips of gears. To overcome this problem, the tip of plastic gears can be glued with a chemical solution which can be dissolved after printing process.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Acknowledgements or Notes

* This article was presented as an oral presentation at the International Conference on Advances in Technology and Innovation (www.icati.net) held in Antalya/Turkey on November 14-17, 2024.

* Researchers conducted the experiments in the laboratory at Hitit University and meet all the costs without getting any incentives.

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To cite this article:

Agca, B.V., & Tunalioglu, M.S. (2024). Experimental investigation of the wear of some polymer gear wheels produced by three-dimensional printer on the variation of fill percentage and shell thickness. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 31*, 52-63.