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Investigation of The Wear And Friction Profile of TPU-Based Polymers at Different Infill Ratios

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Research Article

Abstract

Additive manufacturing is a widely used method in industry and research areas. In particular, fused deposition modelling is the most prevalent technique used by many professional and nonprofessional users. Many polymers can be used with this system, including thermo polyurethanes (TPU). TPUs have excellent elastic properties and high endurance against corrosion, humidity, and oil, and they exhibit a great absorbance capability to noise and vibrations, biocompatibility, and chemical resistance. Thermoplastic polyurethane (TPU) is also preferred for use in 3D/4D printing applications due to its easy casting, injection, and extrusion capabilities. In this study, flexible TPU and carbon-mixed TPU were used to produce specimens with fused deposition modelling techniques at different infill ratios with the same patterns. The effects of the infill ratio within the different and same materials were investigated in terms of wear and friction profiles. Additionally, thermal and worn surface images were taken using a digital microscope. The hardness and diameter value alterations were also investigated for different materials and infill ratios. As a result of the study, material alteration is more effective than the infill ratios in all parameters.

Keywords: Carboflex; Fused deposition; Flexible polymers; Friction; TPU; Wear

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1. Introduction

Additive manufacturing systems have been widely used in manufacturing processes in industry and in the research field over the last two decades. There are many types of additive manufacturing systems [1–3], such as powder bed fusion, stereolithography [4], binder jetting, material jetting [5], directed energy deposition, wire arc additive systems [6], and material extrusion systems [7,8]. The main principle of these systems is to manufacture the designed parts based on the layer-by-layer approach, resulting from the additive production process without any subtractive or removal steps such as milling, drilling, grinding, or cutting. Metal, polymer, and composite materials can be processed with additive manufacturing technologies, and the technology has been used in many industrial areas, such as automotive [9], aerospace [10,11], health [12–15] and construction [16,17].

Systems based on the material extrusion process are the most popular in the additive manufacturing area selected by professional and nonprofessional users due to their availability, cost-effectiveness, accessibility to feedstock, and lack of need to experience. Polymers such as PLA, ABS, PCL, PETG, and many more are the key materials used as feedstock. In particular, fused deposition modelling (FDM) is a widely used fabrication system in material extrusion applications [18,19]. Basically, the system has a heating head where the polymer is melted and extruded through the heating barrel to the nozzle and a heated bed (build platform). Generally, the feedstock can be purchased coiled on a spool in filament form. This filament is transmitted to the heating barrel via drive wheels. Predesigned samples are printed via melted polymers extruded from the nozzle.

TPUs have excellent elastic properties and high endurance against corrosion, humidity, and oil, and they exhibit a great absorbance capability to noise and vibrations, biocompatibility, and chemical resistance [20,21]. These superior features make popular TPUs in health care and sensor applications [22,23], automotive [24–26], agri-food, and military industries [21]. Recently, the demand for TPUs has increased in the industry because they are thermoplastic materials, elastomers, coatings, adhesives, or foams [27].

Thermoplastic polyurethane (TPU) is also preferred for use in 3D/4D printing applications due to its easy casting, injection, and extrusion capabilities and its shape memory features [28,29]. Medical grade TPU was used to produce samples with a fused deposition modelling (FDM) system to investigate tensile stress properties under different raster angles and temperatures in a study [30].

The results of this study show that the best mechanical characteristics were found for the specimens produced at 215 °C and a 45° raster angle. Rahmatabadi et al. examined the fracture toughness, mechanical properties, and morphology of PLA-TPU composite structures fabricated by additive manufacturing processes. As a consequence of the study, they stated that an increase in the TPU amount inside the composite decreases the mechanical endurance due to internal voids in the structures. These voids occur because of the melting resistance, high viscosity and incomplete melting of the TPU material [18]. The tensile properties were investigated for composite structures of PLA/TPU samples prepared via a fused deposition modelling technique. It was found that increasing the TPU volume in the composite structure increases the elasticity of the samples [31].

TPUs are also used as a shape memory or intelligent material in the 4D printing process, which uses 3D printing technology with smart materials that change shapes under the external load and recover after removing the load [32,33]. To investigate the behaviors of the composite structure of PLA/TPU/Fe_3O_4 (polylactic acid (PLA), thermoplastic polyurethane (TPU) and Fe_3O_4 particles) manufactured with fused filament fabrication techniques under magnetic and heat forces, a research study was conducted [33]. They stated that all samples present shape memory capacities; however, structures including more Fe_3O_4 particles have a great recovery speed. In another study, Jing et al. examined the PCL and TPU composite polymer in terms of the responsive shape memory properties to use the product in biomedical applications. They blended two polymers using a twin-screw extruder. After that, they investigated the cell biocompatibility of the product and thermal shape recovery. They suggested that the combination of PCL/TPU polymer samples could be suitable for suture application in the medical area [34].

The adhesive properties of TPU with other chemicals and additives were investigated for automotive applications in a study published approximately 30 years ago [35]. In another study, TPU powder slush was proposed to be used instead of PVC for interior parts such as instrument panels and door trims of an automobile. The results show that samples produced from TPU powder slush present appropriate moldability, material properties, and part performance [25]. Atiqah et al. studied hybrid composites prepared by palm/glass/thermoplastic. A hot-pressing moulding was used to manufacture samples after preparing mixtures with and without saline and alkaline treatment separately. Thermal stability was investigated in each sample. [36]. Dynamic mechanical properties were also investigated for the same hybrid composites in another study by the same authors [37]. The results show that treated samples improve thermal stability and mechanical properties. They suggested that these composites might be appropriate for automotive applications in the two studies. Five different thermoplastic matrices (thermoplastic polyurethane, high-density polyethylene, low-density polyethylene, polystyrene and polypropylene) with hemp fibre were manufactured for the anti-roll part of an automotive [38]. The Quality Function Deployment for Environment (QFDE) technique was used to determine the best material, and a mechanical test was carried out to investigate Young's modulus. As a consequence, in this study, hemp-reinforced TPU parts present a higher Young's modulus of 10.6 GPa, and TPU was the second choice in the QFDE technique; therefore, they claimed that the most suitable material selection for the anti-roll part is TPU composites [38]. Thermoplastic polyurethanes have the potential to be used for nonpneumatic tyres in automotive applications. Wang et al. investigated the potential of TPU-based nonpneumatic tyres that produced FDM in their study. They successfully created a tire with FDM technology [39].

As per our knowledge based on the literature, there have been many studies working on the mechanical, biological, and electronic features of 3D-printed TPU samples. However, the investigation of the wear and friction properties of TPU-based structures is limited in the literature. Therefore, these topics need more and deeper investigation for TPU polymers, especially to understand the friction for nonair tire applications and wear for exterior parts. In this study, flexible TPU and carbon-mixed TPU were used to produce specimens with fused deposition modelling techniques at different infill ratios with the same patterns. The effects of the infill ratio within the different and same materials were investigated in terms of wear and friction profiles.

This preliminary study shows that TPU polymers might have potential usage in absorption, exterior parts, low friction, and elastic applications. Moreover, the study shows that even though it is difficult to print TPU with a layer-by-layer process because of its high elasticity, the specimens were fabricated successfully.

2. Material and Methods

Two types of commercial thermoplastic polyurethane (TPU) flexible filaments (Sava TPU carboflex V60 filament and sava TPU (flex) 92A filament) were used in this study; in the rest of the text, they will be called TPUC and TPU, respectively. The filament properties can be seen in Table 1.

Table 1. TPU and TPUC filament properties

TPU filament properties *	Value
PLA filament diameter	1.75 mm (± 0.05 mm)
Color	Black
Specific gravity	1.22 g/cm^3 (TPU) and 1.23 g/cm^3 (TPUC)
Hardness	92 Shore A (TPU) and 55 Shore D (TPUC)
Print temperature	210~240 °C
Tensile elongation	810% (TPU) and 520% (TPUC)
* provided from manufacturer	

A fused deposition modelling (FDM) system was used to fabricate test samples. These samples are a form of cylindrical 20 mm in height and 10 mm in diameter. They were designed in CAD software and sliced in a Prusa Slicer to obtain G-code for manufacturing in the FDM system. The schematic illustration of the fabrication system is presented in Figure 1. Before fabrication, the FDM system was calibrated to ensure the accuracy of the measurements of the sample sizes.

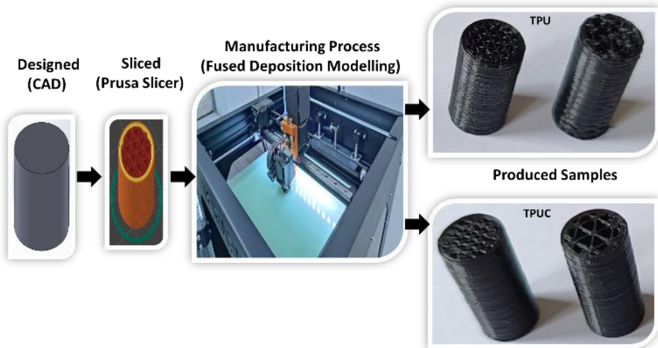

Fig. 1. Fabrication process and produced samples.

Test samples were produced at two different infill densities of 45% and 90% from TPU and TPUC polymers as triangular patterns. When the sample is produced from the TPU filament, the sample with 45% infill density is called TPU45, and the sample with 90% infill density is called TPU90. Similarly, if the samples were fabricated using a TPUC filament, it was called TPUC45 or TPUC90 based on the infill density. All the dimensions of the test samples were 10 mm diameter and 20 mm height. The fabrication properties can be seen in Table 2.

Table 2. Fabrication properties

FDM system specifications	TPU	TPUC
Ambient temperature	20 °C - 25 °C	20 °C - 25 °C
First layer bed temperature	55 °C	65 °C
After the first layer bed temperature	50 °C	60 °C
First layer nozzle temperature	225 °C	235 °C
After the first layer nozzle temperature	220 °C	230 °C
Nozzle diameter	0.4 mm	0.4 mm
Layer height	0.2	0.2 mm
Infill density	45% and 90%	45% and 90%
Infill pattern	Triangular	Triangular
Infill Angle	45°	45°
Number of walls	2	2
Printing speed	80 mm/s	80 mm/s

After the fabrication of test samples, diameters were measured using a digital micrometer to determine deviations from the designed model. The hardness of the samples was determined using a Shore D device, which was calibrated before each measurement. To obtain the weight loss of the samples, a precision balance was used before and after the friction/wear test. All measurements were repeated three times for the samples. After the friction experiment, the temperature was immediately detected at the top of the sample surface using a thermal camera (Flir brand).

Fig. 2. Friction test device

Wear and friction experiments were executed using a pin-on-disc device (Turkyus) (Figure 2), which was calibrated prior to the experiment. Each sample was carefully cleaned before the experiments. Tests were conducted at room temperature for 1200 seconds. The samples were connected to the arm of the device parallel to the CK45 disc. The experimental conditions used in the friction/wear test can be seen in Table 3. Images of worn surfaces of TPU and TPUC samples were taken using a digital microscope (Dino Lite, AM7915MZT).

Table 3. Friction/wear experiment parameters

Experiment Parameters	Value
Load	15 N
Time	1200 s
Revolution	300 rpm
Track diameter	40 mm
Pin material	TPU and TPUC (3D printed)
Disc material	CK45
Ambient Temperature	20 °C - 25 °C

3. Results

3.1 Diameter and Hardness

The diameters and hardness values of the samples produced with a 3D printer were measured. The dimensional stability of the samples was evaluated according to their infill density ratio and filament types. In Figure 3, the hardness and diameter values of the TPU and TPUC samples were determined. The target diameter values of the samples were set as 10 mm. However, the diameter values of the produced samples were smaller than 10 mm. This is related to the shrinkage of the samples after cooling. Diameter deviation values vary according to the types and infill densities of the filaments. The samples produced with TPUC filaments deviate less than 10 mm. When evaluated according to the occupancy rates, the diameter deviation values were close to each other. The hardness values are also similar to the diameter changes. In other words, the hardness values differ according to the filaments. Infill density is not very effective on hardness. The highest hardness value was reached in the TPUC samples. According to the results obtained, filament types are effective on the hardness and diameter deviation values of the samples. Infill densities are not very effective in these results.

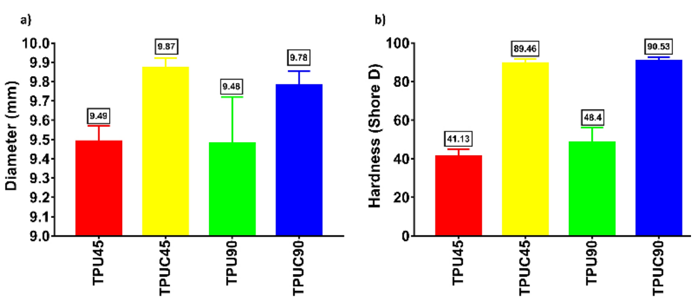

Fig. 3. a) Diameter and b) hardness values of TPU and TPUC samples at different infill densities.

3.2. Temperature Variations

As soon as the friction tests were finished, the temperatures of the samples were measured with a thermal camera. During the test, the effect of different filament and filler ratios on the test temperature was evaluated. The temperatures formed after the test in TPU and TPUC samples are given in Figure 4. The temperatures formed in the samples after the tests vary according to the filament type. It was seen that the change in infill ratios does not have much effect on the resulting temperature. Higher temperatures occurred in TPU filaments. This is due to the frictional behaviour between the disc surface and the test specimen. As the friction coefficient between the sample and the disc increased, the test temperatures of the samples also increased. The fact that the friction coefficient of TPU samples is higher than that of TPUC samples (Figure 3) supports this situation.

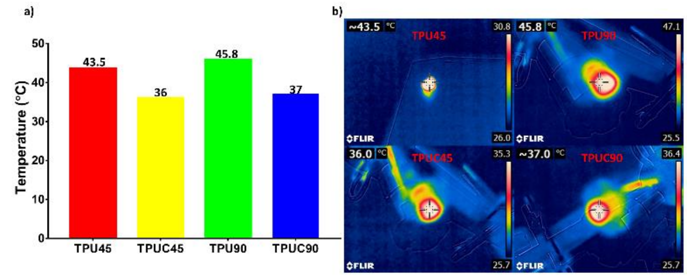

Fig. 4. a) Temperature values and b) thermal images at the top surface of the TPU and TPUC after the experiment

3.3. Friction and Weight loss

The friction coefficient and weight loss graph of the samples are given in Figure 5. Figure 5a shows the friction coefficients of the samples. The average friction coefficients are different according to the filament types. The friction coefficients of the TPUC samples are lower than those of the TPU samples. In this case, the friction coefficient is reduced by adding carbon to the TPUC filament. This situation might be related to the softness and elasticity of the TPU samples. This feature might lead to the behavior of TPU as an adhesive. The friction coefficient changed according to the infill ratios. It was concluded that as the infill ratios of the samples increased, the friction coefficient also increased. This can be explained by the increase in the contact area of the samples in the friction test with increasing infill density. The lowest coefficient of friction was achieved in the TPUC sample (0.419) filled with 45%. The highest coefficient of friction was obtained in the 90% filled TPU sample (0.887). There was a 52.76% difference between these two friction coefficients. These results showed that the friction coefficient can be improved by choosing the appropriate filament and filler density.

In Figure 3b, the weight changes obtained as a result of friction tests are given. The highest weight loss occurred in TPU45 samples. It was observed that these samples were significantly deformed during the test. It has been found that its dimensional rigidity is low. This also affected the weight loss results. The weight losses of the other samples were found to be similar.

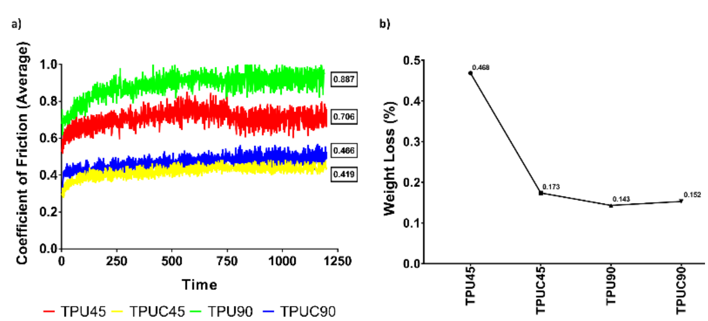

Fig. 5. a) Average coefficient of friction spectrum b) the percentage of weight loss after the experiment

3.4. Wear Defects on Surfaces

The wear images of the contact surfaces of the test samples as a result of the friction tests are given in Figure 6. It was observed that TPU45 samples were deformed after testing. The circular form of the samples is deteriorated. This shows that low filler density with TPU filaments has low resistance to loads and abrasion. It was found that the dimensional and shape deformation is less in TPU90 samples. The TPUC45 samples are more resistant to dimensional and shape deformation than the TPU45 samples. It was determined that the wear marks were more pronounced as the infill density increased. With the increase in the infill density, the traces became more pronounced with the effect of increasing surface area and the resulting temperature.

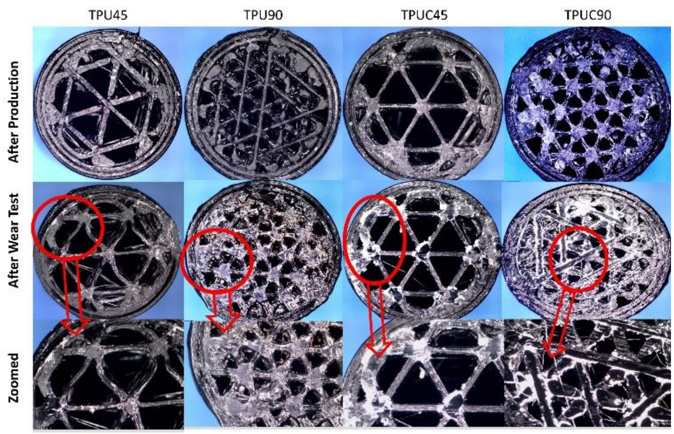

Fig. 6. Images of the samples before and after the friction experiment; zoomed worn surfaces of TPU and TPUC samples

4. Conclusions

The following results were obtained as a result of the friction wear tests of the samples produced with 45% and 90% infill density using TPU and TPUC filaments.

- The hardness and diameter values were higher in TPUC samples, independent of the infill ratios. This shows that whereas differences in material have effects on hardness and diameter, infill ratios are not very effective in these results.
- As a result of the friction test, a higher temperature occurred in TPU filaments than in TPUC samples. The temperatures formed vary according to the filament type. It is understood that the change in infill density does not have much effect on the resulting temperature.
- The friction coefficients of the TPUC samples are lower than those of the TPU samples. It can be said that the addition of carbon to the TPU filament makes it harder and decreases the adhesive properties of TPU.
- It was observed that the samples produced with TPUC filaments presented more resistance to dimensional and shape deformation and abrasions than TPU samples.

As a result of the study, material alteration is more effective than the infill ratios in all parameters. In the future, TPU-based composite materials with other components can be investigated deeply in terms of mechanical and tribological tests. This study might be a starting point for these kinds of research.

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Enes Aslan: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review
Gülşah Akıncıoğlu: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft

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