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TRIBOLOGICAL PERFORMANCES OF THE 3D PRINTED MATERIALS USED IN THE CONSTRUCTION EQUIPMENT FIELD

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Abstract: *The emerging interest in additive manufacturing (AM) technology imposes research aimed to characterize the behavior of the 3D printed materials in real operating condition. 3D printing is a manufacturing method which is growing in popularity because it is faster, more economical, and environmentally friendly than other classical methods. Also, this method provides new possibilities in design and manufacturing machines due to the advantage of obtaining complex shaped parts. This paper presents the results of tribological investigation for different 3D printed materials produced by the fused filament fabrication (FFF) technology. The studies highlight the friction coefficient for three material couples: Poly Lactic Acid (PLA)-on-steel, Acrylonitrile Butadiene Styrene (ABS)-on-steel and Polyethylene Terephthalate Glycol (PET-G)-on-steel. The results show the ranking of the three analyzed materials and which of them has the best tribological properties compared to real coupling.*

Key words: *additive manufacturing, 3D printing, friction coefficient, tribology, fused filament fabrication.*

1. INTRODUCTION

The growing interest in sustainability and a circular economy aims to improve resource efficiency throughout the manufacturing process, usage, and post-disposal of materials. 3D printing technology through additive manufacturing (AM) is becoming increasingly important as a more economical, faster, and environmentally friendly method of material fabrication. 3D printing of thermoplastic composites contributes to reducing production time, enabling recyclability of printed materials, generating less waste, creating lightweight and customizable components, saving resources and energy, and minimizing associated emissions. Sustainability in 3D printing depends on the influence of printing parameters such as ambient temperature, raster angles, and printing speed [1]. 3D printing offers new possibilities in the design and manufacturing of machines and device components due to the advantage of obtaining parts with complex shapes.

As 3D printing technology continues to dominate polymer component production in various engineering fields, the need to scrutinize the mechanical and tribological properties of the newly fabricated surfaces [2] becomes imperative. This in-depth analysis is vital for advancing the understanding of how 3D printing influences the performance of materials in dynamic and friction-prone environments, contributing to the improvement and optimization of 3D-printed components across diverse engineering applications. Several studies [3,4,5] have focused on determining the mechanical properties of distinct materials used in 3D printing. Some research addresses the influence of the printed surface on the durability of parts, while others investigate the thermal effects on the performance and durability of printed parts.

3D printing is a general term used for most technologies working on the principle of additive manufacturing. Over the past three decades, many new 3D printing technologies have been developed worldwide and are still evolving [6]. Nowadays, with the help of additive manufacturing technology, almost any material can be printed, including metals, ceramics, polymers, etc. 3D printing, specifically fused filament fabrication (FFF), is one of the most accessible and widespread rapid prototyping technologies [7,8]. Applications for 3D-printed elements can be diverse; for example, functional mechanical components like a pulley for lifting small objects for drone transport [9]. For such mechanical components, it is crucial to replace rolling bearings (ball bearings) with sliding bearings to reduce the total weight of the device. In this context, the article presents experimental research on evaluating the friction coefficient for bearings made from common and affordable 3D printing filaments in terms of technology and manufacturing cost.

In this paper we studied the performance under load of three different 3D printed materials compared with polyamide, usually used for certain mechanical components.

2. MATERIAL AND METHODS

2.1 Specimen design

The tested coupling consists of a printed ring-shaped part and a steel component belonging to the experimental module where tribological studies were conducted.

To manufacture the elements used in the friction tests, a Creality ENDER-3 3D printer was used with the following functional characteristics: nozzle diameter of 0.4 [mm]; maximum nozzle temperature of 255 [ºC]; print volume is 220 x 220 x 250 [mm]; printed layer thickness of 0.1-0.4 [mm]; positioning precision of 0.1 [mm]; maximum printing speed is 180 [mm/s]; heated print bed with a maximum working temperature of 120 [ºC]. The printer used employs the Fused Filament Fabrication (FFF) technology.

Three materials were used to create the elements for the friction coupling:

- PLA (Polylactide) Filament: is a material made from renewable sources such as cornstarch and sugar cane, and it naturally degrades under certain conditions. It can be used for various mechanical and ornamental parts, with average mechanical strength, low flexibility, medium durability, and easy 3D printing [10]. The filament used has the following technical characteristics: filament diameter 1.75 [mm]; recommended printing temperature of 195-220 [ºC]; recommended heated bed temperature of 50-70 [ºC]; density 1.25 [g/cm^3].
- ABS (Acrylonitrile Butadiene Styrene) Filament: can be used for functional mechanical parts, with medium mechanical strength, medium flexibility, high durability, and it is challenging to 3D print (requires an enclosure to maintain temperature during printing) [10]. The filament used has the following technical characteristics: filament diameter 1.75 [mm]; recommended printing temperature 240-260 [ºC]; recommended heated bed temperature 100-120 [ºC]; density 1.04 [g/cm^3].
- PET-G (Polyethylene Terephthalate Glycol-Modified) Filament: can be used for various parts, is water-resistant, has medium mechanical strength, is shock-resistant, durable, and is easy to 3D print [10]. The filament used has the following technical characteristics: filament diameter 1.75 [mm]; recommended printing temperature of 220-260 [ºC]; recommended heated bed temperature of 70-80 [ºC]; density 1.23 [g/cm^3].

To distinguish the parts during tests, they were printed in distinct colors: PLA in red (figure 1-left), ABS in blue (figure 1-middle), and PET-G in yellow (figure 1-right).

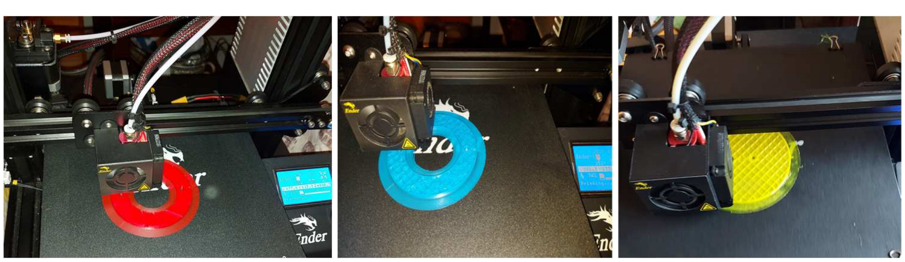

Fig. 1. The production of specimens using 3D printing technology

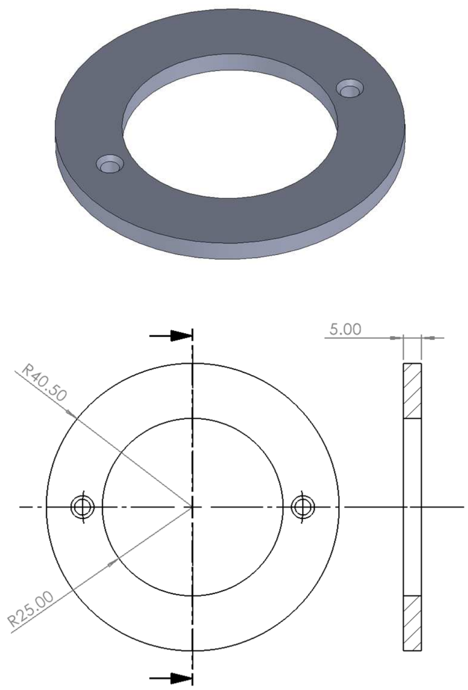

Fig. 2. The sample dimensions

The samples were designed at the dimensions required (figure 2) by the apparatus used for the tests (tribometer), using SOLIDWORKS 3D modeling software. Creality Slicer Software, a 3D printing preparation software, was used for 3D printing [11,12]. The set parameters for 3D printing were: filament diameter 1.75 [mm], printing nozzle diameter 0.4 [mm], layer height 0.2 [mm]; wall thickness 1.2 [mm]; print density 25%; PLA printing nozzle temperature was set to 204 [ºC]; ABS printing nozzle temperature was set to 252 [ºC]; PET-G printing nozzle temperature was set to 250 [ºC]; PLA heated bed temperature was set to 60 [ºC]; ABS heated bed temperature was set to 118 [ºC]; PET-G heated bed temperature was set to 80 [ºC]; printing speed was set to 50 [mm/s].

2.2 Test methodology

For the analysis of the tribological characteristics of the studied pair, the experimental stick-slip module TM 260.04 was used, as depicted in figures 3.a and 4. This module was designed and manufactured by the GUNT company in Germany [13,14]. The speed applied to the contact is controlled, and the friction force can be measured with the aid of the basic control and measurement unit TM 260.00 (figure 3.b). The contact load is achieved by progressively attaching discs of different weights (1) directly to the driven disc (the printed specimen) of the experimental pair.

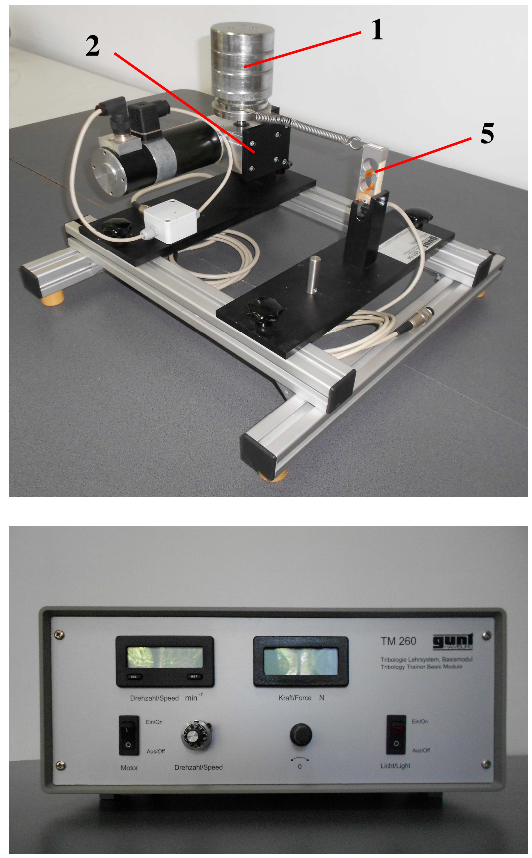

Fig. 3. The experimental stick-slip module on the top image, and the basic control and measurement unit on the bottom image

The drive system (2) imparts a rotational movement to the leading disc at various speeds selected from the base unit of the installation. The driven disc (3) is positioned on the driving disc (4), allowing the two discs in contact to have the possibility of relative displacement. The driven disc is connected to the force transducer (5) through the wire (6) and the helical tension spring (7). By adding other discs with geometric shapes identical to the driven disc but of different weights (1), the variation of the contact load between the two discs, driven and driver, is achieved.

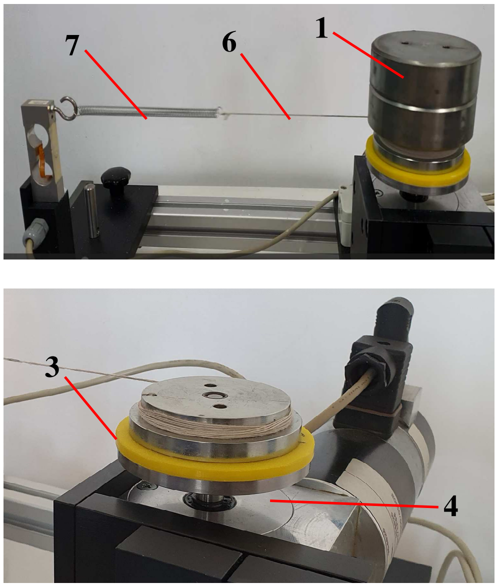

Fig. 4. Detail of the driven (3) and driving (4) discs with the attaching discs of different weights (1)

The relationship between friction force and tension force, developed in the helical spring, highlights the moment of separation of the kinetic friction force from the static friction force. Using this setup, the critical friction force is determined, which is characteristic of the moment when the welded microjunctions shear, marking the onset of the sliding period. The friction coefficient is determined based on the following equation:

$$F_f = F_n \cdot \mu_0. \quad (1)$$

where: $\boldsymbol{F_f}$ is the critical friction force, $\boldsymbol{F_n}$ is the contact load and $\boldsymbol{\mu_0}$ is the friction coefficient.

3. RESULTS AND DISCUSSIONS

The test results consist of comparision of maximum friction coefficients of the three specimens analyzed on the steel disc. For a comparative analysis with a real contact, testes were also carried out on the polyethylene-on-steel coupling, a widely used polymer in engineering applications due to its excellent properties such as low friction coefficient, lightweighting and durability.

The tests were conducted under dry sliding conditions, with applied contact loads of 5, 10, 20, 30 and 35 [N], and selected speeds of 10, 25, 50, 80 and 120 [mm/min].

The results obtained are presented in table 1 and 2. Table 1 shows the measured values of the maximum friction coefficient dependent on speed, for a constant normal load of 20 [N], and in table 2 are the recorded data of the maximum friction coefficient dependent on the contact load for a selected constant speed of 80 [mm/min].

The values are displayed in figures 5 and 6 for a clearer comparision of the obtained data.

Table 1

Measured values of the maximum friction coefficient dependent on speed.

Material pair	**Selected speed [mm/min]**	**Normal load, F_n [N]**	**Friction force F_f [N]**	**Friction coefficient, μ_0**
PLA on steel	10	20	2.8	0.140
	25		3.5	0.175
	50		4.1	0.205
	80		4.7	0.235
	120		5.3	0.265
ABS on steel	10	20	3.4	0.170
	25		4.1	0.205
	50		5.0	0.250
	80		6.2	0.310
	120		7.1	0.355
PET-G on steel	10	20	4.4	0.220
	25		4.6	0.230
	50		5.1	0.255
	80		5.7	0.285
	120		6.3	0.315
Polyethylene on steel	10	20	4.5	0.225
	25		4.5	0.225
	50		4.6	0.230
	80		4.7	0.235
	120		4.8	0.240

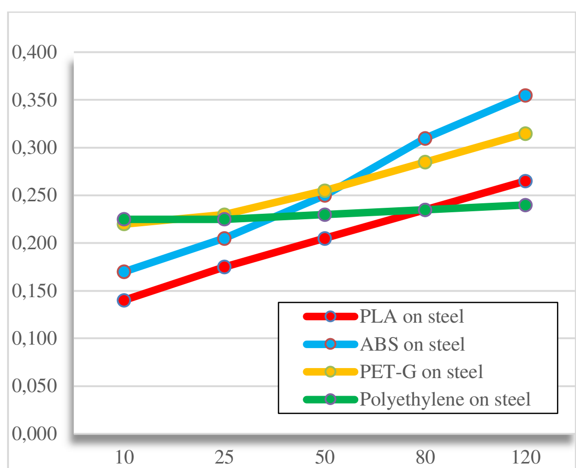

Fig. 5. The variation of the maximum friction coefficient depending on the speed

Table 2

Measured values of the maximum friction coefficient dependent on the contact load.

Material pair	Selected speed [mm/min]	Normal load, F_n [N]	Friction force F_f [N]	Friction coefficient, μ_0
PLA on steel	80	5	1.9	0.380
		10	3.0	0.300
		20	5.0	0.250
		30	6.8	0.227
		35	7.7	0.220
ABS on steel	80	5	2.4	0.480
		10	3.9	0.390
		20	6.6	0.330
		30	8.9	0.297
		35	10.4	0.297
PET-G on steel	80	5	2.0	0.400
		10	3.2	0.320
		20	5.6	0.280
		30	7.6	0.253
		35	8.8	0.251
Polyethylene on steel	80	5	1.9	0.380
		10	2.9	0.290
		20	4.9	0.245
		30	6.8	0.227
		35	7.7	0.220

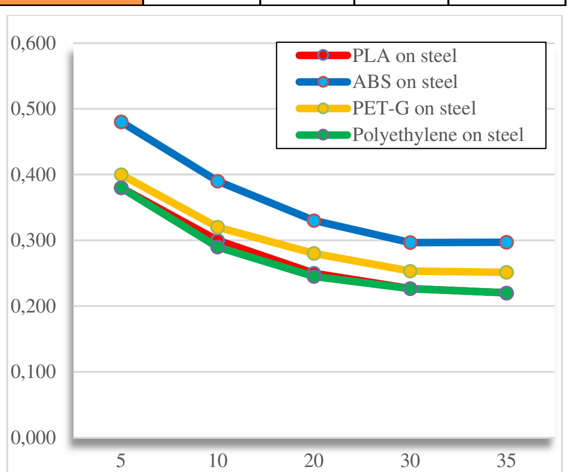

Fig. 6. The variation of the maximum friction coefficient depending on the contact load

By comparing the results from the previous figures, the following conclusions are distinguished:

- For the standard couple (polyethylene-on-steel), almost constant values of the friction coefficient were recorded with increasing speed up to 50 [mm/min], beyond which the friction coefficient shows a slight linear increasing trend. With the increase of normal load up to a value of 30 [N], the friction coefficient shows an exponential decrease; beyond this value it has a constant variation.
- Compared to the standard couple (polyethylene-on-steel), for speeds below 25 [mm/min], the studied sample couples have much lower values of friction coefficients, making them useful for low speeds or system start-ups when dry friction is predominant and favoring the formation of microjunctions. Beyond speeds of 50 [mm/min], the material couples ABS-on-steel and PET-G-on-steel have significantly higher values compared to the standard couple, while for the PLA-on-steel couple, the values of the friction coefficient remain similar as those of the polyethylene-on-steel couple. For all three analyzed material couples, the friction coefficient tends to increase linearly with the speed for all tested speed values.
- For all analyzed couples, the variation of the friction coefficient with normal load is exponentially decreasing up to a value of 30 [N], beyond which the variation becomes constant.
- For the material couples ABS-on steel and PET-G-on-steel, higher values of the friction coefficient were recorded compared to the polyethylene-on-steel couple, while the PLA-on-steel couple has almost identical values of the friction coefficient to that determined for the polyethylene-on-steel couple.
- Among the three tested specimens, PLA is the material with the best friction behavior.

4. CONCLUSIONS

In this study, there were tested three different 3D printed materials (PLA, ABS and PET-G) in comparision with polyamide material. There were recorded values of the maximum friction forces of the three materials in contact with a steel plate.

Through the analysis of the experimental results, it is found that all three printed materials have different friction coefficient values that are higher than the polyamide-on-steel coupling.

This shows that the 3D printed materials type have a great effect on their friction behavior. The values of PLA-on-steel copuling are similar to polyamide-on-steel and these gives the practical possibility of using PLA for manufacturing different components when polyamide cannot be easily provided.

For a more comprehensive analysis, we will continue the research with measurements of the wear of the currently analyzed materials.

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Cercetări privind performanţele tribologice ale materialelor plastice printate 3D utilizate în domeniul echipamentelor de construcţii

Abstract: Interesul tot mai crescut de a obţine piese prin tehnologia de aditivare (AM) impune cercetări care să determine comportamentul acestor materiale printate 3D în condiţii reale de funcţionare. Imprimarea 3D este o metodă de fabricaţie care creşte în popularitate deoarece este mai rapidă, mai economică şi ecologică decât alte metode tradiţionale. De asemenea, această metodă oferă noi posibilităţi în domeniul proiectării şi fabricării maşinilor datorită avantajului obţinerii unor piese cu forme complexe. Acest articol prezintă rezultatele cercetărilor tribologice pentru diferite materiale printate 3D obţinute prin tehnologia de fabricare prin topirea filamentului (FFF). Studiile prezintă coeficientul de frecare pentru trei cupluri de materiale: Acid Polilactic (PLA) – oţel, Stiren-Butadien Acrilonitril (ABS) – oţel şi Tereftalat de Polietilenă (PETG) – oţel. Rezultatele obţinute arată clasificarea celor trei materiale analizate şi care dintre acestea au cele mai bune proprietăţi tribologice în comparaţie cu cupla reală.

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