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THE INFLUENCE OF 3D PRINTING PARAMETERS AND HEAT TREATMENT ON TRIBOLOGICAL BEHAVIOR

Alexandra-Ileana PORTOACA, George-Razvan RIPEANU, Ion NAE, Maria TANASE

Abstract: *3D printing has advanced in manufacturing technology, with increasing use for parts production. The study aimed to modify 3D printing parameters to create samples with different layer thicknesses (0.1, 0.15, 0.2 mm) and infill percentages (50%, 75%, 100%). Both as-built and heat-treated samples (75°C, 3 hours) were evaluated for their microgeometry parameters in order to determine the influence of printing regime. On a CSM universal tribometer, friction coefficients and cumulative linear wear were measured for a class 4 friction pair consisting of a disc and a cube specimen. Heat treatment improved microgeometry (approximately 50% reduction in Ra), while slight increases in friction coefficients were observed after annealing, resulting various values determined by printing regime.*

Key words: *3D printing, friction coefficient, roughness, annealing, layer thickness.*

1. INTRODUCTION

Nowadays, the use of rapid prototyping technologies, commonly known as 3D printing or additive manufacturing, has increased in the design and production of diverse components within different fields such as: agriculture, medicine, industry, etc. FFF (Fused Filament Fabrication) is the most common additive manufacturing technique, operating on a layer-by-layer basis. In this method, filaments are deposited incrementally, one layer at a time, to build the desired object [1] and a wide range of materials (such as polylactic acid (PLA), polycarbonate, poly-caprolactone, actylonitrile butadiene styrene, and composite materials with polymers) can be used [2].

Extensive research has been conducted in the domain of 3D printing to explore the mechanical properties of parts fabricated using these technologies [1,3–12]. The strength, stiffness, weight, and other characteristics of these parts are influenced by various factors related to the 3D printing process, including layer thickness, layer height, fill density, and more. These conditions play a crucial role in determining the properties exhibited by the printed components [13]. On the other hand, post-processing heat treatments can be used to enhance the quality and performance of the printed parts [14–18].

However, limited studies [2,13,19–34] have been performed on the tribological behavior of 3D printed parts, especially to investigate the influence of post-processing heat-treatments.

The objective of the study [23] was to assess the wear rate of PLA by determining the optimal parameters (extrusion temperature, fill density, and nozzle speed) for 3D printing. Based on the findings, it was concluded that fill density had a substantial influence on the wear rate, followed by extrusion temperature and nozzle speed. The optimal set of process parameters was determined to be a fill density of 100%, an extrusion temperature of 220°C, and a nozzle speed of 40 mm/s. Similarly, the experimental results from [13] has revealed that modifying the 3D printing settings has a substantial impact not only on the strength and stiffness of the parts but also the surface quality, which subsequently affects the tribological properties of the tribopairs.

The results[25] revealed that the tribological behavior of the printed parts varied depending on factors such as print orientations and filament colors. Among the parameters investigated, it was observed that white filament color exhibited the highest friction tendency, while test pieces printed at a 45° angle orientation with black filament color displayed the maximum wear depth. Furthermore, it was found that sliding under high loads contributed to a reduction in wear.

A similar investigation was performed in [26] where it was concluded that the transverse direction of the 3D-printed samples resulted in higher coefficient of friction values compared to the longitudinal direction, regardless of the applied loads and sliding speeds. When comparing the friction behavior between the two 3D-printed materials, PLA samples consistently demonstrated lower coefficient of friction values than ABS samples, regardless of the printing direction and under all loads and speeds.

The paper [28] aims to investigate the impact of scaffolding angle and raster gap on the friction behavior, specifically the coefficient of friction and wear rate. Fused Deposition Modeling (FDM) was the used printing method, while graphite flakes were added to the ABS matrix to potentially enhance the properties. It was shown that the scaffolding angle only affects the behavior when a positive printing gap is used, whereas it has no significant effect for a negative gap. The maximum friction coefficient, along with acceptable specific wear rates, can be achieved with a scaffolding angle of 90° and a negative gap. Incorporating graphite into the material composition increases the coefficient of friction, but reduces the wear properties.

The study [24] involved depositing 316L stainless steel coatings onto the previously prepared 3D printed PLA samples at three different levels of thickness (50 μm, 100 μm, and 150 μm). The experimental findings indicated that the coefficient of friction for the sample with a coating thickness of 100 μm was lower (0.11) compared to samples with coating thicknesses of 50 μm and 150 μm. The enhanced wear resistance observed for the sample with a coating thickness of 100 μm can be attributed to the optimal combination of processing parameters, namely a raster angle of 30°, three layers on both the top and bottom surfaces.

Dhakal et al. [34] examined the defects that occur during the material extrusion-based additive manufacturing process of polymers and assessed their influence on the performance of the fabricated parts. Analyzing the surface roughness and tribological data indicates that it is possible to increase the printing speed while minimizing the impact on interlayer bonding and overall part performance. By increasing the printing speed, it was observed that printing time could be reduced by up to 58% while still achieving comparable mechanical properties.

The novelty of the present study is based on a complex experimental investigation regarding the influence on the tribological behavior and microgeometry parameters of 3D printed PLA parts, both for the printing parameters (layer thickness and infill percentage), but also for post-processing heat-treatments (annealing).

2. MATERIALS AND METHODS

For the experimental study it were printed a total of 108 PLA samples in the form of a flat disk and also a cube (54 for the as-built specimens testing and 54 for the annealed specimens testing), considering combinations of 3 different layer thicknesses (0.10 mm, 0.15 mm and 0.20 mm) and 3 infill percentages (50%, 75% and 100%). The shape of the samples is shown in Figure 1. It was used a Raise E2 3D printer, which has a volume capacity of 330×240×240mm. The printing parameters are presented in Table 1.

Table 1.

3D printing parameters.

Constant parameters	Variable parameters
Build orientation X-Y	Layer thickness, L_t = 0.10 mm/0.15 mm/0.20 mm
Print speed – 80 mm/s	Infill percentage, F_p = 50%/75%/100%
Deposition temperature – 200 °C	
Infill model- lines, 45° orientated	

The coefficients of friction were determined using a CSM Instruments THT pin-on-disc tribometer (see Figure 2). The friction pair consisted of the disc sample (10 mm radius) and a cubic sample (4 mm side), both of PLA material, as presented in Figure 1.

Fig.1. The shape of the tested samples

During the tribological test, the following parameters were used: normal load - 7 N, friction length – 50 m, linear speed – 0.314 m/s. The tests were performed at room temperature (18°C) in air with 54% humidity. The coefficient of friction (μ) was calculated from the ratio of the tangential friction force and the normal force. 3 friction pairs were tested for each combination of printing parameters. Continuous measurements were taken during the test to determine the coefficient of friction and cumulative linear wear (the linear wear of both disk sample and cube sample).

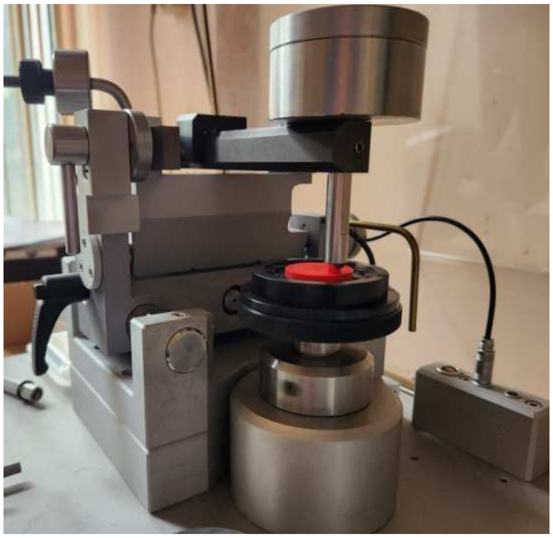


Fig.2. The test machine used to determine the sliding coefficient of friction

The surface roughness the 3D printed samples was measured in terms of R_a (Arithmetic Mean Deviation), R_t (Total height of profile) and R_z (Average peak to valley height) values, using a Surtronic 3+ surface roughness tester, as presented in Figure 3.

The coefficients of friction and the microgeometry parameters were evaluated both for the as-built 3D printed samples, but also for the heat-treated samples.

Fig.3. The surface roughness tester

The annealing heat treatment consisted in keeping the samples for a period of 3h at a temperature of 75°C (just above PLA glass transition temperature), with a very slow cooling. All samples were cooled together in an oven (Figure 4).

Fig.4. Oven used for applying the heat treatment

In order to highlight the influence of printing parameters on coefficient of friction and on wear for the as-built and also for annealed PLA samples, a statistical analysis with Minitab 19 software has been performed.

3. RESULTS AND DISCUSSION

The authors aimed to examine how printing parameters and annealing heat treatment affect the 3D printed parts surface roughness and friction behaviour. The goal was to assess the combined impact of these variables on the value of sliding coefficient of friction. The results, presented in Figure 5, illustrate the average coefficient of friction values and the roughness parameters in relation to the printing parameters (layer thickness and infill percentage) both for as-built specimens as for annealed specimens, providing a clear understanding of different factors influence. The roughness parameters, which are measurements used to quantify the surface roughness, indicated smaller values for the annealed samples, suggesting a smoother surface texture. This finding implies that annealing can be an effective method for reducing surface roughness and improving the overall surface quality of the samples. Figure 6 shows the percentage difference between the results obtained for the annealed specimens, compared with as-built specimens, in order to better visualize the influence of heat-treatment on the tribological behavior of 3D printed parts. Generally, the coefficient of friction increased after annealing, excepting the samples printed with 50% infill percentage and layer thickness 0.1 mm and 0.15 mm. This finding suggests that the annealing process can have varying effects on the coefficient of friction, depending on the specific parameters of the printing process. In most cases, annealing led to an increase of coefficient of friction, which indicates that the surfaces of the annealed samples exhibited higher resistance to sliding or movement against other surfaces. However, the samples with a 50% infill percentage and thinner layer thickness (0.1 mm and 0.15 mm) did not show the same increase of coefficient of friction after annealing.

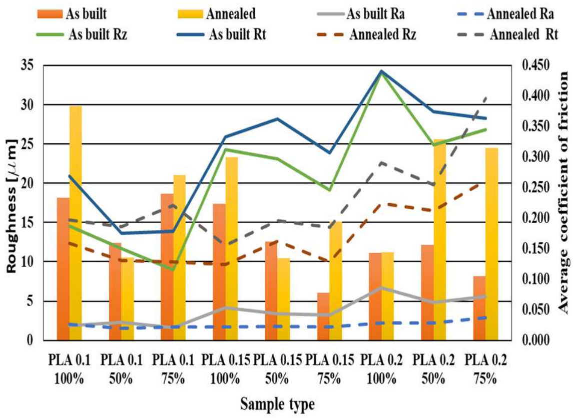


Fig.5. The values of coefficient of friction and roughness parameters for different printing settings of as-built and annealed samples

Correlating the surface roughness with coefficient of friction values after annealing, it can be found that the surfaces of the annealed specimens were noticeably smoother across all printing parameters compared with the as-built specimens.

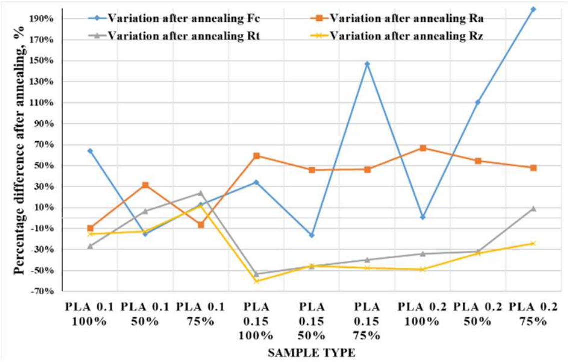


Fig.6. The percentage variation of micro geometric parameters and coefficient of friction after annealing treatment

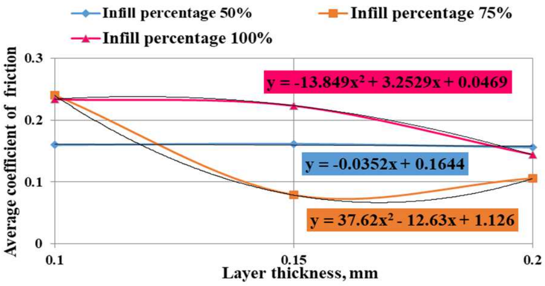


Fig.7. The influence of printing parameters on average coefficient of friction values for as-built samples

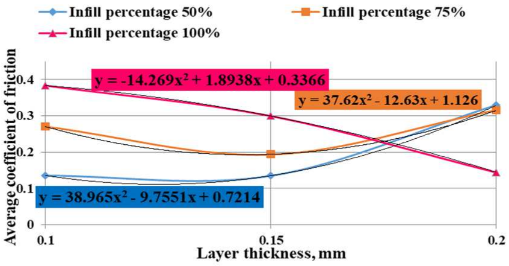


Fig.8. The influence of printing parameters on average coefficient of friction values for annealed samples

The smoother surface finish facilitates increased sliding contact between the testing surfaces, leading to more pronounced friction processes. In contrast, a rougher surface finish reduces contact between the two components of the tribological system, resulting in lower friction. These findings align, as in [27], with the principle that finer surface finishing promotes enhanced sliding contact and, consequently, higher friction, while rougher surface finishes limit contact and contribute to reduced friction.

Both for as-built and annealed samples, the maximum coefficient of friction values was obtained at 100% infill percentage (Figure 7 and Figure 8) excepting the case of annealed sample with 100% infill percentage and 0.2 mm layer thickness, where the average coefficient of friction was almost equal with the minimum value recorded for infill percentage 50% and 0.15 mm layer thickness.

Figures 7 and 8 are also presenting the equations of variation for coefficient of friction with layer thickness, for different values of infill percentage, allowing estimating the values of coefficient of friction by extrapolating the trendline.

In Figures 9 and 10 can be seen the variation of cumulative linear wear for all the analyzed samples.

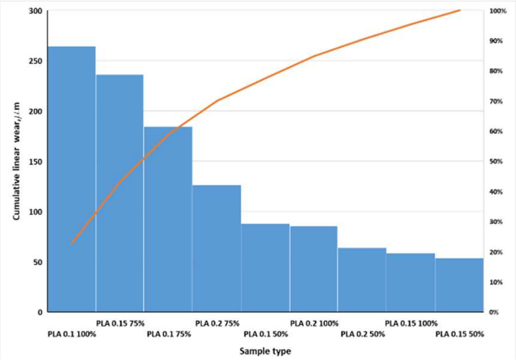


Fig.9. Cumulative linear wear for as-built samples

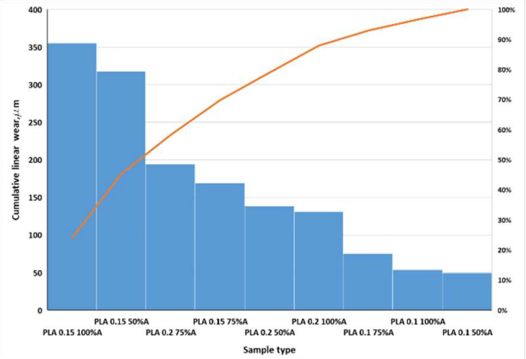
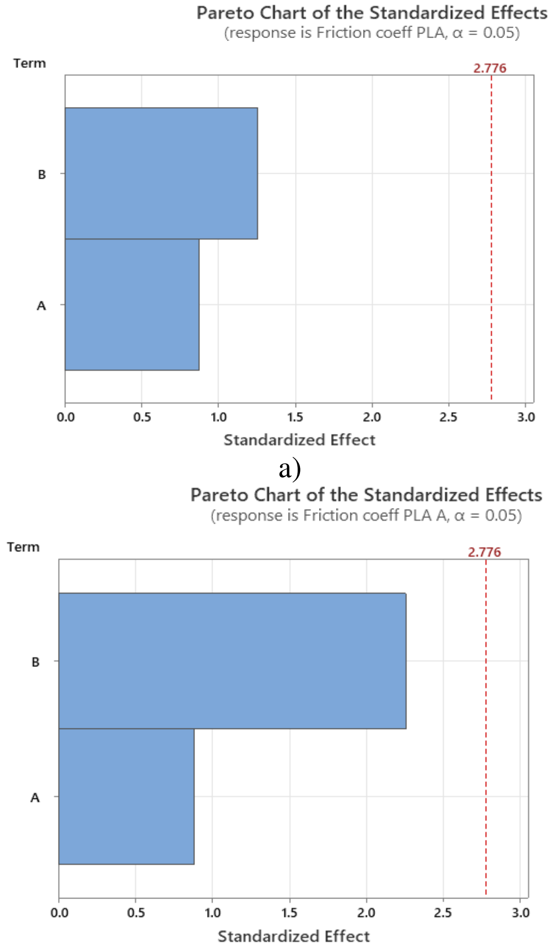


Fig.10. Cumulative linear wear for annealed samples

According to the information presented in Figures 9 and 10, it is evident that the cumulative linear wear differs significantly depending on the printing parameters and annealing treatment. Specifically, the maximum cumulative linear wear was recorded for 100% infill percentage and small layer thickness (0.1 mm layer thickness for as-built samples and 0.15 mm for annealed samples) and the minimum for 50% infill percentage (0.15 mm layer thickness for as-built samples and 0.1 mm for annealed samples). For the sample with 0.1 mm layer thickness and 100% infill percentage, the annealing determined the considerable decrease (4.8 times) of cumulative linear wear (from 264 μm to 54 μm). The annealing process appears to have improved the material's ability to withstand penetration forces, leading to the observed reduction in cumulative linear wear.



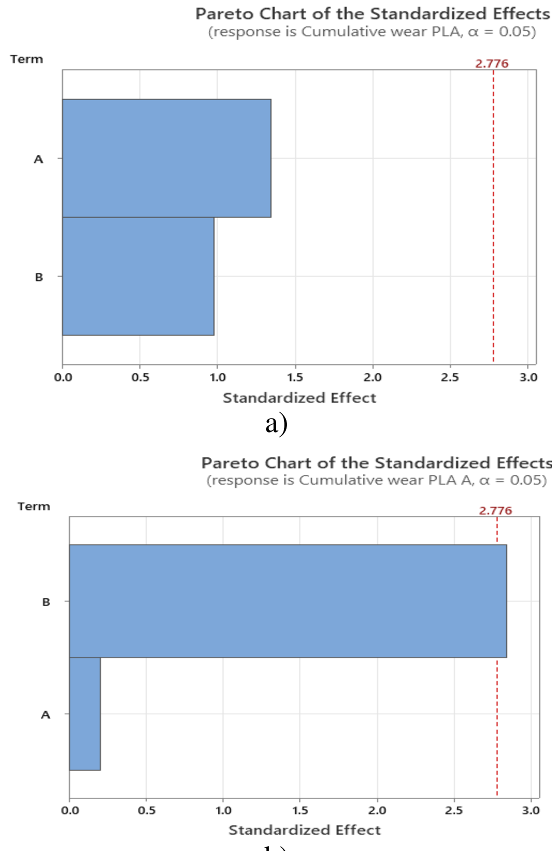
a)

b)

Fig.11. Pareto charts for coefficient of friction: (a) as-built samples; (b) annealed samples

The results of the statistical analysis are presented in Figures 11- 14 (the factor A is infill percentage and B is layer thickness).

Analyzing the Figures 11 and 13, it can be concluded that the coefficient of friction is mainly influenced by layer thickness (for both as-built and annealed PLA samples).



a)

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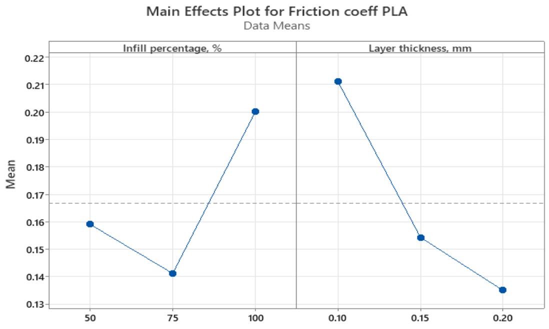
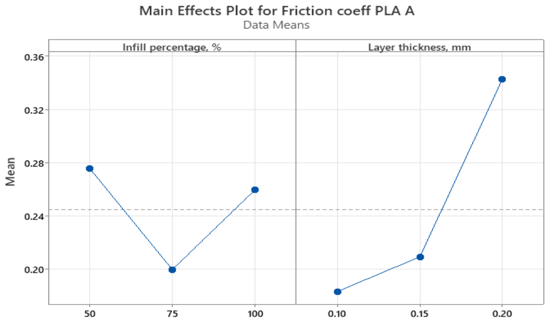
Fig.12. Pareto charts for cumulative linear wear: (a) as-built samples; (b) annealed samples

The most significant factor of cumulative linear wear is infill percentage (for as-built simples), while for annealed samples is the layer thickness – see Figures 12 and 14.

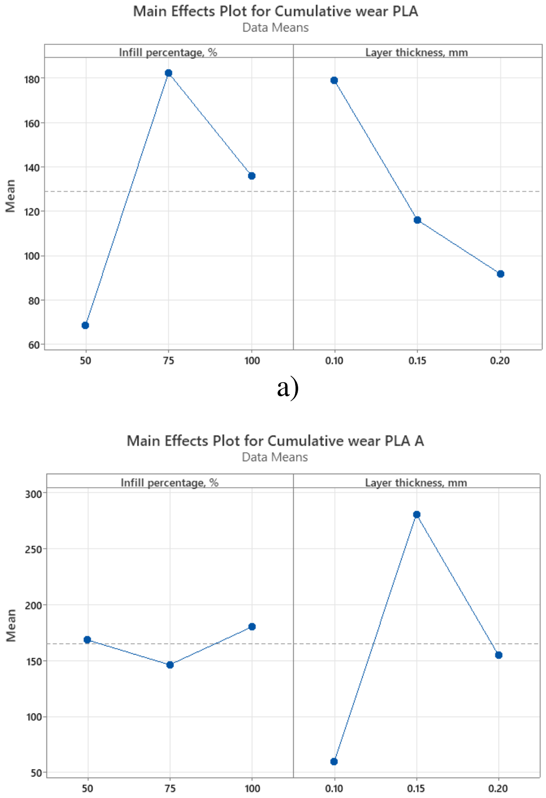


a)



b)

Fig.13. Main effect plots for coefficient of friction: (a) as-built samples; (b) annealed samples

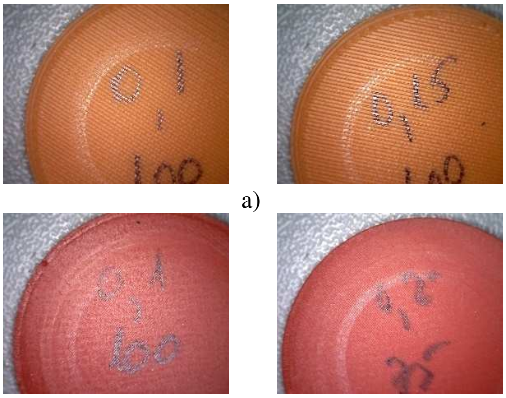


a)

b)

Fig.14. Main effect plots for cumulative linear wear: (a) as-built samples; (b) annealed samples

Figure 15 is dedicated to the visual representation and analysis of wear traces that have emerged on the samples subsequent to the friction experimental testing. The primary objective behind presenting these images is to elucidate the distinctive wear patterns and characteristics that have manifested on the surfaces of the examined materials. A discernible observation from the visual data is the occurrence of uniform wear patterns in both of the tested materials, indicating a consistent mode of wear across these specimens. Furthermore, the nature of wear evident in these images appears to possess attributes consistent with an adhesive-abrasive character, suggesting that the wear process involves a combination of adhesive forces and abrasive interactions between the materials. This characterization provides insights into the underlying mechanisms governing wear in this context, which can be important for informed decision-making in material selection and design considerations.


a)

b)

Fig.15. Wear traces patterns

4. CONCLUSION

The present paper aimed to investigate the tribological behavior of PLA 3D printed parts, taking into account the influence of printing parameters (infill percentage and layer thickness) and also the post-processing treatment (annealing), by measuring the coefficient of friction, cumulative linear wear and the roughness parameters (R_a, R_z and R_t).

The results indicate that the coefficient of friction generally increased after annealing, more accentuated for samples with 75% infill percentage and 0.15 mm layer thickness (+147%) and 0.2 mm (+198.95%), as shown in Figure 6. These results are corroborated by roughness surface measurements, observing that the annealed samples exhibited smaller values for the roughness parameters compared to the as-built samples. This finding suggests that the annealing process contributed to a smoother surface texture in the annealed samples.

The statistical analysis reveals that the coefficient of friction is primarily impacted by layer thickness in both as-built and annealed PLA samples. Additionally, we found that the most significant factor affecting cumulative linear wear differs between the two sample types, with infill percentage being the predominant factor for as-built samples and layer thickness for annealed samples.

The findings highlights the complexity of the relationship between the infill percentage, layer thickness, and coefficient of friction, and suggests that other factors, such as the annealing process, may interact with these parameters to produce varying effects on friction behavior. Further analysis and investigation are necessary to fully understand the underlying mechanisms behind these observations.

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Influența parametrilor de printare 3D și a tratamentului termic asupra comportării tribologice

Printarea 3D a avut o evoluție semnificativă în rândul tehnologiilor de fabricație, fiind utilizată din ce în ce mai mult pentru realizarea diverselor componente. Scopul acestui studiu a fost investigarea influenței parametrilor de printare 3D asupra comportamentului tribologic prin modificarea grosimilor de strat (0.1; 0.15; 0.2 mm) și a procentelor de umplere (50%, 75%, 100%) specific epruvetelor realizate din PLA, atât în starea netratată, cât și după un tratament termic la 75°C timp de 3 ore. În cadrul experimentului, utilizând o cuplă de frecare plan-pe-plan (format dintr-o epruvetă sub formă de disc și una sub formă de cub) și un tribometru universal de tip CSM, au fost determinați coeficienții de frecare și uzura liniară cumulată. S-a observat că tratamentul termic îmbunătățește microgeometria suprafețelor (reducând R_a cu aproximativ 50%) și că valorile coeficienților de frecare variază în funcție de regimul de printare, înregistrându-se o ușoară creștere în urma tratamentului termic.

Alexandra-Ileana PORTOACA, PhD Student, Assistant Professor, Petroleum-Gas University of Ploiești, Bucureşti Avenue, nr. 39, Ploieşti, România, alexandra.portoaca@upg-ploiesti.ro

George-Razvan RIPEANU, PhD Full Professor, Petroleum-Gas University of Ploiești, Bucureşti Avenue, nr. 39, Ploieşti, România, rrapeanu@upg-ploiesti.ro

Ion NAE, PhD Full Professor, Petroleum-Gas University of Ploiești, Bucureşti Avenue, nr. 39, Ploieşti, România, inae@upg-ploiesti.ro

Maria TANASE PhD, Assistant Professor, Petroleum-Gas University of Ploiești, Bucureşti Avenue, nr. 39, Ploieşti, România, maria.tanase@upg-ploiesti.ro