Vol. 03, Iss. 4 (2025) 411-417, DOI: 10.61552/JME.2025.04.005

JME

Journal of Materials and Engineering

www.jme.aspur.rs

Tribological Behavior of 3D-Printed PLA, PLA–Copper Composite and ABS under Dry and Lubricated Sliding

Stefan Miletić[a], Dragan Džunić[a], Marijana Savković[a], Živana Jovanović Pešić[a], Milan Ivković[a,*]

[a]*Faculty of Engineering University of Kragujevac, Kragujevac, Serbia.*

Keywords:

3D printing
PLA composite
ABS
Friction and wear
Tribology

* Corresponding author:

Milan Ivković
E-mail: milan.ivkovic@kg.ac.rs

Received: 5 September 2025
Revised: 19 October 2025
Accepted: 24 November 2025

A B S T R A C T

This scientific study focuses on the evaluation of the tribological properties of polymer materials (PLA, PLA reinforced with copper, and ABS). The experimental methodology involved measuring surface roughness, the coefficient of friction, and the width of the wear track. The test samples were produced using 3D printing technology, while wear experiments were performed on a TPD-93 block-on-disc tribometer. Each specimen underwent three dry friction and wear tests, along with one lubricated test, in order to compare material behavior under different operating conditions and to assess the effect of lubrication on friction and wear mechanisms, which represent essential performance indicators. The experimental input parameters were defined as follows: disc material – 50CrMo4 steel, disc radius r = 35 mm, total sliding distance s = 200 m, , sliding velocity v = 0.5 m/s, test duration t = 400 s, and normal load FN = 4 daN. For clearer analysis and interpretation, the obtained results are presented in graphical form.

© 2025 Journal of Materials and Engineering

1. INTRODUCTION

Additive manufacturing has become an important production approach in modern engineering because it enables the fabrication of components with complex geometries, reduced material waste, and short production times. Among the available additive manufacturing technologies, Fused Deposition Modeling (FDM) is one of the most widely used methods due to its relatively simple processing route, broad material availability, and suitability for rapid prototyping as well as functional part production. In recent years, FDM has moved beyond the production of visual models and conceptual prototypes and has increasingly been used for manufacturing parts intended for service under real mechanical loads. As a result, there is growing interest in understanding not only the

geometric accuracy of printed parts, but also their mechanical, surface, and tribological properties under practical operating conditions. Tribological performance is especially important for polymer components that operate in contact with other bodies under sliding conditions. For such components, friction, wear resistance, and thermal stability in the contact zone strongly influence functionality, service life, and reliability. In FDM-produced parts, these properties are additionally influenced by the layered nature of the structure, anisotropy caused by print orientation, internal porosity associated with infill strategy, and the quality of the surface generated during deposition. Therefore, tribological behavior of 3D printed polymers cannot be explained only by the base material itself, but must be considered as a combined result of material composition, process parameters, part architecture, and operating conditions.

Roy and Mukhopadhyay analyzed the influence of FDM process parameters on tribological properties, highlighting that ABS exhibits significantly more favorable wear resistance characteristics compared to PLA material [1]. The study confirmed that ABS specimens achieve minimal wear and negligible mass loss, while PLA shows substantially greater structural damage due to low thermal resistance and local softening. Based on these results, the researchers conclude that the choice of raw material alone is not decisive; rather, precise optimization of process factors is necessary to ensure functional stability and the formation of a protective layer during friction.

Ramadan et al. conclude that low friction values in polymers do not necessarily guarantee a lower wear rate, but rather that the tribological response depends on the complex interaction of hardness, roughness, and contact mechanics [2].

A direct comparison between ABS and PLA was also reported by Raheja et al. [3], who analyzed the influence of six key printing parameters on tribological behavior and confirmed that ABS exhibits lower friction and wear than PLA. The study showed that optimal performance is achieved using a linear infill pattern and greater layer thickness, whereas hexagonal infill and smaller layer thickness directly increase material wear. Microscopic analysis of the specimens revealed more pronounced wear tracks on the PLA samples, which the authors attribute to its lower thermal stability and susceptibility to damage under frictional loading. Together, studies [1] and [3] establish an important baseline for the present topic, since they repeatedly identify ABS as the more tribologically stable material under dry sliding conditions.

Alongside studies on pure ABS and PLA, increasing attention has been directed toward PLA-based composites reinforced with metallic particles. Such materials are attractive because they retain the printability and dimensional precision of PLA while potentially improving stiffness, hardness, and wear behavior. In this regard, Sava et al. investigated bronze-filled PLA-based filament composites intended for gasket applications [4]. Their results showed that these materials can be used in low-pressure and low-temperature functional conditions and remain sufficiently stable in lubricated environments, although their stiffness is still lower than that of conventionally sintered metallic materials.

A broader tribological comparison of different FDM materials was reported by Maries et al. [5]. By examining eight different 3D printing filaments, these authors showed that there is no direct correlation between coefficient of friction and wear, which highlights the complexity of tribological material selection. For example, some materials exhibited very low wear despite relatively high friction values, whereas others combined low friction with more pronounced wear. This conclusion is highly relevant for the interpretation of results obtained for ABS, PLA, and filled PLA materials, because it suggests that tribological suitability should not be judged using only one parameter. Instead, a complete assessment should include friction behavior, wear magnitude, hardness, roughness, and stability of the contact surface during sliding.

The same topic was further explored by Bochnia et al., who studied thin-walled specimens printed from a bronze-filled PLA-based composite [6]. They found that print orientation and wall structure strongly affect

the mechanical properties of these materials. The best results were obtained for specimens with a wall thickness of 1.4 mm printed in the Y-direction, where tensile strength reached about 16 MPa and the elastic modulus about 630 MPa, while specimens printed in the Z-direction showed very poor performance due to weak interlayer bonding and internal defects. These observations are important because they demonstrate that metal-filled PLA composites cannot be evaluated only on the basis of their nominal composition; their behavior is also strongly controlled by the structural characteristics produced during printing.

Portoacă et al. further clarified the role of process parameters, establishing that PLA possesses higher hardness and friction compared to ABS material [7]. The study identified specific combinations of infill density and layer height that optimize wear resistance and reduce friction for both types of filaments. Based on these findings, the researchers conclude that proper print optimization can significantly alter tribological properties, which is why material comparisons must always be viewed through the lens of the selected manufacturing conditions. A particularly relevant contribution to the present study was provided by Batista et al., who investigated PLA and PLA composites reinforced with aluminum and copper particles [8]. Their results showed that the addition of metallic particles significantly increases hardness, by as much as 83% in the case of aluminum-filled PLA, and that copper reinforcement reduces wear volume by approximately 55% compared with pure PLA. However, the coefficient of friction remained largely unaffected by material type, again confirming that improved hardness does not necessarily imply lower friction. Hanon et al. studied the effect of print orientation and metal content on the mechanical and tribological properties of PLA and bronze-based composites [9]. Their research showed that a specific specimen orientation provides maximum tensile strength, while the inclusion of metallic particles contributes to a reduction in wear depth compared to the pure polymer. These findings are crucial as they confirm the feasibility of using reinforced PLA materials in tribological applications, despite the fact that friction values remain relatively stable.

Surface condition also plays an important role in the tribological behavior of FDM parts, in addition to material composition and printing parameters. Djurović et al. [10] investigated the influence of different finishing methods on the roughness and tribological performance of FDM-produced ABS parts. Their results showed that improved surface finishing leads to smoother surfaces, reduced wear, and more favorable friction behavior. This confirms that tribological performance depends not only on the material and internal structure, but also on the condition of the working surface.

For this reason, a comparative experimental investigation of PLA, PLA with copper, and ABS under both dry and lubricated sliding conditions is fully justified. Such an approach makes it possible to assess not only the influence of material composition, but also the role of lubrication in reducing frictional heating, stabilizing contact conditions, and limiting wear. Since the available literature points to clear advantages of ABS in dry friction, but also suggests that copper-filled PLA may offer improved wear resistance compared with unfilled PLA, the comparative study of these three materials can contribute to a better understanding of their application potential in functional 3D printed components subjected to sliding contact.

2. EXPERIMENT

The aim of the experimental study was to assess the tribological behavior of selected polymer materials under different operating regimes, specifically under dry and lubricated sliding conditions. The materials analyzed were PLA, PLA reinforced with copper, and ABS. Experimental testing was performed using the block-on-disc configuration on a TPD-93 tribometer, equipped with a real-time data acquisition system. Variations in normal load and coefficient of friction during the tests were continuously recorded and further processed using specialized analysis software. The characterization of tribological properties was conducted at the Laboratory for Tribology, Faculty of Engineering Sciences, University of Kragujevac, employing appropriate equipment, specimens, and

controlled testing conditions. The investigation included measurements of coefficient of friction, surface roughness, and wear track width. The experimental conditions were defined as follows: total sliding distance s = 200 m, test duration t = 400 s, disc material 50CrMo4 steel, disc radius r = 35 mm, applied normal load FN = 4 daN, and sliding speed v = 0.5 m/s. The specimens were produced using 3D printing technology. Each material was subjected to three repeated friction and wear tests under dry sliding conditions and one test under lubricated conditions in order to compare their performance under different operating regimes. Special emphasis was placed on behavior in dry contact, as well as on its influence on the tribological mechanisms occurring during sliding. During testing, particular phenomena were observed, including material softening and local melting in certain samples caused by excessive heat generation, and these effects were analyzed in detail. For the determination of the wear track area, it was necessary to measure the wear marks formed on the contact surfaces of the test blocks. These measurements were carried out using a UIM-21 optical microscope. The friction and normal forces were measured using strain gauge sensors, while the acquired signals were processed by dedicated software, which calculated the coefficient of friction. The system generated averaged values of the measured parameters at two-second intervals, based on 100 data points per interval, corresponding to a sampling frequency of 50 Hz. Following completion of the tests, the worn specimens were first examined using a UIM-21 optical microscope. Additional microscopic analysis was then performed with a Meiji FL-150 optical microscope at the Tribology Center of the Faculty of Engineering Sciences in Kragujevac. This step enabled detailed visualization and documentation of the wear tracks formed during testing. Surface roughness measurements were performed prior to the experimental procedure using a contact profilometer. The obtained images are presented in the following section, where all other experimental results will also be discussed and analyzed. Using the previously described equipment and materials, a set of results was obtained and will be presented and analyzed in the following section.

3. RESULTS

The following figures present surface roughness diagrams for three different samples. In addition to the roughness profiles, the material bearing curves are provided for each specimen. These diagrams offer a visual representation of the surface condition after processing. In each diagram, the vertical axis shows the surface roughness values, expressed in micrometers (μm). These values correspond to the maximum surface irregularity height (RMAX), defined as the largest vertical distance between the highest peak and the deepest valley within the reference length. The horizontal axis represents the reference length (l), expressed in millimeters (mm), which defines the evaluated surface segment over which the roughness parameters are measured. Fig. 1. Surface roughness profile of the PLA sample.

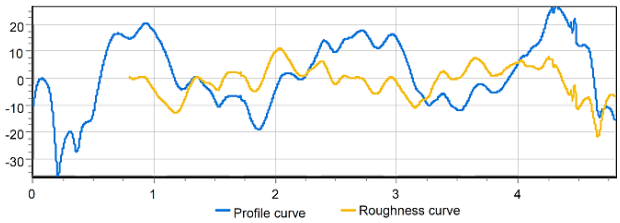


Fig. 1. Surface roughness profile of the PLA sample.

Fig. 2. Surface roughness profile of the PLA + copper sample and Fig. 3. Surface roughness profile of the ABS sample.

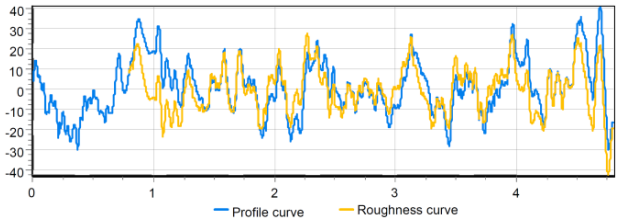


Fig. 2. Surface roughness profile of the PLA+copper sample.

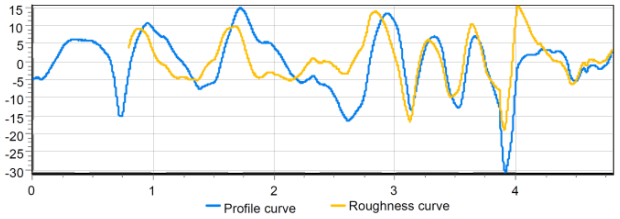
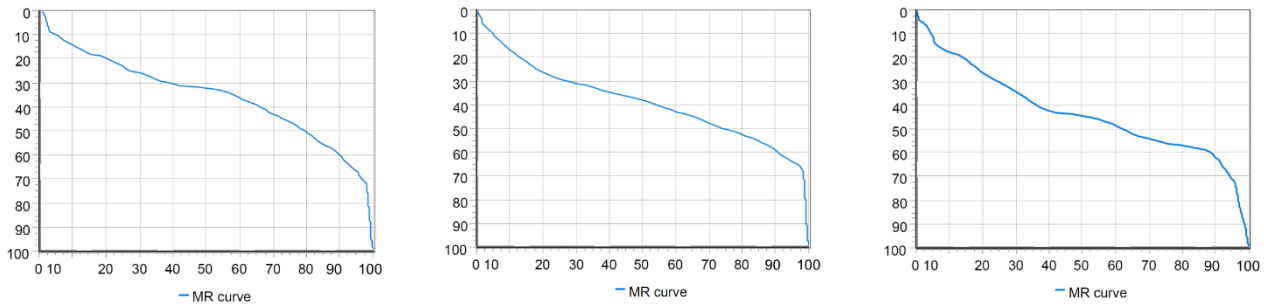


Fig. 3. Surface roughness profile of the ABS sample.

Fig 4a presents the bearing curve of the surface profile for the PLA material. Fig 4b shows the bearing curve for the PLA + copper composite, while Fig 4c displays the bearing curve for the ABS material.



a) b) c)

Fig. 4. a) Bearing curve of the PLA surface profile, b) Bearing curve of the PLA + copper surface profile and c) Bearing curve of the ABS surface profile.

Fig 5a illustrates the average coefficient of friction for all three materials under dry conditions. Fig 5b shows the average coefficient of friction values for the same materials, but under lubricated conditions. These two diagrams clearly demonstrate the differences in friction behavior depending on operating conditions (with and without lubrication).

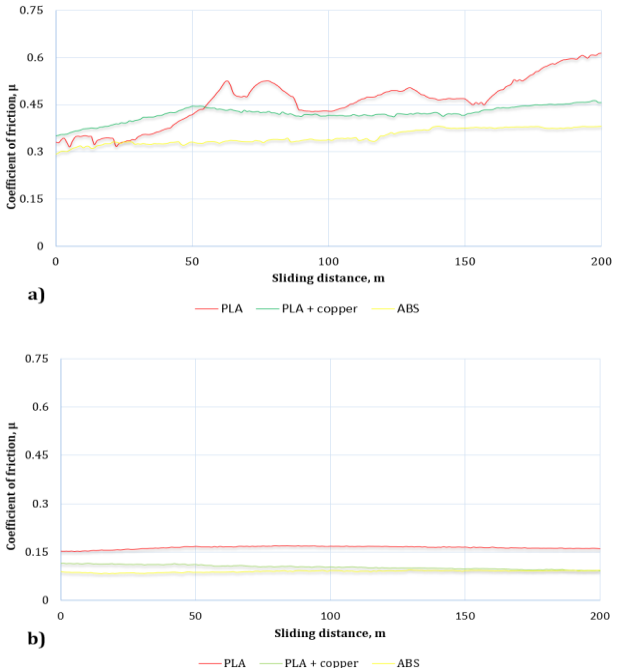


Fig. 5. a) llustrates the average coefficient of friction for all three materials under dry conditions and b) shows the average coefficient of friction values for the same materials, but under lubricated conditions.

Under dry sliding conditions, PLA exhibited the highest coefficient of friction. The PLA + copper composite reached values of approximately 0.45, while ABS remained below this level. As shown in Fig. 5a, the initial coefficients of friction for all three materials were similar, ranging from 0.3 to 0.35, and gradually increased throughout the test. In the case of PLA, the coefficient of friction nearly doubled by the end of the experiment. For PLA + copper, the increase was approximately 50%, whereas ABS showed the smallest rise, which corresponds to the lowest measured wear track widths and wear volumes. When lubrication was applied, the coefficient of friction for PLA remained below 0.18. For PLA + copper, the coefficient decreased over time, while ABS again demonstrated the most stable behavior, maintaining a value of approximately 0.1, as presented in Fig. 5b. In the following phase of the experiment, wear track positions were identified, average track widths were measured, and wear volumes were calculated. The results obtained for PLA and PLA + copper under lubricated conditions indicated that a lower coefficient of friction does not necessarily correspond to a lower wear volume. Figure 6a illustrates the worn PLA specimens tested under dry conditions. Figure 6b shows the worn PLA + copper specimens, while Figure 6c presents the worn ABS specimens, all subjected to identical dry testing conditions. Figures 7a, 7b, and 7c display the corresponding specimens tested under lubricated conditions.



Fig. 6. a) Worn PLA blocks under dry conditions, b) Worn PLA + copper blocks under dry conditions and c) Worn ABS blocks under dry conditions.

Under dry sliding conditions, as shown in the previous figures, two PLA specimens failed due to thermal degradation, manifested as melting and displacement of material toward the edges of the contact zone. As a result, wear track measurements

could be performed on only one PLA block. In contrast, the results obtained under lubricated conditions were significantly different. Wear was minimal and could be observed only when the base surface of the specimen was illuminated, as presented in the corresponding figure.

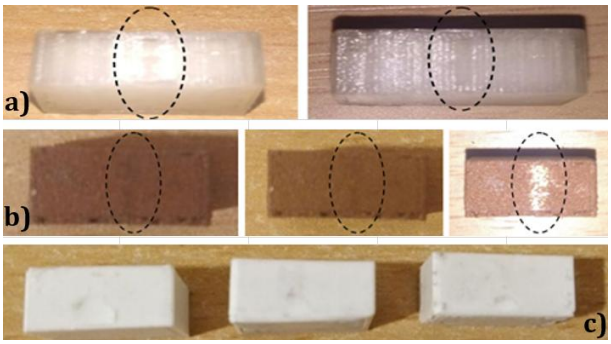


Fig. 7. a)Worn PLA blocks under lubricated conditions, b) Worn PLA + copper blocks under lubricated conditions and c) Worn ABS blocks under lubricated conditions.

For PLA + copper specimens tested under dry conditions, wear was clearly visible and relatively pronounced; however, unlike PLA, no catastrophic failure occurred. Under lubricated conditions, the performance of the PLA + copper composite improved considerably. Although the wear track was visible to the naked eye, it became much more distinct when illuminated, as illustrated in the previous images. Among all materials tested in dry sliding, ABS demonstrated the highest wear resistance. Wear was minimal, and the calculated wear volumes were comparable to those measured for PLA and PLA + copper under lubricated conditions. Considering the already low wear volume without lubrication, even lower values were expected under lubricated conditions. This was confirmed experimentally, as wear tracks on ABS specimens were nearly undetectable, even under direct illumination. It is evident that PLA exhibited the highest wear volume in dry conditions. Although the wear of PLA + copper was somewhat lower, it remained significantly pronounced. Based on the measurements, ABS showed the lowest average wear track width and wear volume, indicating superior wear resistance compared to the other tested materials. When the specimens were tested under lubricated sliding conditions, the results improved markedly. For PLA, the wear volume decreased substantially, yielding even better results than PLA + copper under the same conditions. ABS once again showed the best overall performance, with wear volumes so low that they could be expressed in micrometers, confirming its excellent resistance under both dry and lubricated regimes. The calculated wear volumes for both testing conditions are presented in Figs. 8a and 8b. For dry sliding, the average wear volume for PLA + copper and ABS was calculated based on three tested specimens, whereas for PLA only one valid result was available.

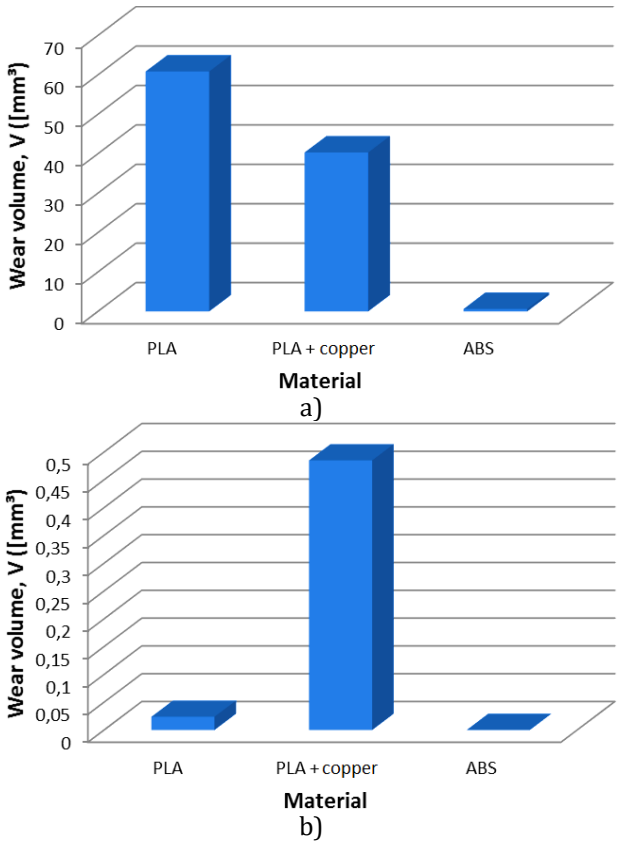


Fig. 8. a) Wear volume of tested materials under dry sliding conditions and b) Wear volume of tested materials under lubricated conditions.

The following Figs display the surface appearance of the test blocks before and after tribological testing, as observed under a microscope. Fig. 9a. Microscopic image of the PLA sample surface before and after testing (dry and lubricated conditions), Fig. 9b. Microscopic image of the PLA + copper sample surface before and after testing (dry and lubricated conditions) and Fig. 9c. Microscopic image of the ABS sample surface before and after testing (dry and lubricated conditions). Surface irregularities were observed on the specimens even prior to testing. This can be attributed to the fact that the blocks were not subjected to fine post-processing procedures such as grinding or polishing.

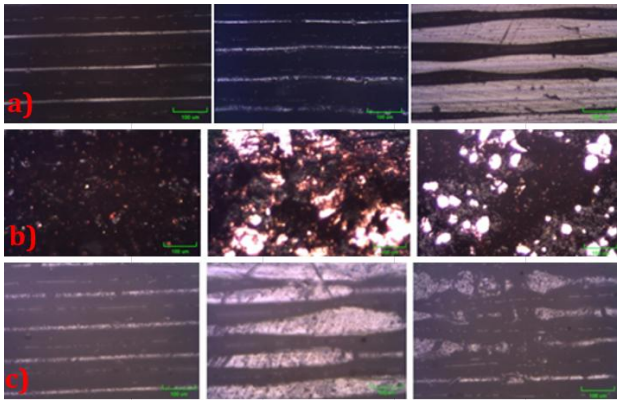


Fig. 9. Microscopic image of the aPLA sample, b) PLA + copper and c) ABS, surface before and after testing (dry and lubricated conditions).

Since the samples were manufactured using layer-by-layer 3D printing, any limitations in printer precision or the use of very thin deposition layers may lead to surface imperfections.

4. CONCLUSION

The conducted research indicates that pure PLA exhibits a pronounced susceptibility to structural deformation and melting due to intensive heat generation under dry friction conditions. Unlike the pure polymer, the PLA-based composite reinforced with copper maintains stability and allows for more precise measurement of wear tracks without the occurrence of catastrophic material failure. The application of lubrication significantly improves the tribological response of all tested specimens, effectively preventing the melting of contact surfaces and reducing overall wear. Nevertheless, ABS stands out as the most superior material, demonstrating the highest level of wear resistance and stability in both operating regimes, whether with or without lubrication. The final conclusion suggests that ABS is the most adequate choice for manufacturing functional components, while the use of PLA materials in dry sliding systems is not recommended due to the risk of compromising the geometry of the parts.

REFERENCES

[1] R. Roy and A. Mukhopadhyay, "Tribologicalstudies of 3D printed ABS and PLA plastic parts," *Materials Today Proceedings*, vol. 41, pp. 856–862, Oct. 2020, doi: 10.1016/j.matpr.2020.09.235.

[2] M. A. Ramadan, Hassan. A. Sabour, and E. El-Shenawy, "Tribological properties of 3D printed polymers: PCL, ABS, PLA and Co polyester," *Tribology in Industry*, vol. 45, no. 1, pp. 161–167, Mar. 2023, doi: 10.24874/ti.1410.11.22.02.

[3] K. Raheja, A. Jain, C. Sharma, R. Rana, and R. Lal, "Comparative study of tribological parameters of 3D printed ABS and PLA materials," *in Lecture notes in mechanical engineering*, 2021, pp. 95–108. doi: 10.1007/978-981-15-8542-5_9.

[4] M. Sava, R. Nagy, and K. Menyhardt, "Characteristics of 3D printable bronze PLA-Based filament composites for gaskets," *Materials*, vol. 14, no. 16, p. 4770, Aug. 2021, doi: 10.3390/ma14164770.

[5] I. Maries, C. Vilau, M. S. Pustan, C. Dudescu, and H. G. Crisan, "Determining the tribological properties of different 3D printing filaments," *IOP Conference Series Materials Science and Engineering*, vol. 724, no. 1, p. 012022, Jan. 2020, doi: 10.1088/1757-899x/724/1/012022.

[6] J. Bochnia, T. Kozior, and M. Blasiak, "The Mechanical Properties of Thin-Walled Specimens Printed from a Bronze-Filled PLA-Based Composite Filament Using Fused Deposition Modelling," Materials, vol. 16, no. 8, p. 3241, Apr. 2023, doi: 10.3390/ma16083241.

[7] A. I. Portoacă, R. G. Ripeanu, A. Diniţă, and M. Tănase, "Optimization of 3D printing parameters for enhanced surface quality and wear resistance," Polymers, vol. 15, no. 16, p. 3419, Aug. 2023, doi: 10.3390/polym15163419.

[8] M. Batista, I. Del Sol, Á. Gómez-Parra, and J. M. Vazquez-Martinez, "Tribological performance of additive manufactured PLA-Based parts," Polymers, vol. 16, no. 17, p. 2529, Sep. 2024, doi: 10.3390/polym16172529.

[9] M. M. Hanon, Y. Alshammas, and L. Zsidai, "Effect of print orientation and bronze existence on tribological and mechanical properties of 3D-printed bronze/PLA composite," The International Journal of Advanced Manufacturing Technology, vol. 108, no. 1–2, pp. 553–570, May 2020, doi: 10.1007/s00170-020-05391-x.

[10] S. Djurović, D. Lazarević, M. Ivković, M. Mišić, B. Stojčetović, and Ž. Šarkoćević, "Tribological behaviour and surface roughness quality of 3D printed ABS material," Journal of Materials and Engineering, vol. 1, no. 3, pp. 116–120, Oct. 2023, doi: 10.61552/jme.2023.03.004.