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INVESTIGATION OF THE TRIBOLOGICAL CHARACTERISTICS OF POLYMER MATERIALS (PLA, PLA+COPPER, AND ABS) UNDER LUBRICATED AND DRY SLIDING CONDITIONS

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Abstract: *This research paper presents the determination of tribological characteristics of polymer materials (PLA, PLA with copper, and ABS). The experimental procedure included measurements of surface roughness, coefficient of friction, and wear track width. The test specimens were fabricated using 3D printing, and wear tests were conducted using a TPD-93 block-on-disc tribometer. Each sample was subjected to three dry friction and wear tests and one lubricated test to observe differences under varying operating conditions, as well as the influence of lubrication on friction and wear processes, which are key performance indicators. The input parameters of the experiment were as follows: disc material – 50CrMo4 steel, disc radius – r = 35 mm, normal load –* F_N *= 4 daN, sliding speed – v = 0.5 m/s, duration – t = 400 s, and total sliding distance – s = 200 m. To facilitate interpretation, the obtained results are presented graphically.*

Keywords: *polymer materials, PLA, PLA with copper, ABS, surface roughness, coefficient of friction, wear track, tribometer, block-on-disc.*

1. INTRODUCTION

The scientific research paper "Tribological studies of 3D printed ABS and PLA plastic parts" by Rahul R. and Abhijit M. aimed to examine how FDM 3D printing parameters (infill density, layer thickness, infill angle, and pattern) affect the wear behavior and coefficient of friction of ABS and PLA materials. Samples were fabricated using a Stratasys F170 3D printer and tested on a TR-25 tribometer with an EN8 steel roller. For ABS specimens, the lowest wear (77 µm) and mass loss (0.002 g) were achieved with lower infill density, thicker layers, and single-direction infill pattern. PLA samples exhibited significantly higher wear (up to 452 µm) and higher friction coefficient due to lower thermal stability. Tribological performance strongly depended on raster angle, where smaller angles yielded better results. The coefficient of friction stabilized during the test due to the formation of a tribofilm. PLA also exhibited greater dimensional deviations, especially along the Z-axis. The study concluded that ABS is more wear-resistant under dry conditions and that optimized printing parameters are key to improving the mechanical performance of 3D printed parts. Additionally, applied load and sliding speed were found to significantly influence material behavior [1].

In the paper "Tribological Properties of 3D Printed Polymers: PCL, ABS, PLA and Co-Polyester", the objective was to investigate friction, wear, and hardness of four FDM 3D printed polymers (ABS, PLA, PCL, and Co-polyester) for potential applications in industry and medicine. Samples were printed with 100% infill and a 0.1 mm layer height, and tested using a pin-on-disc method under dry conditions. PLA and Co-polyester exhibited the lowest coefficients of friction (0.3 and 0.29), while ABS and PCL showed the highest (0.4 and 0.39). Hardness and wear were found to be inversely proportional – PLA had the highest hardness (20.5 HV) and lowest wear (4 mg), whereas PCL had the lowest hardness (18.3 HV) and highest wear (9 mg). Surface roughness significantly influenced friction – smoother specimens demonstrated better tribological behavior. SEM analysis revealed plastic flow and grooves on all tested surfaces, with minimal wear on PLA and Co-polyester samples. All materials showed good wear resistance due to strong interlayer bonding. The study confirmed that both material selection and print parameters play a crucial role in determining tribological performance of 3D printed parts [2].

A group of authors (Keshav R., Ashu J., Chayan S., Ramakant R., and Roop L.) compared the wear and frictional behavior of 3D printed PLA and ABS samples using FDM technology. The research encompassed six print parameters: infill density, infill type, layer thickness, infill angle, material type, and layer orientation method. Experiments were conducted using a pin-on-disc tribometer in accordance with ASTM G99 standard [3]. Samples were tested under 16 different parameter combinations (DOE design generated in Minitab software using Taguchi method). The results showed that ABS had lower wear and friction values compared to PLA, making it more suitable for mechanical applications. Optimal performance was achieved at medium infill density (50%), linear infill pattern, larger raster angles, and thicker layers. In contrast, hexagonal infill patterns and lower layer thickness resulted in increased wear. Microscopic images revealed more pronounced wear tracks on PLA specimens. The study concluded that selecting optimal print parameters can significantly reduce friction and improve durability of 3D printed components [3].
In [4], the authors investigated the mechanical properties of PLA filament reinforced with metallic alloy powder to assess its applicability for gasket fabrication. The goal was to compare 3D printed samples with conventional sintered metallic materials in terms of pressure resistance and elastic behavior. Specimens were fabricated using FDM technology in two print orientations – vertical and horizontal – and tested under compressive loading. Results indicated that vertically printed samples had higher stiffness (elastic modulus of 565 MPa) compared to horizontal ones (490 MPa). Compared to sintered alloys (up to 2500 MPa), the PLA-metal composite had lower strength, but it was easier to manufacture and suitable for producing complex geometries. The material was chemically stable in oil and fuel environments, although mechanical performance decreased at temperatures above 40 °C. Experimental tests indicated a maximum working pressure of up to 19.5 MPa. Cyclic loading tests were also conducted to evaluate elasticity under low-pressure conditions relevant to hydraulic applications. The study concluded that PLA-metal composites can serve as a potential replacement for traditional gaskets in low-pressure, low-temperature environments. Additionally, from a tribological standpoint, the material demonstrated chemical and structural stability in lubricated environments, without degradation or surface damage [4].

Study [5] investigates the coefficient of friction and wear behavior of eight different 3D printed filaments. The samples were fabricated using FDM technology on a Zortrax M200 printer with 90% infill and tested using the pin-on-disc method under normal loads ranging from 10 to 18.5 N. Mechanical properties were determined by measuring mass loss and friction values before and after testing. The highest coefficient of friction was observed in Z-HIPS (0.497), while Z-PETG demonstrated the lowest friction (0.071) and minimal wear (0.25%). Z-GLASS exhibited extremely low wear (0.08%) despite having a relatively high friction value (0.401), whereas Z-ASA PRO experienced the most severe wear (6.95%). No direct correlation was found between friction and wear, highlighting the complexity of tribological behavior. Material selection should align with specific application demands: Z-GLASS is recommended for high-friction but low-wear applications; Z-ABS or Z-PLA PRO provide a balance between wear resistance and friction; and Z-PETG is suitable where low friction is prioritized. The experiment provides valuable guidelines for material selection in functional 3D printed components that interact with other parts in mechanical or tribological systems. The findings support the development of personalized and functional components across industries, including footwear manufacturing [5].

The objective of study [6] was to evaluate how printing parameters affect the mechanical behavior of thin-walled PLA specimens reinforced with 80% metal alloy powder. Samples with wall thicknesses of 1.0, 1.4, 1.8, and 4.0 mm were fabricated using FDM in X, Y, and Z directions and tested under tensile loading according to ISO 527 standard. The highest tensile strength (~16 MPa) and elastic modulus (~630 MPa) were obtained for specimens 1.4 mm thick, printed in the Y-direction. Samples printed in the Z-direction exhibited extremely low strength due to poor interlayer bonding and internal voids. SEM analysis revealed pronounced microstructural defects—gaps between layers and weak adhesion between the PLA matrix and metal alloy particles. Testing demonstrated high anisotropy in mechanical properties depending on print orientation. Dimensional deviations and deformation were most pronounced in thinner samples. Thicker specimens (4 mm) exhibited lower elastic modulus due to the presence of infill and core structure. The study concluded that PLA–metal composites can be used for functional components, but require optimization of print orientation and layer structure, especially for thin-walled applications [6].

A. I. Portoacă, R. G. Rîpeanu, A. Diniță, and M. Tănase conducted a study investigating the influence of FDM 3D printing parameters (infill density and layer height) on friction, wear, surface roughness, and hardness for ABS and PLA samples. A total of 108 specimens were tested using the pin-on-disc method, and results were analyzed using ANOVA and Grey Relational Analysis (GRA). Findings revealed that PLA exhibited higher friction and hardness, while ABS had rougher surfaces and lower wear resistance at greater layer thicknesses. The optimal parameters for ABS were: 50% infill and 0.1 mm layer height; for PLA: 50% infill and 0.15 mm layer height—resulting in minimal wear and friction. PLA demonstrated 28.57% higher hardness than ABS, indicating greater resistance to plastic deformation. Surface roughness values (Ra, Rz, Rt) increased with layer height, with notably smoother surfaces achieved at lower heights. Wear track analysis showed uniform abrasive-adhesive wear behavior. GRA confirmed and quantified optimal parameter combinations in alignment with results from Minitab software. The study concluded that precise control of printing parameters significantly improves surface quality and durability of 3D printed parts. The findings are particularly relevant for producing geometrically complex components with demanding tribological requirements, such as irregular gear shapes [7].

A study by M. Batista, I. Del Sol, Á. Gómez-Parra, and J. M. Vazquez-Martinez examined the tribological performance of PLA materials and PLA composites reinforced with aluminum and copper particles, produced using FFF (Fused Filament Fabrication) technology. The tested materials included standard PLA, modified PLA with commercial additives, and PLA reinforced with 20%Al and 20% Cu. All samples were printed with 100% infill and tested via pin-on-disc method under constant parameters (15 N load, 105 mm/s sliding speed, 250 m sliding distance). Results showed that metal particles significantly increased hardness (up to 83% for aluminum), but also contributed to increased surface roughness. Copper reinforcement notably reduced wear volume (~55% compared to pure PLA), although increased hardness did not always correlate with reduced wear depth or width. The coefficient of friction remained relatively unaffected by material type, but a "stick–slip" phenomenon was observed during circular motion tests. ANOVA analysis confirmed statistically significant differences in surface parameters (Sa, Sz, Sdc) between filled and unfilled materials. While metal additives did not reduce friction, they contributed to improved behavioral stability and wear resistance. The study suggests that PLA+Cu composites are particularly suitable for systems requiring durability and long-term performance, though not necessarily high surface finish quality [8].

In study [9], the mechanical and tribological effects of print orientation and the presence of metallic particles in a PLA matrix were analyzed using FDM technology. Samples were printed in three orientations (Flat, On-Edge, Upright) and tested for tensile strength and wear under dry conditions. The On-Edge orientation demonstrated the highest tensile strength (28 MPa), whereas the Upright samples exhibited brittle behavior with minimal elasticity and rapid fracture. Tribological tests revealed that vertical orientation resulted in the highest coefficient of friction but the lowest wear depth, while horizontal samples showed lower friction but greater wear. The inclusion of metallic particles within the PLA matrix significantly reduced wear depth compared to pure PLA, while friction values remained relatively constant (~0.5–0.6). Surface roughness and hardness depended on orientation—On-Edge and Upright samples displayed higher Shore D values due to testing on the hardened outer layer. Microscopic analysis showed varying fracture patterns and wear traces, with noticeable stick-slip behavior at lower loads. The lowest wear was observed in vertically printed samples, attributed to the reduced contact area during sliding. The study concluded that both print orientation and the addition of metallic fillers critically influence the performance of components used in sliding systems such as bushings and bearings.

The study in [10] focused on the influence of different surface finishing methods on the surface roughness and tribological behavior of ABS specimens manufactured via FDM. Samples were printed using a Creality CR-10s printer with 100% infill at 240 °C and a print speed of 60 mm/s, and then processed using five techniques: milling, polishing, sanding, acetone vapor treatment, and left untreated. The highest surface roughness (Ra = 13.315 µm) was observed in the untreated sample, while acetone-treated samples achieved the smoothest finish (Ra = 0.443 µm). Tribological testing was performed using a TPD-93 tribometer in block-on-disc configuration under normal loads of 20, 50, and 80 N, at a sliding speed of 0.75 m/s. The results showed that wear width increased with load across all finishing types. Additionally, the coefficient of friction decreased with increasing load—values ranged from ~0.21 to 0.31 at 80 N. Polished and acetone-treated samples demonstrated improved tribological performance compared to rougher surfaces. Microscopic inspection confirmed reduced wear on finely finished specimens. The study concluded that post-processing techniques significantly enhance surface quality and reduce wear in FDM-printed ABS parts [10].

Across most of the reviewed literature, ABS (Acrylonitrile Butadiene Styrene) has proven to be a reliable material with good wear resistance, especially under dry sliding conditions. Studies [1], [3], [7], and [10] confirm that ABS generally exhibits lower coefficients of friction than PLA, typically ranging from 0.21 to 0.45, with friction decreasing as load increases. Study [10] demonstrated that acetone treatment and polishing substantially reduce surface roughness (from 13.3 µm untreated to 0.44 µm post-treatment), thus contributing to lower wear rates at higher speeds and loads. Horizontally printed ABS samples showed better homogeneity and mechanical strength [3], whereas vertically printed parts suffered from weaker interlayer bonding. ABS's resistance to heat, impact, and vibration makes it ideal for engineering applications, including electronic housings and mechanical components exposed to long-term operational loads.

PLA, a biodegradable polymer, typically exhibits higher friction values (0.3–0.6) compared to ABS but also displays greater hardness [2], [5], [7]. However, its lower thermal stability and tendency toward local softening under load lead to increased wear at higher speeds and stresses [1], [3], [8]. Nonetheless, PLA remains the material of choice for highly detailed visual models and prototypes due to its excellent surface quality and print precision. Study [8] showed that the addition of aluminum particles can increase PLA sample hardness by up to 83%, while copper reinforcement significantly reduced wear volume—by up to 55% compared to pure PLA. Printing in the XY orientation yields the best mechanical properties, while Z-direction prints suffer due to poor interlayer adhesion [6], [9].

PLA's printability and environmental friendliness make it well-suited for packaging, educational models, and toys. With the addition of reinforcing particles, it can also be adapted for light-duty functional parts. Composites made from PLA with metallic fillers represent a significant advancement in additive manufacturing by combining the aesthetic qualities of metals with the mechanical characteristics of thermoplastics. Studies [4], [6], and [9] show that bronze-filled PLA has lower strength than conventionally sintered bronze but performs sufficiently under moderate pressure (up to 19.5 MPa) and lower temperature conditions (up to 40 °C). The best mechanical results were achieved with 1.4 mm wall thickness and Y-axis print orientation, yielding tensile strengths up to 16 MPa and elastic modulus values up to 630 MPa [6]. Bronze PLA composites demonstrated lower wear and more stable tribological performance, making them suitable for applications that balance functional performance with visual and dimensional quality.

2. EXPERIMENT

The objective of the experimental investigation was to evaluate the tribological performance of selected polymer materials under different operating conditions (with and without lubrication). The polymers examined in this research are PLA, PLA reinforced with copper, and ABS. The tests were carried out using the block-on-disc method on a TPD-93 tribometer (Figure 1), with a data acquisition system recording results in real time. Changes in normal load and coefficient of friction over time were monitored and analyzed using specialized data processing software. Tribological property characterization of the polymeric materials was conducted at the Laboratory for Tribology, Faculty of Engineering Sciences, University of Kragujevac, using appropriate tribometers, samples, and testing conditions required for experimental implementation.

The investigation included measurements of the coefficient of friction, surface roughness, and wear track width. The experimental parameters were as follows: total sliding distance – s = 200 m, disc material – 50CrMo4 steel, disc diameter – r = 35 mm, normal load – FN = 4 daN, and sliding speed – v = 0.5 m/s.

Figure 1. Universal Tribometer TR-95

The samples were fabricated using 3D printing technology. Each specimen underwent three repetitions of friction and wear measurements under dry conditions and one measurement under lubricated conditions to highlight differences between these operating modes. Particular attention was given to the behavior under dry conditions and its effect on tribological processes. Specific phenomena observed during the tests—such as material softening or melting due to excessive heat generation in some samples—were explained in detail. To calculate the wear track area, it was necessary to measure wear tracks on the test blocks. These measurements were performed using a UIM-21 optical microscope (Figure 2).

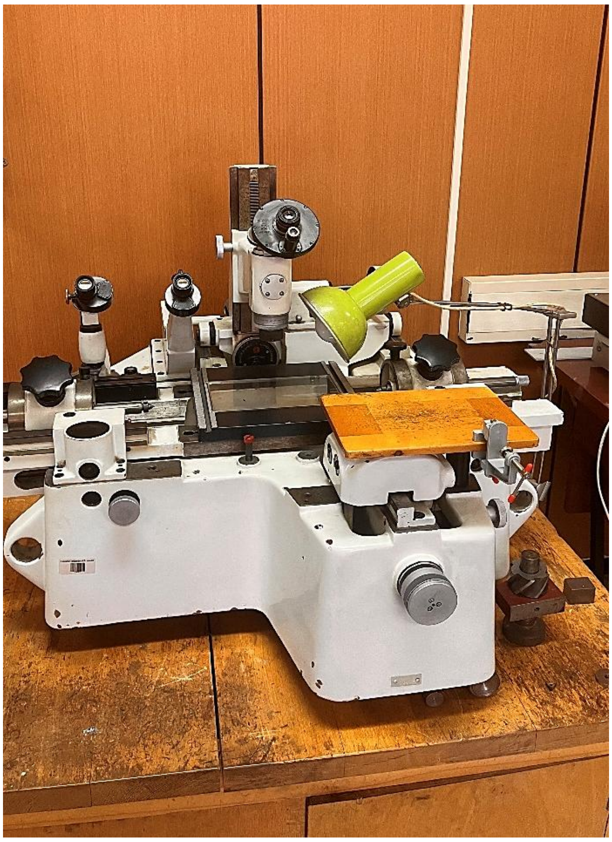

Figure 2. UIM-21 microscope

The measurement of friction force and normal force was performed using strain gauges, while the accompanying software processed the signal and calculated the coefficient of friction.

The software provided an averaged value of the measured quantities every two seconds, based on 100 data points per time unit, corresponding to a sampling frequency of 50 Hz.

After testing, the worn blocks were examined under a UIM-21 microscope, followed by additional analysis using the Meiji FL-150 optical microscope (Figure 3), located at the Tribology Center of the Faculty of Engineering Sciences in Kragujevac. The purpose of this step was to capture detailed images of the wear tracks using microscopy.

Figure 3. Meiji MC-50 optical microscope

Surface roughness measurements were performed prior to the experimental procedure using a contact profilometer, shown in Figure 4.

Figure 4. Surface roughness measurement device

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 next figures show surface roughness diagrams for three different samples. In addition to the surface roughness profiles, the material bearing curves are also included for each sample.

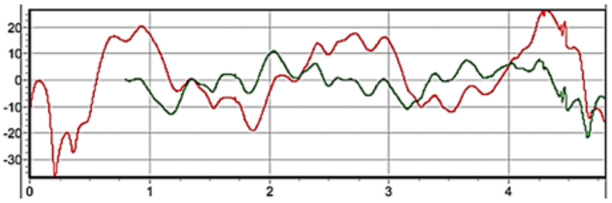

Figure 5. Surface roughness profile of the PLA sample

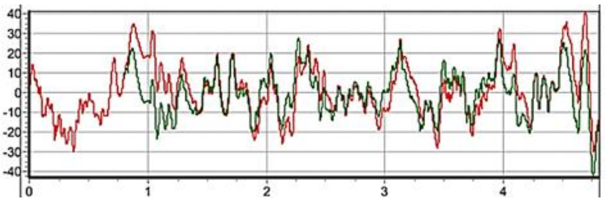

Figure 6. Surface roughness profile of the PLA + copper sample

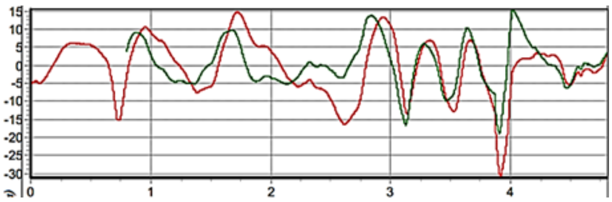

Figure 7. Surface roughness profile of the ABS sample

These diagrams provide a visual representation of the surface condition after processing. The vertical axis of each diagram represents the surface roughness values. These values indicate the maximum height of surface irregularities (RMAX), measured in micrometers (µm). RMAX denotes the maximum difference in height between the highest peak and the lowest valley within the reference length. The horizontal axis represents the reference length (l), expressed in millimeters (mm), and serves as the baseline for surface roughness evaluation over a defined surface distance.

Figure 8 presents the bearing curve of the surface profile for the PLA material.

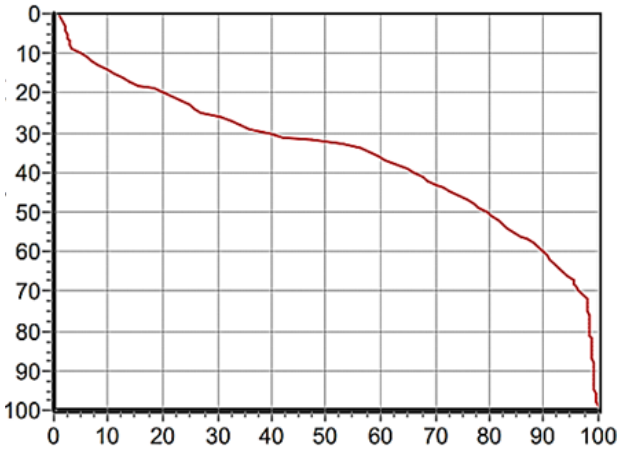

Figure 8. Bearing curve of the PLA surface profile

Figure 9 shows the bearing curve for the PLA + copper composite, while Figure 10 displays the bearing curve for the ABS material.

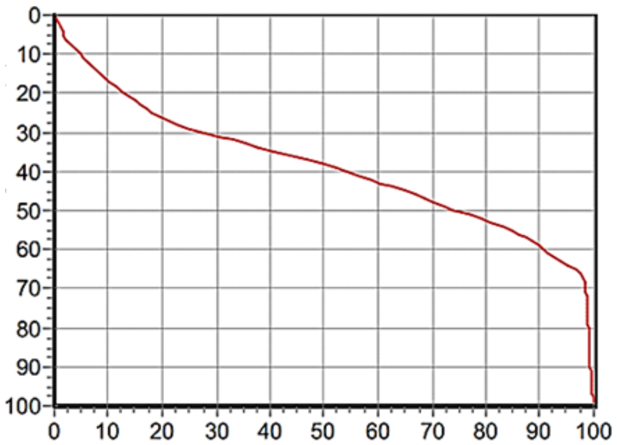

Figure 9. Bearing curve of the PLA + copper surface profile

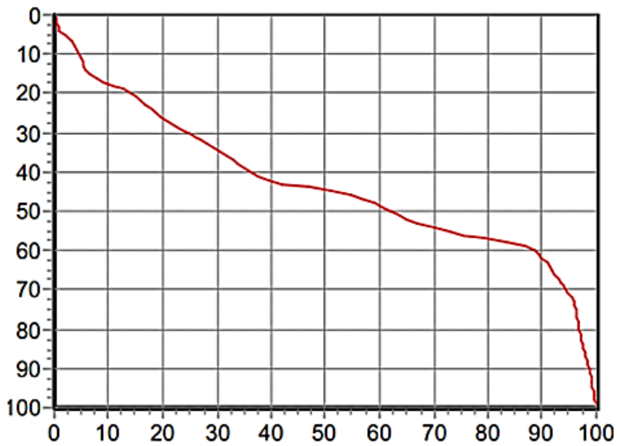

Figure 10. Bearing curve of the ABS surface profile

Figure 11 illustrates the average coefficient of friction for all three materials under dry conditions.

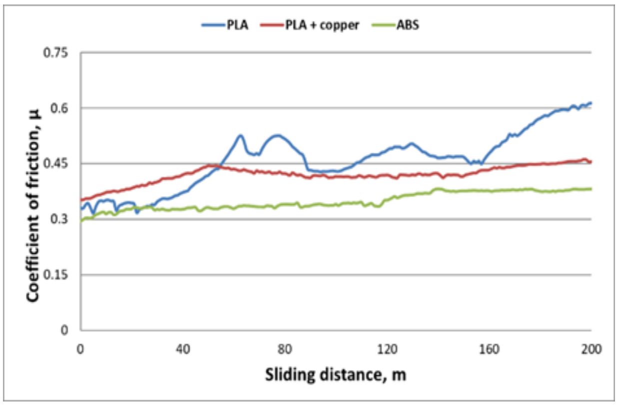

Figure 11. Coefficient of friction diagram for all three materials under dry conditions

Figure 12 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).

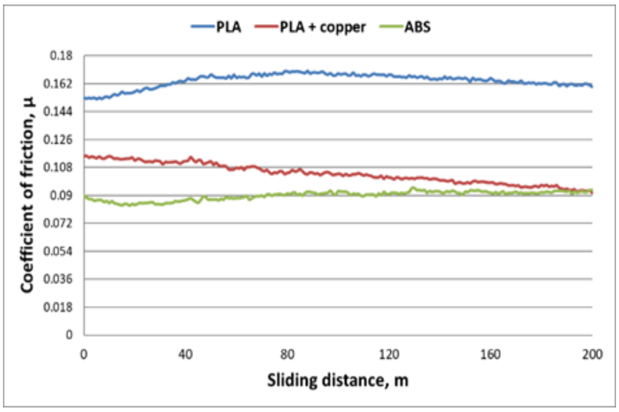

Figure 12. Coefficient of friction diagram for all three materials under lubricated conditions

PLA exhibited the highest coefficient of friction under dry conditions. The PLA + copper composite showed a friction coefficient of approximately 0.45, while ABS remained below this threshold. In the diagram shown in Figure 11, the initial values for all three materials were similar (around 0.3–0.35), gradually increasing over the duration of the test. For PLA, the coefficient of friction nearly doubled by the end of the test. For PLA + copper, it increased by about 50%, while ABS demonstrated the smallest increase, correlating with the lowest wear track widths and volumes.

Under lubricated conditions, the coefficient of friction for PLA did not exceed 0.18. For PLA + copper, the coefficient decreased over time, while ABS again performed best, maintaining a value around 0.1, as shown in Figure 12. The next phase of the experiment involved determining wear track locations, measuring average track widths, and calculating wear volumes. Results for PLA and PLA + copper under lubrication revealed that a lower coefficient of friction does not necessarily imply a lower wear volume.

Figure 13 shows the worn PLA blocks under dry conditions. Figure 14 presents worn PLA + copper blocks, and Figure 15 displays worn ABS blocks, all tested under identical dry conditions. Figures 16, 17, and 18 show the same materials tested under lubricated conditions.

Figure 13. Worn PLA blocks under dry conditions

Figure 14. Worn PLA + copper blocks under dry conditions

Figure 15. Worn ABS blocks under dry conditions

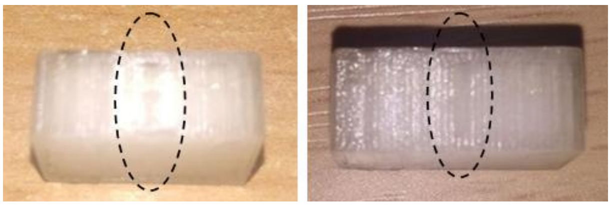

Figure 16. Worn PLA blocks under lubricated conditions

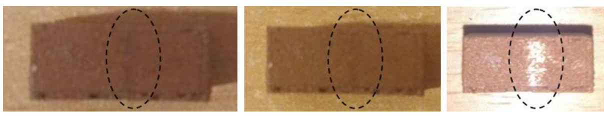

Figure 17. Worn PLA + copper blocks under lubricated conditions

Figure 18. Worn ABS blocks under lubricated conditions

Under dry sliding conditions, as illustrated in the previous images, two PLA samples experienced failure due to thermal degradation—melting and material displacement toward the edges. Consequently, wear track measurements could only be conducted on one PLA block. In contrast, results under lubricated conditions were drastically different; wear was minimal and visible only when the base surface of the block was illuminated, as shown in the corresponding figure.

For PLA + copper samples under dry conditions, wear was clearly visible and relatively severe, although no catastrophic failure occurred, unlike with PLA. In lubricated conditions, the PLA + copper material performed significantly better, as expected. The wear track was visible to the naked eye but became much clearer when illuminated, as also shown in previous images.

Among all materials tested under dry conditions, ABS exhibited the best wear resistance—wear was minimal, and the wear volume results were comparable to those of PLA and PLA + copper under lubricated conditions. Given the already low wear volume without lubrication, it is reasonable to expect even lower values with lubrication, which was confirmed by the fact that wear tracks were nearly impossible to detect, even under direct lighting.

It is evident that PLA had the highest wear volume under dry conditions. Although wear on 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 all other tested materials.

When samples were subjected to lubricated wear conditions, the results were markedly improved. For PLA, the wear volume decreased drastically—yielding even better results than PLA + copper under the same conditions. ABS once again proved to be the best-performing material, with wear volumes so low they could be expressed in micrometers, confirming its excellent resistance under both dry and lubricated sliding conditions. The wear volume values for both testing conditions are presented in Figures 19 and 20. In the case of dry sliding, for PLA + copper and ABS materials, the average wear volume was calculated based on all three tested samples, while for PLA, only one result was available.

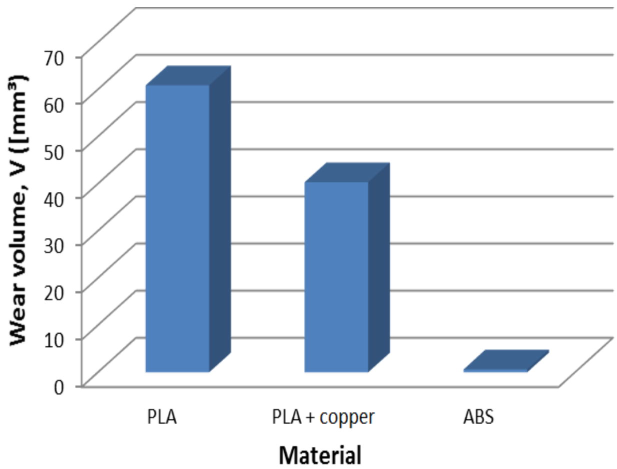

Figure 19. Wear volume of tested materials under dry sliding conditions

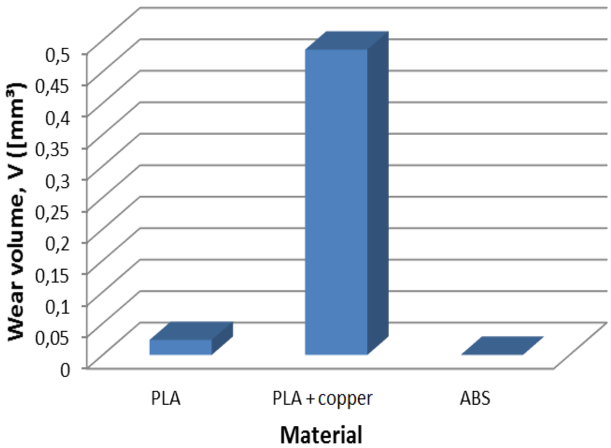

Figure 20. Wear volume of tested materials under lubricated conditions

The following figures display the surface appearance of the test blocks before and after tribological testing, as observed under a microscope.

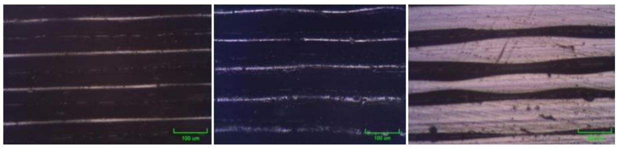

Figure 21. Microscopic image of the PLA sample surface before and after testing (dry and lubricated conditions)

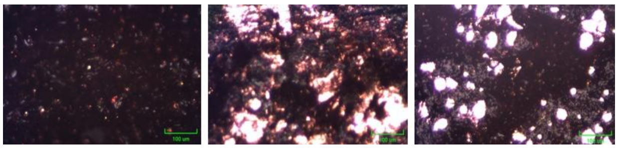

Figure 22. Microscopic image of the PLA + copper sample surface before and after testing (dry and lubricated conditions)

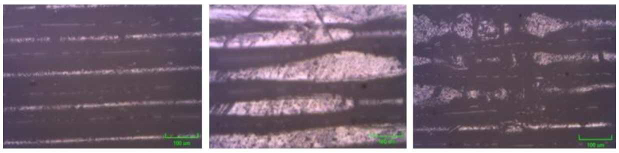

Figure 23. Microscopic image of the ABS sample surface before and after testing (dry and lubricated conditions)

As observed in the previous figures, surface irregularities were present even before testing. This is due to the fact that the blocks were not subjected to fine post-processing, such as grinding or polishing. They were produced using layer-by-layer 3D printing, and any lack of printer precision or application of very thin layers can result in surface imperfections.

4. CONCLUSION

Based on the experimental procedures and analysis of the obtained results, several conclusions can be drawn.

When the PLA block was subjected to dry sliding, a significant amount of material was lost due to intense plastic deformation of the surface, caused by excessive heat generation. However, when lubrication was applied, the amount of removed material was considerably lower, although the wear track appeared wider. The microscopic image of the worn PLA surface under dry conditions represents only a segment of the wear path and does not fully reflect the overall wear process.

For PLA + copper, wear tracks were large but measurable across all three tested samples. Notably, no melting of the material occurred during testing, unlike with PLA.

The ABS samples exhibited the highest wear resistance of all tested materials, with up to 10 times greater resistance compared to PLA and PLA + copper under the same conditions.

Under lubricated sliding, the wear results for all materials showed a consistent pattern. It is important to note that lubrication prevented melting of the PLA samples; however, ABS once again demonstrated the best wear resistance under both testing conditions.

From the presented results, it can be concluded that ABS offers the best frictional and wear resistance properties, both with and without lubrication. Therefore, ABS is highly suitable for 3D printing of functional components intended to operate under low loads and low to moderate sliding speeds. In contrast, the use of PLA and PLA + copper in dry sliding applications is not recommended, particularly in the case of PLA, where severe deformation of the contact surface geometry can occur.

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