Investigating Tribological Behaviour of Multiple Layer Copper Coating on 3D-Printed Biodegradable PLA Composite

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Abstract: The study explores the tribological behavior of multi-layer copper coatings on 3D-printed plastics through an electroplating technique. Copper, known for its exceptional properties in electrical sliding contacts, was electroplated onto polylactic acid (PLA) composites. We evaluated the wear performance of these copper-coated PLA composites under dry sliding conditions using a pin-on-disc wear test. The tests were conducted with a 25N applied force and a sliding velocity of 300 mm/s. The specific wear rates and coefficients of friction for the PLA-Cu polymer composites were analyzed to assess their tribological characteristics.

Keywords: *PLA, 3D Printing, Electroplating, Tribology, Rapid Prototyping*

1. Introduction

3D printing possesses the capacity to address the challenges of the global economy. Thin sections can be produced and utilized as templates for investment casting. (Fries et al., 2014). Metal powder, plastic, and other materials can be combined with many layers of printed ceramic ink using this technology, which leverages data from computer models to make items. The mold forming and manufacturing industries utilize three-dimensional printing for design purposes. It has since been progressively utilized for the direct creation of a variety of goods, with the addition of 3D printers to the park facilitating this process (Frick, 2013). Additive manufacturing techniques like as fused deposition modeling (FDM) are widely utilized for modeling, prototyping, and manufacturing. The "additive" principle is used in FDM, a fast-prototyping method, to deposit materials into layers. The plastic or metal wire opened from the coil delivers the product to the extrusion nozzle, which controls the flow of the product(Hergel & Lefebvre, 2014). The two most popular materials for FDM 3D printing are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). PLA is a harmless, odourless, biodegradable substance that doesn't harm the environment. FDM has found extensive use in the field of three-dimensional printing (Dima et al., 2014). Design, engineering, architecture, aerospace, automobile, medical, and many more fields make use of this technique. It has a variety of uses. As an example, the shock absorber's outlet line frequently comes into contact with liquid during intercourse. Selecting a surface material with adequate wear resistance and performance is, thus, crucial (Israelsen et al., 2017). Consequently, in some areas of application wear and friction are unavoidable. FDM 3D printed goods feature a rough surface. As so, the assembly is not easy to operate (Jurčišin et al., 2015). Many different machines utilize engineering plastics with great mechanical qualities as components. Consequently, more investigation is required on the tribological characteristics of PLA utilized for FDM three-dimensional printing (Chia & Wu, 2015). The structure and characteristics of 3D printing polymer materials have attracted much study. This work studied the tribological behavior of multilayer copper coating on polylactic acid (PLA). Using fused deposition modeling (FDM), Rajeev et al., 2017 investigated the tribological characteristics of PLA composites strengthened with copper powder. The objective is to find that metal reinforcement affects the performance of the material in technical uses with engineering applications. Microstructure and elemental composition were examined in the work using energy-dispersive X-ray spectroscopy (EDAX) and scanning electron microscopy (SEM). PLA and copper powder were blended using twin screw extrusion; examples were 3D printed for tensile and wear tests. Twin screw extrusion was used to blend PLA and copper powder, and specimens were 3D printed for tensile and wear testing. Data significance was determined by means of analysis of variance (ANOVA). According to Köhler et al. (2016), composite filaments are more uniformly produced when copper powder is added. Mechanical and tribological properties are significantly improved when the quantity of copper powder is increased to 20%. A study conducted by Li et al. (2015) examined the utilization of Stratasys F170 printers for the 3D printing of ABS and PLA thermoplastics. Using a multi tribo tester, the printed parts are tested for their friction and wear behavior. The impacts of printing parameters on the tribological and friction behavior of the 3D printed samples are investigated by means of tabulating and graphing results (Stubenruss, 2017). The objective is to ascertain the influence of metal reinforcement on the material's performance in engineering applications.

2. Need of Research

Roy et al. (2021) evaluate the friction and wear characteristics of ABS and PLA thermoplastics produced using Stratasys F170 printers, although they do not assess the performance of these materials against other thermoplastics or composites under the same conditions. This may assist in determining which materials exhibit enhanced performance and the reasons behind this, facilitating the selection of the best appropriate material for particular applications based on their tribological characteristics. Vinay et al. (2024) and Roy et al. (2021) are unable to thoroughly integrate microstructural analysis with tribological testing, which could offer a more comprehensive understanding of the ways in which material composition and structure affect friction and wear. The literature primarily evaluates the immediate tribological properties of 3D-printed materials without investigating their long-term performance under a variety of environmental conditions. By addressing these gaps, it is possible to offer a more comprehensive solution for the application of 3D-printed materials in a variety of engineering disciplines and to gain a more comprehensive understanding of the factors that influence their performance (Geiger et al., 2016).

3. Materials and Methodology

3.1 Preparation of Samples

Polymeric material of Poly Lactic Acid (PLA) is used for the study due to relatively high strong and high elastic modulus that makes it effective option for various components in industrial packaging sector. PLA filaments used here were extruded at 190°C, with a printing speed of 40 mm/s. Fused Deposition Modelling (FDM) was utilized to create 3D-printed PLA samples (Fig 1) with the help of an Ultimaker extended 2+ 3D printer. This 3D Printer produces a model with a dimension of 12 mm in diameter and 32 mm in length according to ASTM G99 (Jack et al., 2017). 3D Printing process parameters are shown in Table 1, and mechanical properties of material (Table 2) considered as per farah et.al [11].

Figure 1: Wear test specimen

Table 1. 3D Printing Parameters

Printing Parameter	Value
Nozzle Diameter	0.4 mm
Layer Height	0.15 mm

Bed Temperature	60°C
Infill	Grid
Infill Percentage	100%
Print Speed	50mm/s
No. of Bottom and Top Layer	4
Nozzle temperature	200°C
Wall Thickness	1.68 mm
Top/bottom Thickness	1.2 mm

Table 2. Mechanical Properties of PLA [11]

Material Properties	Value
Melting Temperature	170-180 ℃
Glass Transition Temperature	60-65 ℃
Melt Flow index	9g/10 min
Moisture	≤455ppm
Specific Gravity	1.24g/cm^3
Tensile strength	55 MPA
Tensile Modules	3725 MPA
Elongation at Break	≤4.25%
Charpy Notched Impact	5.5-6.5 kJ/m^2

3.2 Copper coating on the 3D Printed specimen

The specimens are submerged in an electrolytic cell for electrolysis during the copper electroplating procedure(Haffner et al., 2018). The electrolytic solution is made by dissolving 200g of copper sulphate in 1L of distilled water and then adding 30 mL of sulfuric acid. In electroplating, a DC power supply of 10V and 1.5A is employed (Nam et al., 2019). A single layer of copper coating with a thickness of 0.5 mm is deposited across the surface of the object in 4 hours, followed by the next layer of copper with a thickness of 0.5 mm and the third layer of copper with a thickness of 0.5 mm, as shown in Figure 2.

Figure 2: Copper-Coated Wear Test Specimens

3.3 Tribological testing conditions

The Tribometer TR 20 Micro, equipped with Winducom data collecting software, was employed to examine the tribological properties of materials, focusing on friction and wear under dry conditions. This cutting-edge tribometer is engineered to provide precise measurements across a wide range of operational parameters, rendering it a valuable instrument for evaluating material performance in a variety of situations (Jayaraman et al., 2021).

The Tribometer TR 20 Micro is notable for its extensive operational range, which includes a load capacity of 2-1000 N, a rotational speed range from 0.3 to 3000 rpm, and adjustable test durations. These capabilities enable the device to simulate a wide array of real-world conditions and measure how materials perform under different stresses and speeds. For this study, the tribometer was used to evaluate the tribological behavior of test samples under controlled dry conditions(Kishore et al., 2021).

3.4 Test Setup and Parameters

The testing involved using an EN 8 standard roller with a diameter of 50 mm and a hardness of 62 HRC. This specific roller was selected as it provides a standardized and consistent counter face against which the samples could be tested. The hardness of the roller ensures that it remains durable and resists wear, thereby providing reliable and reproducible data on the wear performance of the test materials(Basurto-Vázquez et al., 2021; Mathews et al., 2021). The fixed operational parameters 300 rpm rotational speed, 25 N load, and 600 seconds run time were chosen based on a combination of factors including typical operational conditions and previous literature findings. This setup allows for a thorough evaluation of the materials' frictional and wear characteristics under conditions that mimic real-world applications.

3.5 Data Analysis

Following the tests, the data collected from the Tribometer TR 20 Micro was meticulously analyzed. The analysis involved comparing the results with existing literature to validate findings and understand the materials' performance relative to previously benchmarks (Vadodaria et al., 2021). This comprehensive approach ensures that the results are both accurate and relevant, providing useful information about the tribological behaviour of the tested materials. The Tribometer TR 20 Micro and Winducom data collection software (shown in Figure 3) were used to analyse tribological behaviour such as friction and wear in dry conditions.

The three most significant criteria for assessing wear rate are load, speed, and motion (Loskot et al., 2023). This tribometer has a load range of 2-1000 N, a speed range of 0.3-3000 rpm, and an adjustable test period. At room temperature, all samples were tested against an EN 8 standard roller with a diameter of 50 mm and hardness of 62 HRC. Following extensive literature study, the data was thoroughly analysed.

Figure 3: Tribometer TR 20 Micro Machine

4. Result and discussion

Wear rate and coefficient of friction (COF) are by far the most critical aspects of the problem. In the current experiment, attrition was measured using weight loss data collected at the end of a 600-second run. Micron wear values are also collected immediately during the data collection process. Figures 4, 5, and 6 indicate that the wear rate increases or reduces with increasing layer thickness (Ichihara & Ueda, 2022a). Thus, increasing the wear rate lowers the friction coefficient in tribological applications. Because of the sample's strong performance when sliding on the new abrasive surface, the coefficient of friction is initially high, but it will stabilise over the test. The friction coefficient stabilises once the transfer process has covered the surface. As the sample slides on the collision, a large amount of heat is created and released by the contact region, causing the local temperature to rise. Dry sliding makes it difficult to dissipate friction heat (Ichihara & Ueda, 2022b).

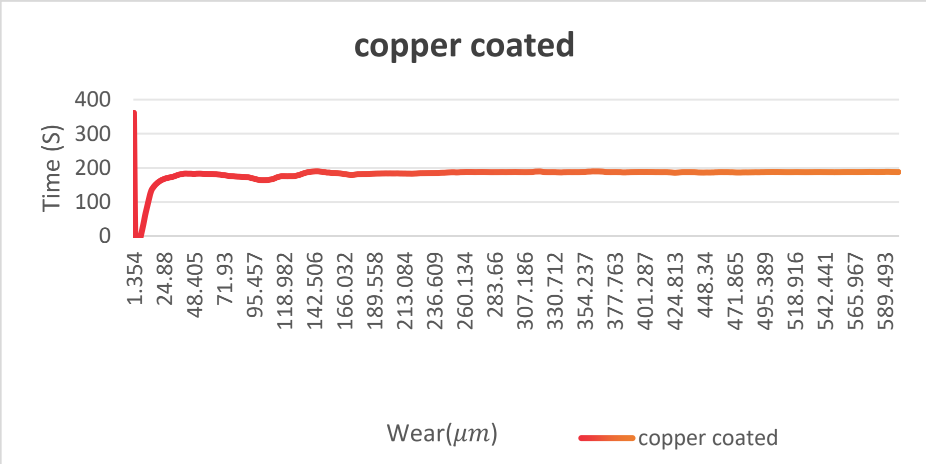

Figure 4: Wear vs Time curve of single coating copper wear tests specimen

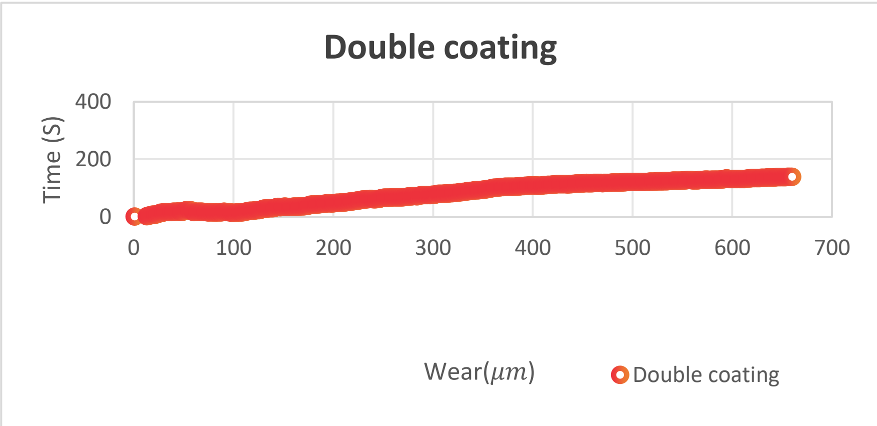

Figure 5: Wear vs Time curve of double coating copper wear tests specimens

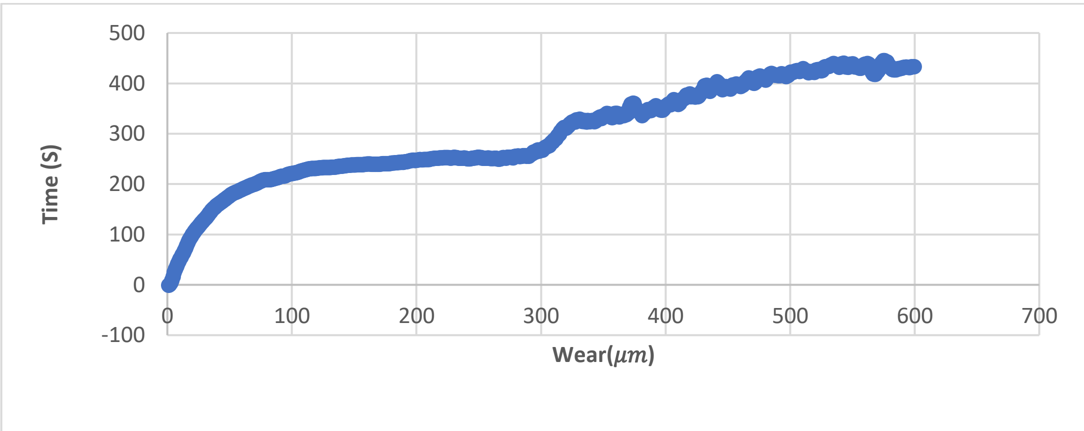

Figure 6: Wear vs Time curve of triple coating copper wear tests specimens

5. Conclusions

Copper particles reduce the quality of interface bonding between PLA filaments during the 3D printing of PLA-Copper composites. Copper particles released from the surface cause debris to accumulate throughout the wear process. At low temperatures, the wear process is abrasive as copper particles leave the surface, however at high temperatures, the wear qualities are sticky. Copper particles implanted in the specimen's surface allow filaments to create interfacial bonds. Furthermore, the particles buried on the sample's surface do not cause surface damage.

6. References

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