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# Wear characteristics of PLA-Cu composites manufactured by fused deposition modelling under different temperature conditions

**Sencer Süreyya KARABEYOĞLU[*], Olcay EKŞİ, Kamil FERATOĞLU**

*Kirklareli University Faculty of Engineering,*
*Department of Mechanical Engineering, Kayali Campus, Kirklareli*

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## Abstract

*Copper shows promising characteristics for applications in electrical sliding contacts. In this study, copper reinforced polylactic acid (PLA-copper) composites manufactured by fused deposition modeling (FDM). Wear behaviour of PLA-copper composites under dry sliding conditions at three different temperature conditions (20°C, 50°C, 70°C) was evaluated by using pin-on-disc wear test equipment with attached heating module with 5N load applied at a sliding velocity of 104.7 mm/s. Tests have presented for 1040 steel bead interacting with polymer composite. Specific wear rates and coefficient of frictions of PLA-Cu polymer composites were evaluated. EDX analysis were conducted to examine the microstructure and scanning electron microscopy is used for the characterization of the worn surfaces.*

***Keywords:*** *Wear, 3D printing, polymer composite.*

# Eriyik yığma modelleme ile imal edilen PLA-Cu kompozitlerinin farklı sıcaklık şartları altında aşınma karakteristikleri

## Öz

*Bakır, özellikle elektriksel yüzey temaslarının bulunduğu durumlarda iyi özellikler göstermektedir. Bu çalışmada, bakır ile takviye edilmiş polilaktik asit kompozitleri eriyik yığma modelleme yöntemi ile imal edilmiştir. Üretilen PLA-bakır kompozitlerinin aşınma davranışları kuru sürtünme ve üç farklı sıcaklık durumlarında (20°C, 50°C, 70°C) ile*

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[*] Sencer Süreyya KARABEYOĞLU, sencerkarabeyoglu@klu.edu.tr, https://orcid.org/0000-0001-8253-6412
Olcay EKŞİ, olcayeksi@klu.edu.tr, https://orcid.org/0000-0002-2433-6700
Kamil FERATOĞLU, kamilferatoglu@klu.edu.tr, https://orcid.org/0000-0002-2280-6529

*normal kuvvet 5N, kayma hızı ise 104.7 mm/s alınarak incelenmiştir. Aşınma testleri ısı modülü eklenmiş pin-on-disk aşınma test cihazı ile gerçekleştirilmiştir. Aşındıran karşı malzeme olarak 1040 çelik bilya kullanılmıştır. Üretilen polimer kompozitlerin spesifik aşınma oranları ve sürtünme katsayıları belirlenmiştir. Malzemelerin mikroyapısını irdelemek adına EDX analizleri gerçekleştirilmiş ve aşındırılmış yüzeylerin karakterizasyonu için taramalı elektron mikroskobu (SEM) ile görüntüleri alınmıştır.*

**Anahtar kelimeler:** *Aşınma, 3B yazma, polimer kompozit.*

## 1. Introduction

Functionally used mechanical components are conventionally manufactured from metals and their alloys. These materials' performances are remarkably improved over the years. However, parts manufactured from polymers show better performance in terms of lightweight and ease in production. Due to their good tribological properties, light weight and low costs polymers are commonly using in many engineering applications such as journal bearings, seals, bushes, gears and electrical applications, etc. [1-6]. Due to adhesive transfer film that occurs during the friction, polymeric materials shows great wear resistance in dry sliding conditions [2].

Wear is referred as material removal from the surface during sliding motion. Surfaces in contact during sliding motion are damaged due to fatigue, abrasion and erosion basically [7]. Wear resistance and frictional properties of materials play a significant role in technologic innovation and also crucial economy wise. Many studies in the literature have been focused on this subject in recent years [8]. Ignoring these tribologic phenomenas cause wasting of resources.

Recently, polymers take place of metals due to their low cost and lightweight in tribologic applications. Polymer tribology is much more burdensome comparing to that of metals [9]. Polymers show promising characteristic in tribological usage due to their self lubrication by nature. Despite that, some of the properties like durability and strength cannot be satisfied. To fulfill this problem, polymers are reinforced with different fillers [10]. Numerous micro-scale particles could be used as fillers to enhance mechanical properties like hardness, modulus of elasticity and fracture toughness but at the same time other mechanical properties like impact strength and tensile strength reduce [11].

The other advantage of the polymers is that they could be manufactured by using rapid prototyping techniques like Fused Deposition Modelling (FDM) process. This technique is one of the additive manufacturing process that is cost effective and fast. In spite of the fact that the parts manufactured by this technique are generally used as prototype. However, parts produced with this technique are generally used as prototypes. In recent years , FDM fabricated products are increasingly used as functional products that require superior mechanical performance[21]. For this reason, it's important to investigate the mechanical properties of these parts. Researchs in the literature about wear characteristics of these parts are very limited. There are several studies on the wear behavior of polymers built by Fused Deposition Modelling [10,12-14]. These studies mostly focuses on improving wear resistance of polymer by adding wear resistant materials as reinforcement such as $Al_2O_3$, SiC, Graphene etc.

Due to the biodegradable properties of PLA it is used as a biopolymer for orthopedic scaffolds[17,18]. There are a few studies on PLA (Poly Lactic Acid)'s wear behavior. Jenniffer Bustillos et al. [14] have studied the wear properties of PLA and PLA-Graphene composites. In mechanical engineering applications, ABS material is more preferable than PLA as a plastic material. Because PLA's glass transition temperature range is smaller than ABS. However, PLA is used frequently in biomechanical applications due to its biodegradability.

Copper and its alloys are widely used in machines parts which have frictional contact such as bearing, bushings, etc. High strength and ductility, fatigue strength, wear resistance are essential for these materials [23]. Composite materials containing copper show promising characteristics for applications in electrical sliding contacts [19]. Using copper as reinforcement in polymer matrix considerably improve the tribological properties of the composites [22]. Although there are tremendous studies on 3D printing of polymer composites in the literature, there is lack of knowledge about wear characteristics of these composites. Hence, copper was selected as reinforcement material and PLA as matrix material in this study. Filament has been developed by 3D printing and specimens were manufactured by FDM. To examine the wear behavior of these composite parts in different conditions, environment temperature had been changed while other parameters kept constant. Wear tests had been conducted by a pin-on-disk wear testing apparatus with attached heating module.

## 2. Materials and methodology

### 2.1. Specimen preparation

PLA is used as the matrix material in granular form. Copper is used as the reinforcement material in the powder form and added manually into the composite. Besides, copper powder sizes varied from 5 micron to 20 micron. Firstly coppers were melt blending with PLA matrix. After the granulation of the resulting mixture twin screw extruder was used for the final composite filament. All of the samples have the same dimensions as 10 mm x 10 mm x 5 mm and were manufactured by FDM at 220$^{o}$C with the extrusion speed of 1 mm/s. Specimens were produced with a layer height of 2 mm and 100% infill. Extrusion nozzles with diameter of 0.4 mm were used.

### 2.2. Wear tests

Dry sliding behaviour of PLA-Copper composites was evaluated at different temperatures using pin on disc wear-testing setup with added heating module for determining the coefficient of friction and wear rate. Test parameters were selected in accordance with ASTM G99, Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus [20], for laboratory tests, which are shown in Table 1.

The block specimen was fixed on the base plate carefully and placed in a heat chamber. 100Cr6 steel bead was used as a counter material. Wear tests were caried out at 100 rpm under dry sliding conditions at 20, 50 and 70 $^{o}$C environment temperatures. Temperatures were measured using RTD sensor mounted in the heat chamber. The experiments were subjected to certain restrictions at each 13145mm sliding distance. For each temperature three specimen were used within the test. Friction coefficient and wear rate curves obtained from the average values of these tests.

Table 1. Wear test parameters.

| Test Parameters | Values |
|---|---|
| Track diameter (mm) | 20 |
| Duration (second) | 300 |
| Normal Load (N) | 5 |
| Temperature (°C) | 20,50,70 |
| Environment | Air |

## 3. Results and discussion

### 3.1. Microstructure

Figure 1 shows EDX analysis of PLA-Cu composites. Copper weight fraction of the composite material was determined as 1.09%. Other elements can be observed from Figure 1. Because of the oxidation, oxygen comes into existence as seen in Figure 1. High carbon content is observed in PLA-Cu composite.

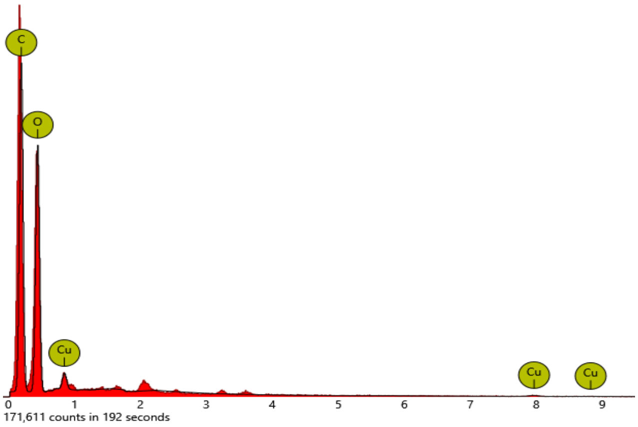
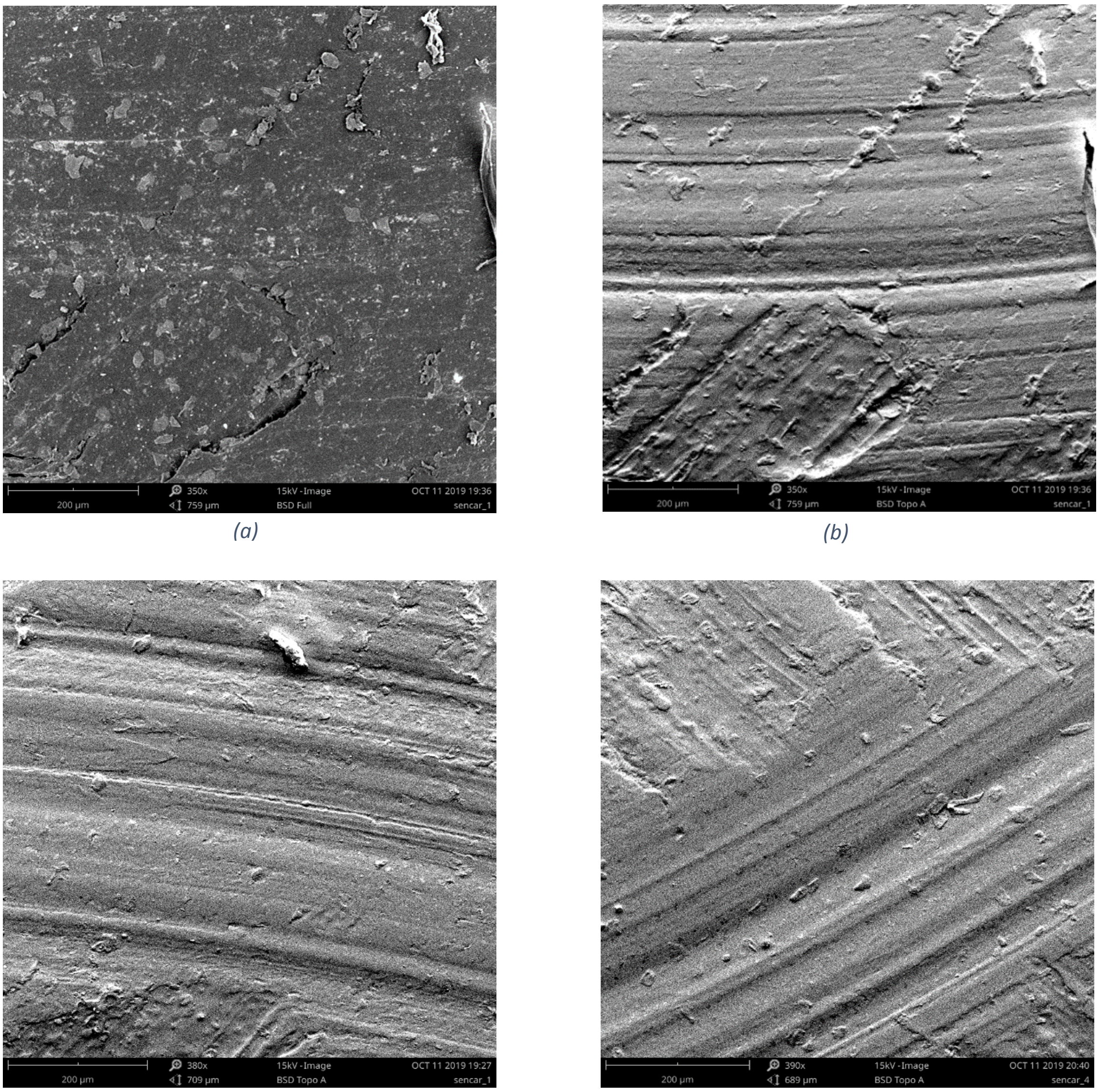


Figure 1. EDX analysis of PLA-Cu composite samples

### 3.2. Worn surface analysis

The SEM images of worn surfaces of PLA-Cu composites are shown in Figure 2. Since the melting temperature of copper is much higher than that of PLA, occurring interface bonding between the filaments is not clean due to copper particles as seen in Figure 2a. At 50 $^{0}$C testing temperature, adhesive wear mechanism transforms into a delamination wear. It can be observed in Figure 2b. Micro sized scratch, seen in Figure 2c, is occurred due to test that is conducted at room temperature. In contrast to the tests conducted at higher temperatures, copper particles don’t rub in the subsurface at room temperature. Therefore, these particles cause scratch on the worn surface.



*(a)* *(b)*

*(c)* *(d)*

Figure 2. SEM images of the worn surfaces, (a) Interface bonding of filaments at room temperature, (b) Delamination wear at 50 $^0$C, (c) Observed scratch due to Cu particle at room temperature, (d) Rubbed Cu particles in subsurface at 70 $^0$C.

### 3.3. Wear rate and friction coefficient

Wear behavior of the parts developed by FDM process was examined with variation of testing temperature. Figure 2 shows variation of wear rate under different temperatures. Wear depth and scar width were used to determine the volume loss. Then, the wear rate is calculated via Eq. 1.

$$K = \frac{\Delta V}{L.F_N} \tag{1}$$

where, $K$ is the wear rate, $\Delta V$ is the volume loss, $L$ is the sliding distance and $F_N$ is the normal force.

Wear volume loss was determined by using the equation provided from ASTM G99 [20] with Eq. 2.

$$specimen\ volume\ loss = 2\pi R\left[r^2 sin^{-1}\left(\frac{d}{2r}\right) - \left(\frac{d}{4}\right)(4r^2 - d^2)^{\frac{1}{2}}\right] \qquad (2)$$

where:

$R$= wear track radius, and
$d$= wear track width.
$r$= spherical pin end radius.

As seen from the Figure 3, coefficient of friction is higher due to abrasive wear mechanism at room temperature. Copper particles which are chopped from the surface act as a grinder at this level of temperature. However, at higher degree of temperature, abrasive wear transforms into adhesive wear and copper particles which are rubbed with PLA decrease the friction between steel bead and sample. In Figure 4, the wear rates were observed at high levels at the beginning due to surface roughness of the specimens and after some time the wear rates get through to steady state regime. At lower testing temperatures, wear volume rate is high as expected due to abrasive wear mechanism. As temperature level rises, wear volume rate seems to be decreased with involvement of adhesive wear mechanism.

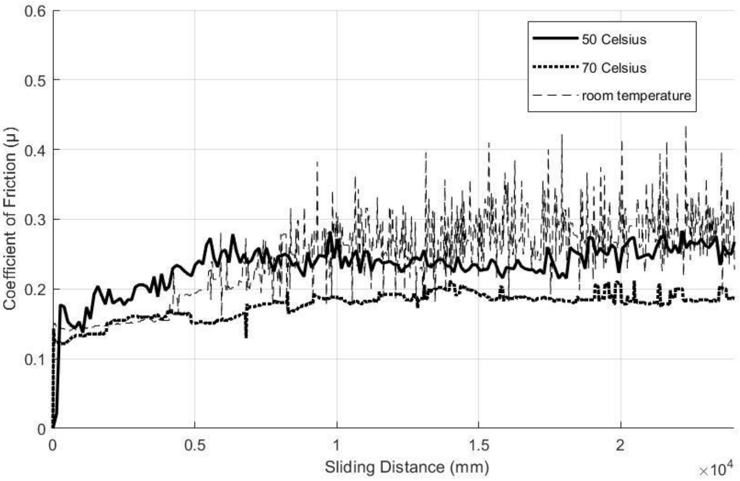


Figure 3. Friction coefficient-Sliding distance variation.

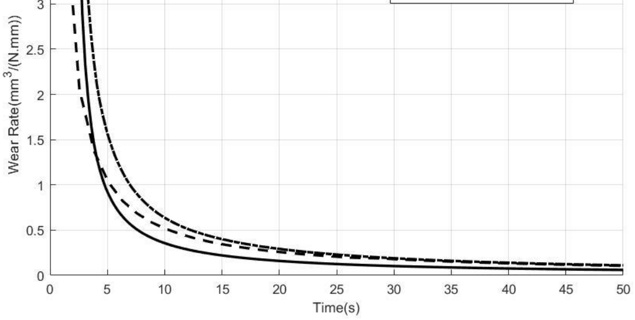


Figure 4. Wear rate of PLA-Cu at different temperatures.

## 4. Conclusion

Throughout the 3D printing process of PLA-Copper composites, copper particles provoke poor quality interface bonding between PLA filaments. During the wear process, copper particles preleased from the surface give rise to debris forming. While wear mechanism is abrasive due to copper particles that leaves the surface at low temperature, characteristics of wear is adhesive at high temperatures. Besides that, plastic deformation can be observed from SEM images. Temperature increases in testing environment stimulate the plastic deformations and these deformations occur as debris on the sample’s surface. Copper particles submerged into the specimen’s surface allow to form interface bonding between filaments. Moreover, these submerged particles in the sample’s surface do not cause damage on the surface. Therefore, less friction and less wear rate could be observed at high temperatures.

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