



Tribological properties improvement of 3D-printed parts by in-process addition of graphite particles into the top layer

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KEYWORDS	ABSTRACT
Additive manufacturing 3D printing PLA Graphite Tribology FDM	3D printing comprises various manufacturing technologies that build parts layer-by-layer, with fused deposition modeling (FDM) being a widely favored method due to its affordability. It enables the creation of complex shapes and the ability to shape or mix materials to the object's interior. Currently, 3D-printed polymer products are primarily utilized as conceptual prototypes rather than functional components. This is because pure polymer prints lack the necessary mechanical properties to serve as fully operational load-bearing parts, primarily due to high friction and wear. In this study, graphite was added to the top layer of the filament during the printing process to attempt to improve its tribological properties. Using pin-on-disc tester, the tribological performances of 3D printed graphite added PLA disc was compared with that of unmodified PLA disc paired with high chromium steel ball. Results showed that the graphite added PLA disc had lower coefficient of friction compared to the plain PLA disc.

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1.0 INTRODUCTION

Additive manufacturing, commonly known as 3D-printing, has emerged as a transformative technology revolutionizing various industries by enabling rapid prototyping, complex geometries, and customized production (Matias and Rao, 2015). As the demand for functional 3D-printed components grows, there is an increasing focus on enhancing the mechanical properties and performance of these parts to meet real-world engineering applications (Fouly et al., 2022; Mohammadi Zerankeshi et al., 2022; Norani et al., 2021; Pawlak, 2018; Przekop et al., 2020). One of the expected use of parts by 3D-printing is for tribological usage, which encompasses friction, wear, and lubrication performances.

Poly(lactic acid) (PLA), a biodegradable and renewable thermoplastic, has gained significant popularity as a widely used material in 3D-printing due to its eco-friendliness and ease of use (Mohammadi Zerankeshi et al., 2022). However, PLA's inherent limitations in terms of tribological properties, such as friction and wear resistance (Norani et al., 2021; Przekop et al., 2020; Zainal et al., 2023), have hindered its wider adoption in engineering applications that involve sliding and contact interfaces. Various methods have been employed to address these challenges such as blending (Oosterbeek et al., 2019), copolymerization (Dorati et al., 2007), surface modification (Bakry et al., 2012) and incorporation of filler into PLA matrix (Esposito Corcione et al., 2019).

In this study, a novel approach was introduced to enhance the tribological properties of 3D printed parts by incorporating functional additives during the finishing process of 3D-printing. Graphite, known for its excellent self-lubricating properties, low friction coefficient (Miyoshi, 2001) and low cost offers the potential to reduce wear and enhance the overall tribological behaviour of PLA parts. The incorporation of graphite particles in-process of the 3D-printing of the surface layer presents a new method to achieve improved performance without compromising the structural integrity or design complexity of the printed parts.

The present research aims to investigate the effects of in-process addition of graphite particles on the top layer of 3D printed parts to enhance their tribological properties and provide insights into the effectiveness of in-process graphite particle addition to improve performance in friction and wear-intensive environments.

2.0 EXPERIMENTAL PROCEDURE

2.1 Preparation of PLA Sample with and Without Graphite layer

Disc-shaped PLA samples were prepared using a consumer 3D printer (Ender 3 V2, Creality, China). The slicing software UltiMaker Cura 5.2.2 was used to convert the 3D model to G-code. PLA filaments (PLA Pro 3D Printer Filament, Flashforge Corporation, China) were utilized, with a tensile strength of 45.5 MPa and flexural strength of 73 MPa. The printing parameters are summarized in Table 1.

Slicers offer various advanced features to improve print quality or modify the printed materials or both. One such feature is "ironing" which is primarily available in some slicers like Cura, PrusaSlicer, and others. Ironing is used to smooth out visible layer lines present on the top surface of the print thus improving the surface finish of the top layers of a 3D printed object (Butt et al., 2022). To implement ironing in the 3D printing process, heat was utilized to smooth the surface. The nozzle was moved back and forth over the top layer, melting and pushing back any protruding material. Additionally, a small amount of material was extruded to fill any gaps on the

top layer, resulting in a smoother surface. This ironing feature will be used to embed the graphite particles on the surface of the printed specimen.

For the preparation of PLA samples with in-process addition of graphite in the top layer, 0.2 g of graphite flake with grain size of around 40 μm was mixed with 10 ml of ethanol and sonicated for 10 minutes. During the printing process, the G-code was modified to pause before the ironing process. Subsequently, 0.5 ml of the graphite ethanol mixture of graphite was carefully added to the top of the PLA specimen using a dropper and allowed to dry before proceeding with the ironing process. The distribution of graphite particles on top of specimen surface is equivalent to 0.02 mg/mm². Figure 1 illustrates the shape and dimension of the disc specimens.

Table 1: 3D Printing parameters.

Print Parameter	Value
Nozzle diameter (mm)	0.4
Print temperature (°C)	200
Bed temperature (°C)	60
Layer height (mm)	0.20
Top and bottom layer style	Line
Layer line direction	45 and 135 degrees
Infill percentage (%)	100
Cooling (%)	100
Print speed (mm/s)	60
Ironing on last layer	Enabled

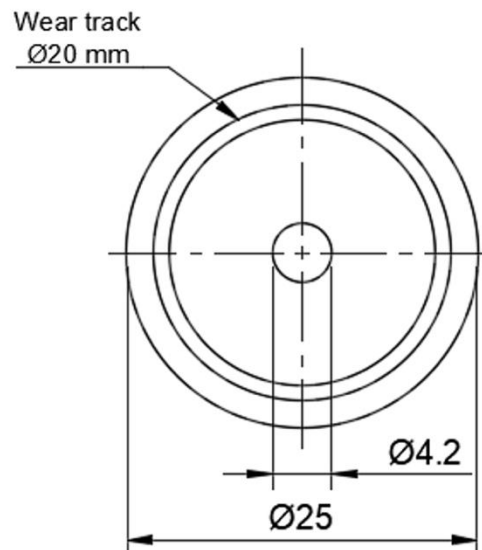


Figure 1: Shape and dimension of printed specimen.

2.2 Surface Characterization

The surface roughness, imaging, and elemental composition of the specimens were analysed. The surface roughness was measured using the 3D Optical Microscope (Hirox KH-8700). Multiple points were sampled and averaged to ensure representative data. Prior to surface imaging, the PLA specimens were coated with a thin layer of gold for 1.5 minutes to improve the sample's electrical conductivity and allowing better electron flow during the imaging process. Surface morphology of neat PLA and PLA with added graphite samples was obtained using Scanning Electron Microscopy (SEM). The graphite particle concentration and distribution on the specimens' surface were analysed using Energy-dispersive X-ray Spectroscopy (EDS).

2.3 Tribological Test

The tribological test was conducted on a custom-made pin-on-disc tribometer. An 8 mm diameter ball specimen made of JIS SUJ2 high chromium bearing steel served as the stationary pin counterpart against the rotating 3D printed PLA disc. The average surface roughness (Ra) of the pins is less than 0.05 μm . Prior to the experiment, the PLA discs were wiped with ethanol, and the SUJ2 pins were ultrasonically cleaned with ethanol for 10 minutes. Table 2 gives the experimental conditions of pin-on-disc test. The friction force and applied load was obtained using a strain-gauge-based load cell and the data was recorded into the computer.

Table 2: Pin-on-disc experimental condition.

Parameter	Value
Load (N)	10
Sliding speed (m/s)	0.063
Sliding distance (m)	125.7
Lubrication	Non
Ambient Temperature ($^{\circ}\text{C}$)	25
Relative Humidity (%)	50

3.0 RESULTS AND DISCUSSION

3.1 Surface Characterization of Printed Samples

The 3D surface profiles of PLA specimens with and without added graphite particles on top layer are presented in Figure 2. The average roughness parameter, Ra was calculated and the results are summarized in Figure 3. For simplification purpose, the PLA sample added with graphite particles on the top layer may be refer to as PLA + Graphite Layer in following figures and tables.

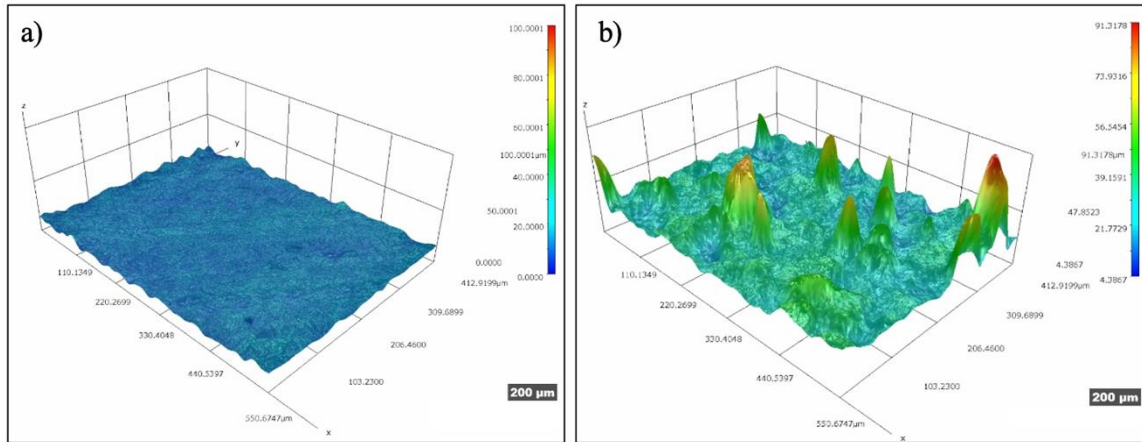


Figure 2: 3D surface profile of (a) unmodified PLA and (b) PLA added graphite particle on surface.

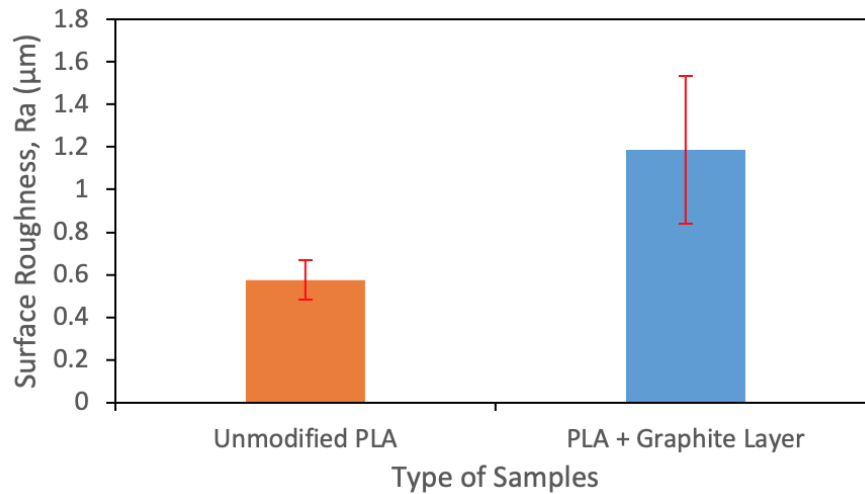


Figure 3: Average surface roughness of PLA and PLA added graphite particle on top layer.

As shown in Figure 3, the addition of graphite particles on the top layer resulted in a notable increase in surface roughness. The PLA specimen without added graphite exhibited an Ra value of 0.573 μm, whereas the PLA specimen with graphite particles on the top layer showed a higher surface roughness with an Ra value of 1.187 μm. Scanning Electron Microscopy (SEM) was employed to analyse the surface morphology of the 3D printed PLA specimens. Figure 4 shows the SEM images of both samples.

Despite the visually smooth appearance of unmodified PLA sample without magnification, SEM analysis revealed the presence of clear print lines on its surface. Additionally, the SEM images showed that the PLA specimens with added graphite particles exhibited a coarser surface texture compared to the unmodified PLA specimens, which displayed a smoother and more uniform appearance.

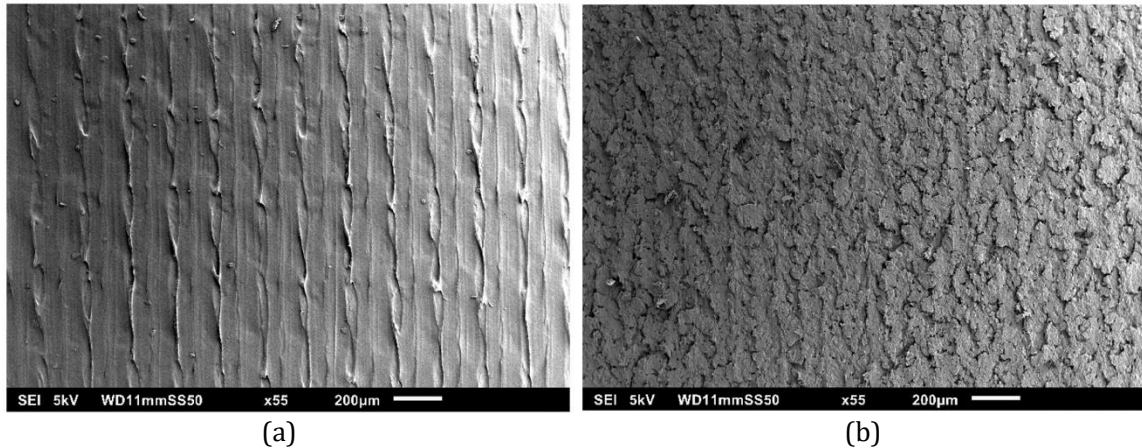


Figure 4: Surface morphologies of (a) Unmodified PLA specimen and (b) PLA added graphite particle on top layer.

Energy-dispersive X-ray Spectroscopy (EDS) was utilized to investigate the elemental composition and distribution on the surface of the 3D printed PLA specimens. PLA is composed of repeating lactic acid units linked together through ester bonds (Hagen, 2012). Lactic acid, also known as 2-hydroxypropionic acid, has a molecular formula of $C_3H_6O_3$, consisting of three carbon atoms (C_3), six hydrogen atoms (H_6), and three oxygen atoms (O_3). In its pure form, PLA should ideally exhibit an almost 1:1 ratio of carbon (C) and oxygen (O) elements.

Table 3 summarizes the EDS mapping of carbon (C) and oxygen (O) elements of both specimens. The analysis revealed a higher concentration of carbon, attributed to the presence of graphite particles, on the surfaces of PLA specimens with added graphite confirming the successful in-process addition and distribution of graphite particles onto the top layer.

Table 3: Chemical composition of PLA and PLA added graphite layer samples

Sample	Weight %	
	C	O
Neat PLA	51.92	48.08
PLA + Graphite Layer	56.93	43.07

3.2 Tribological Test

The tribological performance of the 3D printed PLA specimens was evaluated using a pin-on-disc tribometer. Figure 4 shows the results of the friction coefficient measurements. Figure 5(a) presents the average coefficient of friction for unmodified PLA and PLA with added graphite layer. The average coefficient of friction was measured from the 200th rotation until the 1990th rotation to eliminate the initial running-in period characterized by unpredictable results, possibly due to contaminants like adsorbed water or oil layers during handling. The friction coefficient of unmodified PLA falls within the range of previous studies (Amirruddin et al., 2022; Pawlak et al., 2019; Przekop et al., 2020). Overall, the test results indicate that the addition of graphite particles on the top layer reduced the coefficient of friction of the PLA specimens.

Figure 5(b) illustrates the real-time coefficient of friction against the number of rotations throughout the full sliding cycle for both unmodified PLA and PLA with added graphite. It is evident that, during the initial sliding stages, the friction coefficient of PLA with added graphite is significantly lower than that of unmodified PLA. This can be attributed to two factors: the surface properties of the sample and the lubricating film function of graphite on the surface.

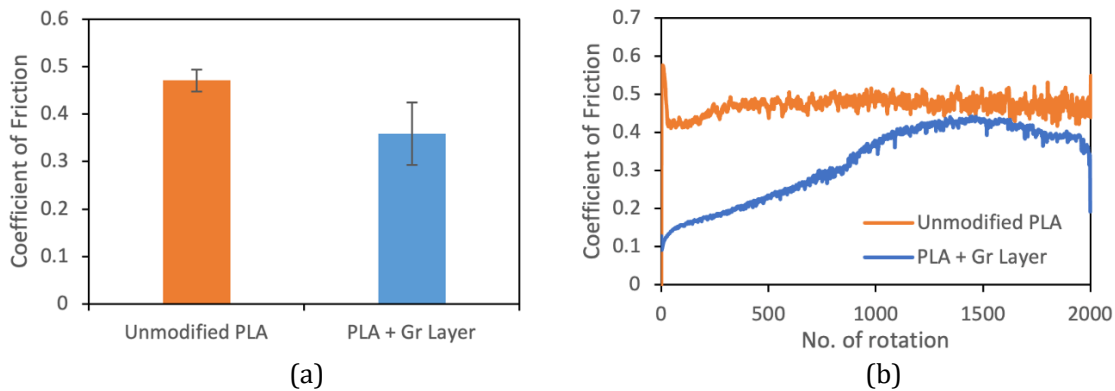


Figure 5: (a) Average coefficient of friction of unmodified PLA and PLA added graphite layer (b) example of real-time coefficient of friction against number of rotations for both samples.

The addition of graphite particles distributed on the specimen's surface causes an uneven and coarse texture, leading to an increase in surface roughness. Consequently, higher surface roughness results in higher asperity peaks upon contact and a smaller initial contact area, extending the running-in period before achieving a steady-state friction (Dhakal et al., 2023). Furthermore, graphite particles can generate transfer films that adhere to the counterpart, effectively covering the contact area and preventing direct contact between sliding surfaces. This characteristic results in low shear at or near the sliding interface (Scharf and Prasad, 2013). However, as the transfer film gradually wears away, its effectiveness diminishes until it is eventually depleted. This depletion causes the friction coefficient to approach that of unmodified PLA.

These findings indicate that the addition of graphite particles on the top layer has a notable effect on the surface roughness, morphology and tribological behaviour of 3D printed PLA specimens, making it a viable approach for improving the tribological properties of PLA components in tribological applications.

CONCLUSIONS

In this study, the improvement of tribological properties in 3D-printed parts by introducing graphite particles into the top layer during printing process was successfully demonstrated. A method was developed to prepare in-process addition of particles on the top layer during printing, utilizing the ironing feature to embed the particles on the surface of the printed specimen.

The addition of graphite particles on the top layer of the PLA specimens resulted in a noticeable increase in surface roughness, with Ra measuring 1.187 μm , compared to the unmodified PLA's 0.573 μm . SEM analysis revealed a coarser surface texture of the PLA with added graphite layer

compared to the unmodified PLA specimens. EDS analysis further confirmed the presence of graphite particles on the surface of PLA specimens with added graphite, showing a higher concentration of carbon, attributed to the successful in-process addition and distribution of graphite particles on the top layer. Moreover, the friction coefficient of PLA specimens with added graphite showed a noticeable reduction, especially during the early stages of sliding before the PLA specimens underwent wear. These findings indicate the feasibility of the in-process addition technique in enhancing the tribological performance of 3D-printed components.

Further research opportunities lie in investigating the influence of different graphite content levels and exploring the potential of other reinforcement particles to improve the tribological performance of 3D-printed PLA components. Additionally, the printing temperature during the ironing process and other printing parameters may also influence the behaviour of particles on the printed surface.

In summary, this study contributes to the growing body of knowledge surrounding the improvement of 3D-printed parts through various methods. The findings open up new possibilities for utilizing 3D printing technology, especially in enabling the possibility of 3D printable polymers for load-bearing, friction and wear intensive applications.

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