Tribology Behavior of *In-Situ* FDM 3D Printed Glass Fibre-Reinforced Thermoplastic Composites

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Abstract: Fused deposition modeling (FDM) 3D-printed parts are generally weaker compared to injection-moulded parts. Fibre reinforcement is one of the techniques used to enhance the mechanical strength and the tribological behavior of the FDM-printed parts. Recently, a new method for creating FDM 3D-printed composites was developed. Current work focuses on the tribological behavior of the glass fibre-reinforced PLA, manufactured using this new composite manufacturing method. Experiments were conducted to investigate the effect of Glass Fibre (GF) reinforcement on FDM 3D-printed thermoplastic composites, specifically polylactic acid (PLA) under different linear sliding speed and directions. All 3D printed glass fibre-reinforced PLA (PLA-GF) composites exhibited a lower wear rate and a higher friction coefficient compared to 3D printed PLA. Increasing in disc's linear speed or sliding speed of the pins resulted in a lower coefficient of friction and wear rate. In addition, a perpendicular raster direction towards the disc rotation or pin motion experienced greater friction and greater wear.

Keywords: Additive manufacturing, Fused deposition modeling, Extrusion, Polymer composites.

1. INTRODUCTION

Additive manufacturing (AM) or 3D printing is referring to the production of three-dimensional objects layer by layer [1]. It is also known as layered manufacturing, additive fabrication, and layered manufacturing. Compared to the traditional subtractive manufacturing, AM enables more flexible fabrications that cope with almost every shape of design. AM is gaining advantages over traditional manufacturing [2]. In detail, the uses of AM have increased over various industries during the past few years. The phenomena of retailers urging to cut down the cost of supply chain in the 20th century was coincidentally simultaneous to the decreased of 3D printing's costs and lead time, which gained the attraction or interest of scientists and customers, which make the practicality of 3D printing grew even more rapidly. The industry change was an identified opportunity that encouraged people to focus on the improvement of machine performance and product qualities.

AM can be categorised into several techniques, which are Fused Deposition Modelling (FDM), Stereolithography (SLA), Liquid Polymerization, Selective Laser Melting, Ballistic Particle Manufacturing, Binder Jet Printing, and Laser-Engineered Net-Shaping. FDM is widely used in various sectors. In this technology, the main activity involves heating of thermoplastic filament through a nozzle and then directed to desired areas using X-Y-Z motions for solidification later. Since FDM is the extrusion of material and later has the material solidified for further extrusion, the material should be able to flow and harden to create a desired object [3]. Thermoplastics are common polymers that can be reformed after melting. The selection of thermoplastics for FDM considers several factors such as melting temperature, thermal expansion coefficient, glass transition temperature, strength, material durability, ductility. Common thermoplastics for FDM are acrylonitrile-butadiene-styrene copolymer (ABS), polylactic acid (PLA), and polycarbonate (PC). PLA has it unique advantages, for example does not require heating bed or is not easily deformed during the cooling process like ABS [4]. Furthermore, PLA is friendly to the environment since it is made from natural ingredients produced from potato, corn and sugar-beet as well as having a better look of design.

Although PLA is environmentally friendly, it has weaker elasticity than ABS and a low melting point, which causes it to melt or deform at lower temperatures. Additionally, FDM 3D printed PLA parts have drawbacks, such as low mechanical properties [4]. To improve the application of FDM 3D printing technology in industry, it is essential to enhance the mechanical properties of the FDM printed parts. Research has been conducted to enhance the mechanical properties of FDM printed parts by using various methods, including optimizing printing parameters, annealing, mechanical pressing and fibre reinforced thermoplastics [5]. Among these methods, reinforce polymer with reinforcement is the most promising method, and different types of reinforcement can be added to the polymer matrix to achieve the desired outcome. Fibre reinforced polymer composites (FRPCs) are produced by adding fibres or particles as reinforcement into the thermoplastic matrix to improve

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the mechanical strength of the polymer components. Furthermore, reinforcement will also enhance the tribological properties of the thermoplastic composites [6,7]. FRPCs were traditionally manufactured using manual lamination (hand lay-up) and have been widely investigated [8-11] . FRPCs can now be manufactured using FDM 3D printing technology. The advantages of 3D printed fibre reinforced thermoplastic are widely studied [12,13,14]. Three different fibre embedding methods can be used to manufacture FDM 3D printed fibre-reinforced polymer composites: embedding before the printing process, embedding in the nozzle, and embedding in the component [5]. An *in-situ* 3D printed polymer composite method was developed recently, where the glass fibres were deposited in between printing [15]. The tensile strength of the *in-situ* 3D printed PLA composite increases with an increase in the glass fibre reinforcement up to a limit of 2.39 wt% [13]. In comparison, the tribological aspect of 3D printed parts,especially the *in-situ* 3D printed polymer composites are less explored, although some investigations into 3D printed neat polymers has been reported [16–20].

Therefore, current work aims to investigate the tribological behavior of in-situ 3D printed glass fibre-reinforced PLA composites. The present study focuses on the friction and wear behavior of two different pin materials (PLA and PLA-Glass fibre) slides against a steel disc in a pin-on-disc test. Furthermore, the tribological performance of both materials at different sliding speeds, and orientation (perpendicular and parallel) are also studied in this work.

2. METHODOLOGY

2.1. Preparation of the 3D Printed Pins

Circular pin samples of 10 mm diameter and length of 47 mm were 3D printed from PLA and glass fibre reinforced PLA composite (PLA-GF). A CAD software (CATIA V5) was used to create the 3D model of the pin and then a slicing software (Ultimaker Cura 4.3) was used to slice the 3D models of the pin. 18 PLA pins and 18 PLA-GF pins were 3D printed using a 3D printer (Forcemaker3D S220, Nazca Scientific Sdn. Bhd, Cheras, Malaysia). PLA filaments (Nazca Scientific Sdn. Bhd, Cheras, Malaysia) of diameter 1.75 mm were used to fabricate the pin specimen. The printing parameters used were shown in Table **1**.

The PLA-GF composite pins containing 2.39 wt% glass fibre (GF) were produced using an innovative 3D printing technique designed for polymer composites [15]. Figure **1** illustrates the setup of the 3D printer equipped with two extruders. The first extruder deposits pure polymer (PLA), while the second, referred to as the fibre doser, dispenses milled glass fibre at a motor speed of 235 rpm. This fibre doser was specifically designed to introduce glass fibre powder

Table 1: Table Showing the Parameters of a 3D Printer when Printing the Pins

Printing parameters	Information
Printer nozzle temperature (°C)	210
Heating bed temperature (°C)	70
Infill pattern	Rectilinear
Raster angle (°)	± 45
Layer thickness (mm)	0.2
Printing speed (mm/min)	60
Build orientation	Flat

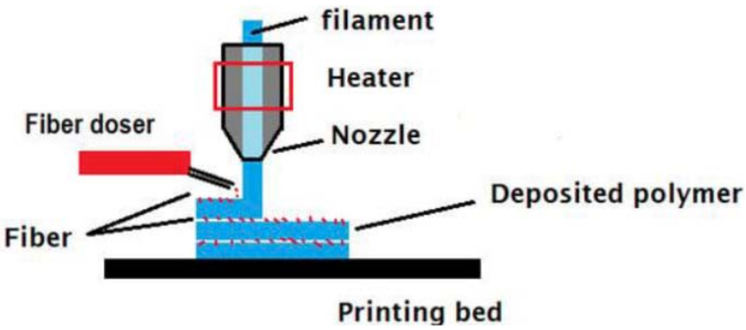


Figure 1: Fabrication of 3D-printed *in situ* fibre-reinforced polymer (blue—polymer; red particles—short fibre) [15].

during the printing process [15], and its deposition rate can be adjusted by controlling the motor speed. Positioned next to the printer nozzle, the fibre doser operates alongside the primary extruder, which extrudes PLA thermoplastic material through a heated nozzle. The glass fibre content was selected based on the optimum results from preliminary tests. The milled E-glass fibre type was provided by Shenzhen Feige Composite Fibre Co., Ltd., Shenzhen, China. The details of glass fibreused to print the glass fibre-reinforced PLA pins are provided in Table **2**.

2.2. Tribological test

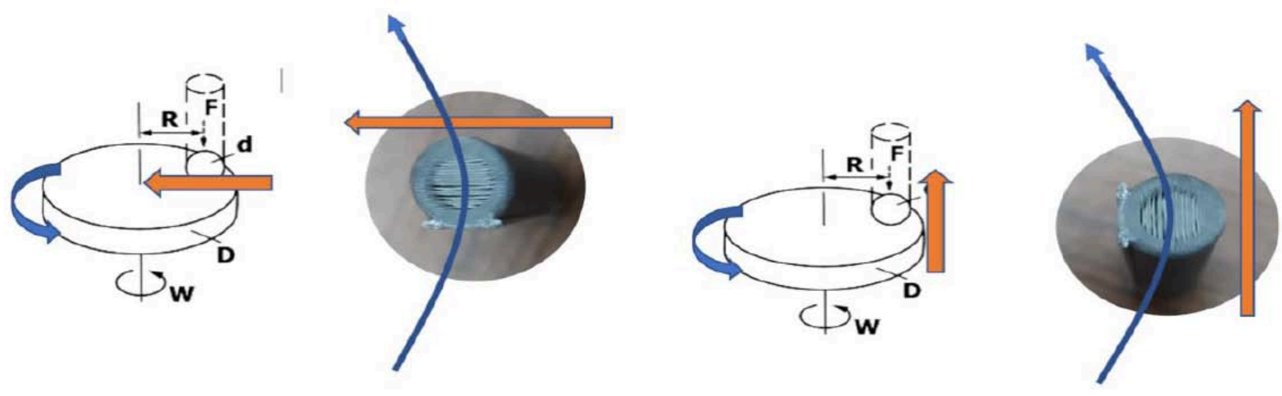
A pin-on-disc apparatus was utilised to evaluate the friction and wear properties of the PLA and PLA-GF composites, following the ASTM G99-17 standard. The counter surface was made of ASSAB 760 steel with a hardness of 34 HRc. The pin was positioned 0.034 m from the center of the disc. All tests were conducted for a fixed duration of20 minutes, under a normal load of 10 N. Three rotation speeds were investigated: 65 rpm, 111 rpm, 136 rpm, corresponding to linear speeds of 0.2313, 0.3965, 0.4856 m/s respectively. The rotation speeds were selected based on the optimum results from preliminary tests, where the friction and wear results are measurable. The rotation speeds were measured with a tachometer (CT6 LED Hand Tachometer, Compact Instruments, Lanceshire, UK). Two different orientations of pins were investigated: perpendicular (D1), where the sliding direction is perpendicular to the raster direction, and parallel (D2), where the sliding direction is parallel with the raster direction, as shown in Figure **2**. The masses of the pins before and after the tribological test were measured and recorded using an electronic balance and the difference in mass was calculated. Wear rate was also obtained through the calculation of net mass loss of the pins per applied load and per sliding distance. Each test was repeated twice.

RESULTS AND DISCUSSION

The wear rate and friction coefficient of PLA and PLA-GF slides against steel at different sliding velocity are shown in Figures **3** and **4**. As shown in Figures **3a**

Table 2: Table Showing the Information of Glass Fibre Used

Aspects	Information
Fibre glass model and type	MEF-13-100 (E-glass)
Fibre glass colour	White
Fibre dimensions (micron)	13 (diameter) and 160 (length)
Aspect ratio	12:1
Bulk density (g/cm^{-1})	0.67
Moisture content (%)	<1.5
Loss of ignition (%)	<1.5
Alkali content/ R_2O (%)	< 0.8
Sizing	Silane
Contamination	Free from dirt, lumps, unmilled fibre



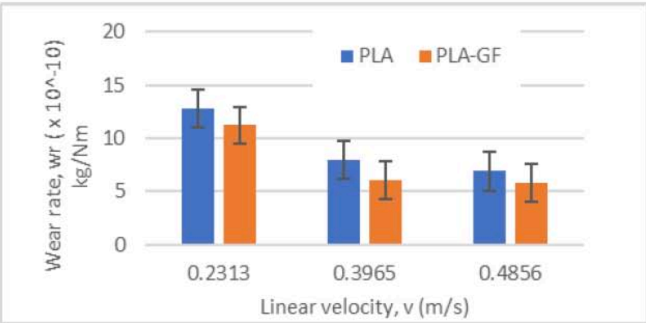
a b

Figure 2: Sliding direction (in blue arrow) vs raster direction (in orange arrow) **a**) perpendicular **b**) parallel.

and **4a**, the glass fibre-reinforced PLA pins were having lower wear rate than the PLA pins. Similar results were reviewed and reported by Prabhakar *et al.* (2018), where the reinforcement using glass fibre would reduce the wear of epoxy. This indicate that the adding of glass fibre was a successful reinforcement that reduced the damage or removal of pin material, due to the effective load sharing between surfaces in contact [6]. In addition, polymers reinforced with glass fibre have higher hardness compare with the neat polymers [21]. As mentioned in Archard equation $Q=\frac{KWL}{H}$, the wear volume, Q is inversely proportional to the hardness of the softest contacting surface, H and directly proportional to the normal load W, sliding distance L *and* a dimensionless constant K [22]. As such the PLA-GF has a better wear resistance than the PLA. In addition, as shown in Figure **2a** and **3a**, the wear rate of both PLA and PLA-GF decreased when the linear velocity increased. The temperature of the sliding interface increased with the increase in sliding velocity [23,24]. The tribological behavior of polymeric materials sliding against steel is influenced by the material transfer to the steel counterface [25]. At high sliding speed, the development of PLA transfer film was contributed by thermal softening of PLA that occurred at the sliding interface. As such, the tribo pair was changed from PLA-steel to PLA-steel coated with PLA.

On the other hand, Figures **3b** and **4b** showed that the friction coefficient increased when linear velocity increased. Similar trend was reported previously [6], where friction coefficient increased with the velocity. Higher linear velocity in a fixed duration would result in a greater distance travelled, hence it would produce more heat, soften the pin and result in greater adhesion frictional force. Furthermore, the coefficient of friction depends on the true contact area. When the temperature of the tribo-pairs was increased due to frictional heat, more asperity on the PLA pin was deformed and in contact with the steel counter face, as a result, friction force was increased. However, the friction coefficient trend of current work is opposite with a previous finding [20], where the friction coefficient reduced when the sliding speed increased from 0.46 m/s to 0.7 m/s. The difference in friction trend is mainly caused by different friction mechanisms as different ranges of sliding speed and infill pattern were used in both studied. Figures **3b** and **4b** showed that the PLA-GF has higher friction than PLA, regardless of sliding orientation (D1 or D2). The inclusion of reinforcement in the PLA altered the hardness of PLA [26,27]. In current work, incorporating glass fibre into PLA increased the hardness of the composite PLA-GF pin, and the harder composite PLA-GF pin generated more frictional resistance against the counter face material. Furthermore, the glass fibre also acted as an abrasive and increased the abrasion friction.

As shown in Figure **5**, the perpendicular direction (D1) appeared to produce greater coefficient friction and wear rate than the parallel direction (D2) all the time. The experimental results suggest that the surface orientation (D1 or D2) relative to the sliding direction



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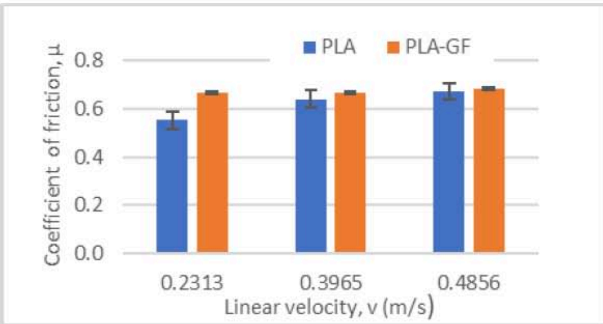
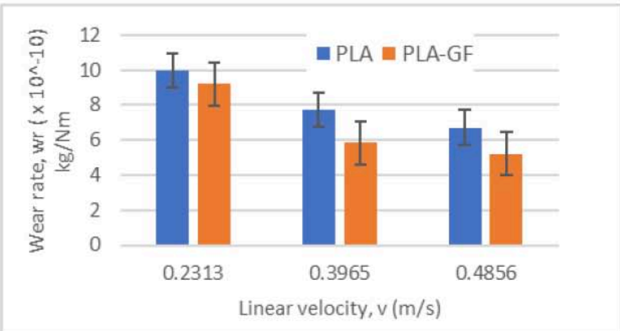


b

Figure 3: Tribological behavior of PLA & PLA-GF at different sliding under D1 condition **a**). Wear rate **b**) friction coefficient.



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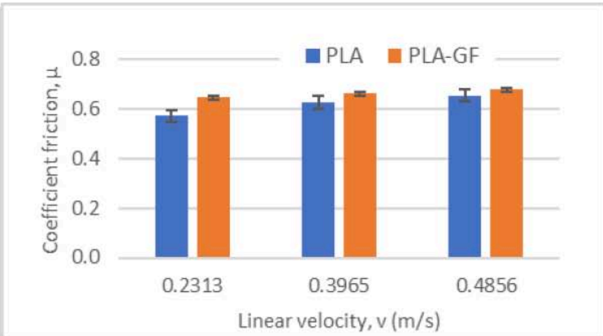
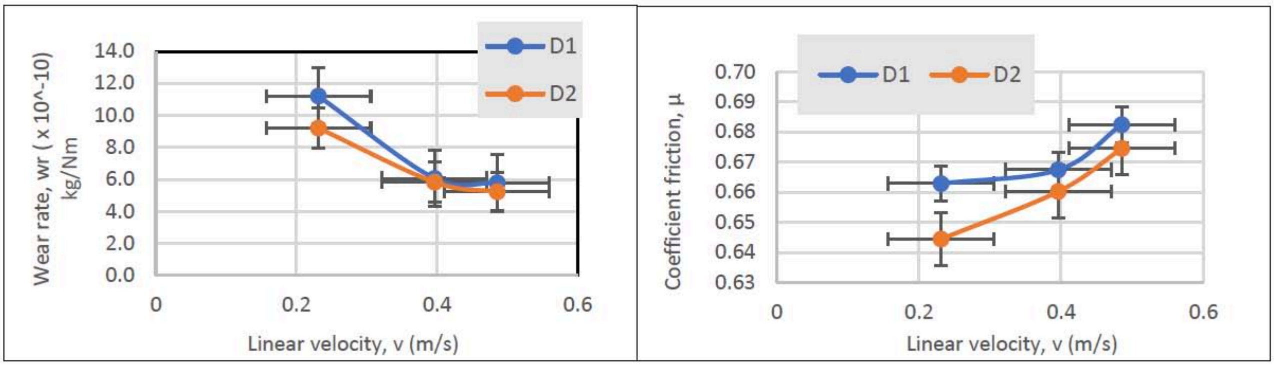


b

Figure 4: Tribological behavior of PLA & PLA-GF at different sliding under D2 condition **a**) Wear rate **b**) friction coefficient.



a **b**

Figure 5: Tribological behavior of PLA- GF pin at two different orientations, **a**) wear rate **b**) friction coefficient.

Table 3: Table Showing Observations on Pins' Wear Condition at D1 (Perpendicular)

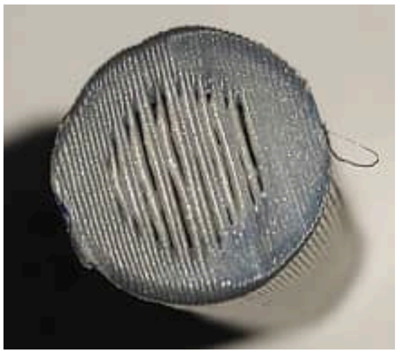
Pin materials		PLA	PLA-GF
		Sliding direction	**Sliding direction**
Linear velocity, v (m/s)	0.2313		
	0.3965		
	0.4856		

Table 4: Table Showing Observations on Pins' Wear Condition at D2(Parallel)

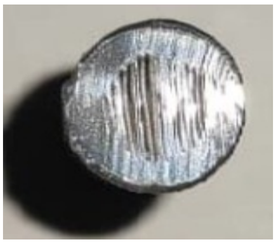
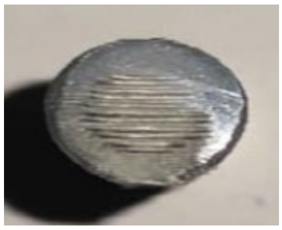
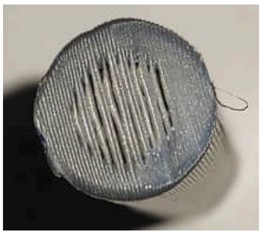
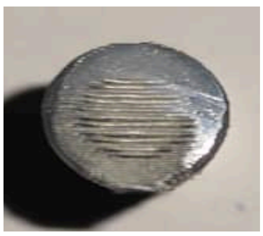
Pin materials		PLA	PLA-GF
		Sliding direction	Sliding direction
Linear velocity, v (m/s)	0.2313		
	0.3965		
	0.4856		

Table 5: Table Showing Observations on Reinforced Pins' Wear Condition at Different D

Pin materials		D1 – Perpendicular	D2 - Parallel
		Sliding direction	Sliding direction
Linear velocity, v (m/s)	0.2313		
	0.3965		
	0.4856		

can affect the wear rate and friction coefficient of FDM printed PLA and PLA-GF. This could be explained that the perpendicular raster direction to the sliding direction of the disc would lead to greater contact length to the disc whereas the parallel direction reduces the abrasion wear of the test specimen surface. The worn surfaces of PLA and PLA-GF slides against steel in orientation D1 at different sliding speeds are shown in Table **3** whereas the worn surface of PLA and PLA-GF slides against steel in orientation 2 at different speeds are shown in Table **4**.

All PLA-GF showed less worn surfaces if compared to PLA pins. This indicated that the reinforcement was successful by minimizing the material loss. Also, the worn surfaces increased as the linear speed increased.

Similarly, the reinforced pins experienced more worn as linear velocity increased. Besides, perpendicular direction of infill pattern to the disc rotation appeared to have more wear than the parallel direction.

In summary, it was observed that glass fibre-reinforced PLA pins were having lower wear rate but greater frictional force than PLA pins. Based on observations, the loss of mass in PLA or PLA-GF was caused by two different wear mechanisms, abrasion and adhesion. Abrasion wear serves as the initial phase of wear. During the initial stages of the tribo testing process, noticeable mass loss was observed on the neat PLA pin, predominantly attributable to abrasion wear. Similarly, the PLA-GF pin, oriented perpendicular to the disc rotation during printing, exhibited signs of abrasion wear. As the testing progressed, an elevation in temperature caused by friction led to adhesive wear on the contact surface of the neat PLA pin. This phenomenon highlights the transition from primarily abrasion-based wear to a combination of adhesive and abrasive mechanisms as the test continued.

CONCLUSION

In conclusion, all PLA-GF exhibited a lower wear rate compared to PLA, albeit with a higher friction coefficient in the case of PLA pins. This reduced wear rate underscores the effective reinforcement achieved through the incorporation of glass fibres, suggesting that reinforced thermoplastics could provide a durable material combination suitable for long-term applications. Additionally, increasing sliding speed was found to correlate with a lower coefficient of friction and increased wear rate. Furthermore, the study identified that a perpendicular raster direction relative to disc rotation or pin motion resulted in higher friction coefficients and increased wear. These findings may be leveraged in the future to enhance grip or reduce reliance on lubricants in various applications.

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