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Tribological Properties of PLA 3D Printed at Different Extrusion Temperature

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Abstract. Fused deposition modelling (FDM) 3D printing is widely used to manufacture prototype. To manufacture functional products with FDM 3D printing, several existing challenges have to be solved. Tribological behaviour of 3D printed parts has to be improved and optimised. In current study, friction and wear behaviours of 3D printed polylactic acid (PLA) printed at different extrusion temperature (190°C, 200°C, 210°C, 220°C, 230°C) sliding against steel disc were investigated. Pin on disc experiments that complies with ASTM G99-95a (2000) were conducted at a normal load of 15 N, and rotational speed of 150 RPM (0.69 m/s). Results showed that increasing the extrusion temperature resulted in a lower pin wear (specific mass loss) and higher friction coefficients. Pins printed at 190°C showed to have the biggest pin mass loss and lowest friction coefficients, whereas pins printed at 230°C showed to have the lowest pin mass loss and highest friction coefficients. This indicates the higher the extrusion temperature, the more capable it is for the deposited material to flow and homogenise with the neighbouring material which creates a flatter surface with less void between layers. Thus, effectively improving the interlayer bond making the FDM 3D printed part less susceptible to shear stress and delamination.

1. Introduction

Over the past decade, 3D printing has become a widely used and effective tool in the manufacturing industry. 3D printing offers several key advantages that have made it a key element in the design and manufacturing process. 3D printing is typically used to quickly produce prototypes. Designers and manufacturers have taken advantage of this by continuously improving and revising the geometric design elements of an object and producing prototypes to test their suitability for the intended application [1]. This is crucial as it allows companies to conveniently improve a design without having to compromise the main production line with more costly and complex manufacturing methods. This phenomenon has only been possible due to several factors, namely the low cost and quick and easy handling of 3D printing an object. Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF) is the most common and widely used method of 3D printing due to its printing speed and affordability. FDM 3D printers use polymer filament materials or thermoplastics that melt at a certain temperature and solidify and harden after cooling. However, FDM still has its drawbacks, such as handling anisotropic material properties, the staircase effect of smooth surfaces, the required supports for overhanging geometries [2], relatively weak mechanical properties for injection-moulded parts and the coarseness of the surfaces. However, these drawbacks can be overcome by various adjustments to certain pressure or process parameters. Extrusion temperature is one such parameter that can drastically improve or degrade the mechanical properties of a printed object [3,4]. This in turn has led to a plethora of literature studies investigating other possible printing parameters that could improve the mechanical properties of a 3D printed object. On the other hand, the study of the tribology of a 3D printed object is a relatively less compared to mechanical properties of 3D printed parts. Nevertheless, the wear and friction of FDM 3D printed objects is still an important factor if FDM 3D printed parts are used in engineering applications. Literature studies have found that various printing parameters affect the tribological properties of 3D printed fused deposition modelling (FDM) parts. Hervan et al. investigated the relationship of 2 printing parameters (layer thickness and orientation) on the hardness, friction and wear behaviour of FDM 3D printed PLA [5] and they found that layer thickness affects the wear rate while printing orientation affected the friction coefficient. However, opposite results were reported by Amirruddin et al., where they conducted similar test on PLA and ABS and they concluded that when the layer thickness increased from 0.127 mm to 0.32 mm, friction forces were reduced for both ABS and PLA [6]. Sharma et al. investigated the effects of process parameters on the wear rate of FDM-printed thermoplastic polyurethane (TPU) and acrylonitrile styrene acrylate (ASA) and multimaterial polymers (TPU + ASA)[7]. They investigated several process parameters such as fill density, printing speed, wall thicknesses, screen angles and extrusion temperatures. They concluded that extrusion temperature and fill density significantly affect the wear rates of the printed sample. The extrusion temperature that was found to be most effective against wear is 240°C when printing with multi-materials. This is the highest extrusion temperature tested out of the 220-240°C range tested. A similar study was carried out by Pant et al. [8]. They investigated the wear of FDM 3D printed PLA parts under variation of process parameters. These process parameters include layer thicknesses, build orientations and extrusion temperatures. Based on their regression model, it was found that build orientation has a great influence on the wear performance of the printed sample and ranks first among the most effective means of minimising wear. Layer thicknesses and extrusion temperatures ranked second and third, respectively. However, it should be noted that the extrusion temperature tested only covered a small range, between 220-230°C, which is well within the margin of error. Similar test was conducted by Singh and Bharti [9] and the process parameters tested were layer thicknesses, fill densities, printing speeds and extrusion temperatures. From the mathematical model created in the paper, the ideal extrusion temperature should be between 195-202°C, which is very low for PLA. Eutionnat-Diffo et al. [10] investigated the wear resistance of conductive 3D-printed PLA on woven polyethylene terephthalate materials. They found that process parameters such as bed and extrusion temperatures affect the abrasion resistance of the material when printed on woven polyethylene terephthalate (PET) textiles. Recently Zagorski et al. investigated the effects of extrusion temperature on the tribological properties of PLA under lubricated sliding conditions [11]. They found that linear wear, wear intensity, wear resistance, roughness and microhardness were affected by the printed extrusion temperature. They concluded that the wear resistance is directly related to the extrusion temperature. The higher the extrusion temperature, the greater the wear resistance.

The effects of temperature-dependent parameters on the mechanical strength of PLA parts 3D printed with FDM was also investigated [12]. Temperature-dependent parameters such as the extrusion temperature, the intensity of the part cooling fan, the printing speed and the time between printing each layer were considered. The researchers identified two generalising factors: the temperature of the previously applied layer and the flow efficiency. Together with the strength of the bonds between the layers, these two factors determine the microstructure formation of FDM 3D printed parts. The researchers concluded that increasing the extrusion temperature and optimising the cooling settings of the part have a positive effect on the mechanical strength of the part. The printing speed, on the other hand, has an unclear effect on the strength of the part. However, this work focuses mainly on the mechanical properties rather than the tribological properties, although they are closely related. While there is some work looking at the effects of extrusion temperature on the wear behaviour of FDM printed polymers, most of the research to date has focused on a narrow range of extrusion temperature. To further explore the effects of this specific temperature parameter, this research aims to investigate and understand the effects of extrusion temperature on the tribological properties of FDM printed PLA.

2. Methodology

2.1. Preparation of FDM 3D printed sample

All pin specimens for friction and wear experiment were printed with a Prusa MINI + 3D printer (Prague, Czech Republic). The cylindrical pin has a diameter of 10 mm and a height of 48 mm. A 0.2 mm bevel was added to one side of the pin to prevent the effects of "elephant foot" during printing, as shown in Figure 1. The pins are designed in Autodesk Fusion 360 and exported as a 3MF file. This file is imported into PrusaSlicer slicing software version 2.4.0. The print profile used is a modified "0.20 mm QUALITY" standard print profile for the Prusa MINI + 3D printer. The modified settings were rectilinear infill pattern, 15% infill density, 4 perimeters and no top and bottom solid layers. Table 1 shows the FDM printing temperatures used. The cylindrical pins are printed vertically in the Z-axis orientation. The print bed temperature is set to 60 °C as recommended by the filament manufacturer. A total of 10 FDM 3D pins were printed from PLA filament (eSUN, Shenzhen, China) with a diameter of 1.75 mm. The manufacturer's filament specification is listed [13]. Figure 2 shows the specimen printed with FDM.

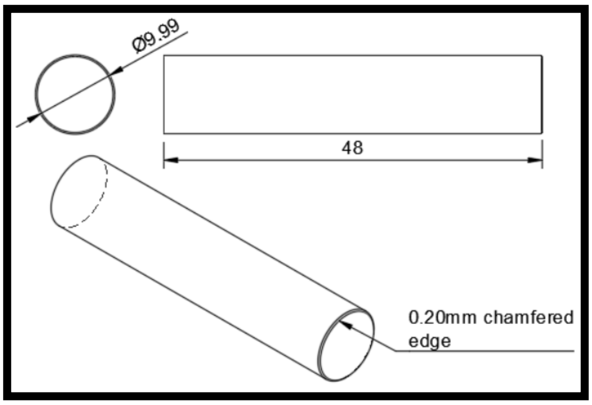

Figure 1. Pin dimensions (all dimensions are in mm)

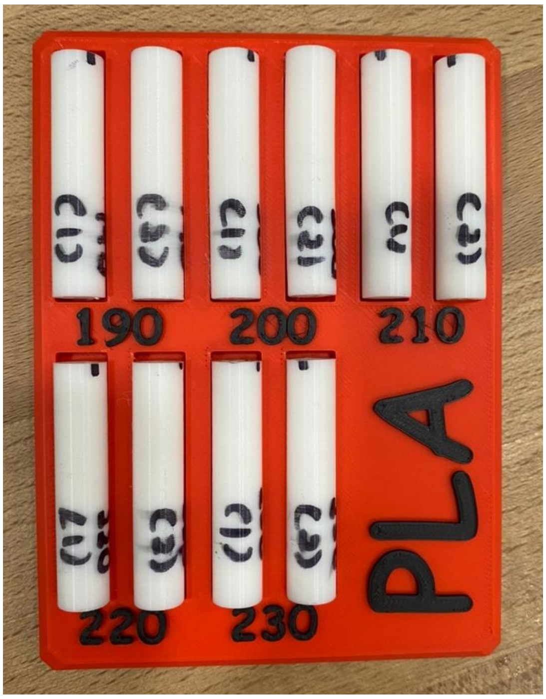

Figure 2. FDM 3D printed PLA pin specimens. Each individual pin is labelled with its printed extrusion temperature, its pin number with respect to its printed extrusion temperature as well as a line indicating the sliding direction when clamping the pin into the pin holder during the tribological test experiment.

Table 1. FDM printing parameters

Variable	**Value**				
Extrusion Temperature (°C)	190	200	210	220	230

2.2. Tribological test

Pin on disc tribological experiments were carried out with a pin-on-disc tribometer under dry sliding conditions and the test procedures of ASTM G99 were followed. The 3D printed PLA pin were slide against the ASSAB 760 steel disc at fixed test conditions. The speed of the rotating disc was measured with a tachometer (Compact Instruments, CT6 LED HAND, with a resolution of 1 RPM). A speed of 150 RPM (linear speed of 0.69 m/s) was used as the constant test parameter for tests. Before each test, the disc was cleaned with abrasive paper from coarse to fine grit (500, 600, 800 and 1600). Acetone was then used to remove all residues and dust. A pin was placed in the pin holder and clamped down to prevent the pin from moving and vibrating strongly in the pin holder. A marker was marked on the pins (as shown in Fig 2) so that all pins are slide at a same raster angle (parallel to direction of movement). Recent studies have shown varying raster angles have direct effects on the wear of 3D printed pins [14]. The test conditions are listed in Table 2. The frictional force experienced by the pin is measured by the load cell and displayed as an output voltage on the connected multimeter (GDM-397), this output voltage is interpreted as the frictional force. Each test lasts 20 minutes and a voltage value is displayed for each minute. After the pin test is successfully completed, the final mass of the pin is measured on the measurement scale. The difference in mass before and after the test is the mass loss of the 3D printed pin. The mass was measured with the digital scale AND FZ -500i, with a resolution of 0.001 g and converted to volume (mm^3). Two samples for each condition were tested and the average was calculated. The specific wear rate (mm^3/Nm) is measured by the difference in volume (mm3) of the PLA pins, per total distance travelled (m) per unit load (N). The close-up view of worn surface of PLA pin was observed with 1600x digital microscope (CoolingTech, China, Shenzhen). The testing conditions for all tribological experiments are summarized in Table 2.

Table 2. Tribological test testing conditions

Testing conditions	**Value**
Rotating disc speed (RPM, m/s)	150, 0.69
Normal load (N)	15
Time duration (min)	20
Lubricant	Dry
Room temperature (℃)	23 ± 2

3. Results and discussion

Figure 3 shows the coefficient of friction as a function of the printed extrusion temperature. The results show that pins printed at 190℃ have the lowest average coefficient of friction, while pins printed at 230℃ have the highest coefficient of friction. Moreover, the coefficient of friction increases linearly with the increase of extrusion temperature. Thus, when the FDM 3D printed pins are printed at a higher extrusion temperature, the coefficient of friction of the pins increases. Figure 4 shows the specific wear rate of the pin extruded at 190°C to 230°C. The results show that pins printed at 190℃ have the highest specific wear rate, whereas pins printed at 230℃ have the lowest specific wear rate. Furthermore, the specific wear rate decreases linearly with extrusion temperature within the investigated range. Thus, when the 3D printed pins are printed at a higher extrusion temperature, the mass loss or wear rate of the pins decreases.

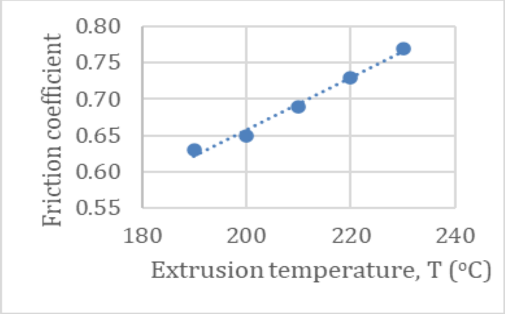

Figure 3. Friction coefficient against extrusion temperature

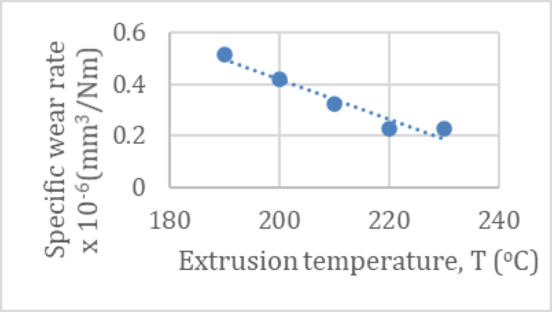

Figure 4. Specific wear rate of FDM printed PLA pins, extruded at different extrusion temperature

Figure 5 showed the images of the worn surface (top and side close-up). At lowest extrusion temperature (190°C), slight deformation was observed from the pin surface (Fig 5a and 5d). At higher extrusion temperature (210°C, Fig 5b and e), deformation and material transfer can be observed at the bottom of the pin (circled in red, Fig 5b). At the worn surface of pin extruded at 230°C, more deformation and material transfer can be seen clearly on the pin (circled in red, Figure 5c) and delamination was detected (Figure 5f).

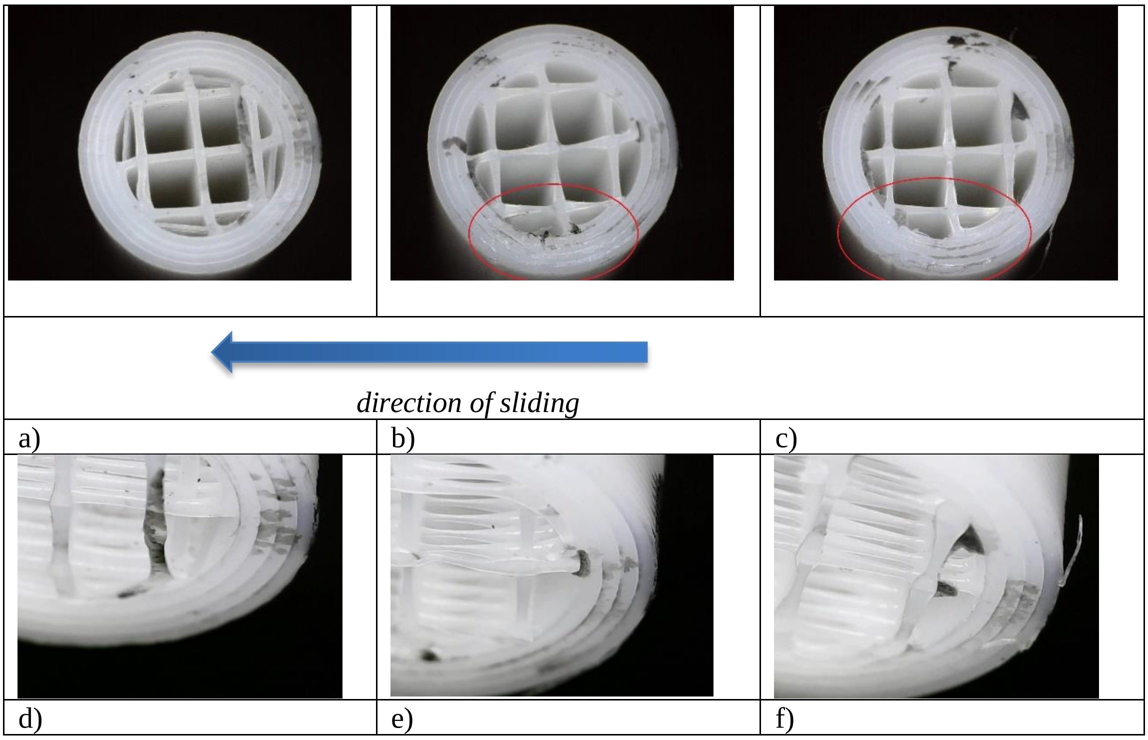

Figure 5. Images of pins’ worn surface (a) 190°C (b) 210°C (c) 230°C (d) 190°C (close-up) (e) 210°C (close-up) (f) 230°C (close-up)

The experimental results indicate behavioural changes in the tribological properties of the FDM 3D printed pin samples when printed at different extrusion temperatures. A lower extrusion temperature resulted in the lowest coefficient of friction (Fig 3) and the highest specific wear rate (Fig 4). This can be attributed to the low strength of the joints between the layers, as delamination was found on the adjacent layers during the final inspection of the pins. Since FDM 3D printed parts are built layer by layer, each interfacial layer to another poses a weak point in the object. This vulnerability is further exaggerated as the pin is printed in an orientation where the printing direction is at right angles to the sliding direction during the test. The extrusion temperature during printing is obviously higher than that of the applied material and the ambient temperature [15]. Kuznetsov et al. monitored the thermal distribution between the print head, the PLA print samples, and environment [12]. They showed that the extrusion temperature has the highest temperature relative to the last printed layer applied and to the environment. Furthermore, as the extrusion temperature increases, the number of sub-layers with relatively higher temperatures also increases. These sublayers appear to be in the range of 50-60°C. PLA has a glass transition temperature of 50-60°C. The glass transition temperature is the temperature range at which a stiff glassy material transforms into a soft (non-melted) substance. This means that the deposited PLA material is still able to diffuse and homogenise with the surrounding material long after extrusion.

This variation in thermal mass results in heat transfer from higher to lower regions [16]. As the depositing extrusion temperature is higher compared to the already deposited material, heat is transferred and allows the material to diffuse locally and melt against the neighbouring filament within its layer and especially between the neighbouring layers, leading to the formation of bonds [17]. The quality of these bonds between each deposited lines depends on the ability of the deposited material to flow and homogenise with the adjacent material. A microstructure with fewer voids or air gaps provides more bonding areas between the individual filament extrusion lines. This results in a more cohesive microstructure reminiscent of an injection moulded part. During filament extrusion, the printed polymer melts in an uneven distribution, which inevitably results in the layers exhibiting poor adhesion [18]. The strength of these bonds depends on several factors, including the extrusion temperature. The extrusion temperature is closely related as it directly affects the localised diffusion and remelting, which in turn directly affects the presence of air gaps within the microstructure. Generally, the higher the extrusion temperature, the greater the temperature difference between it and the already deposited material. This allows for greater local diffusion and re-melting towards the adjacent layers as well as the adjacent filament within its layer. Therefore, a higher extrusion temperature leads to stronger interlayer bonding. A stronger interlayer bond is less likely to wear because the strength of the bond resists the shear stress of relative movement, resulting in less loss of mass of the pin.

Furthermore, the yield behaviour of PLA is dependent on crystallinity of PLA [19] and crystallinity depends on crystallization temperature. Different forms of crystal form compositions were reported when the crystallization temperature, where only α’ form can be formed below 100°C, and α’ and α forms coexist from 100° C to 120°C, and only α forms appeared after 120°C [19][20]. Although the duration for PLA in molten form is short during FDM printing process, and shorter than duration required for complete crystallization process, but previous work showed that changed in crystalline structure and increase in porosity when extrusion temperature was increased from 40°C to 80°C [21]. Crystallinity of PLA for extrusion temperature beyond 80°C was not reported. As such the wear behaviour might be affected by crystallinity of PLA and further investigation is required.

As for the coefficient of friction, the results show that as the extrusion temperature increases, the average coefficient of friction also increases. This could be due to the increasing surface roughness of the specimens at elevated extrusion temperature. Previous research works have investigated the relationship between printing parameters and surface roughness of the printed parts where surface roughness was influenced by temperature of print bed [22] and also flow rate [23]. Mohan et al. investigated the effect of process parameters on the surface roughness of a FDM 3D printed ABS part [22]. Their results showed that as the surface roughness increased with heating bed temperature due to the thermal deformation of the manufactured part. In addition, flow rate has a significant effect on surface roughness, with flow rate linearly proportional to printing speed, extrusion width and layer height [23]. The flow rate is then related to the extrusion temperature, because the effective flow rate of an FDM 3D printer is influenced by the extrusion temperature. In general, the volumetric flow rate is inversely proportional to the viscosity of the extruded material (which makes a material printable). It can be deduced that at a higher printing temperature, the extruded material will have a lower viscosity and therefore a higher volumetric flow rate. This allows the FDM 3D printer to extrude more material volume at the same flow rate setting. When the surface roughness (Ra) is low, the uneven and wavy surface that is parallel to the surface of the rotating disc leads to higher wear and higher coefficient of friction [24], which is consistent with the current results. In addition, a study [25] that investigated the effects of surface roughness on friction force concluded that the coefficient of friction increases with increasing surface roughness. Therefore, it can generally be agreed that higher surface roughness leads to a higher coefficient of friction. The samples printed at a higher extrusion temperature had a higher surface roughness and thus a higher coefficient of friction.

4. Conclusions

In summary, the effects of extrusion temperature on the tribological properties of FDM 3D printed PLA have been identified. From the results, the wear coefficient decreases as the extrusion temperature increases. This is because the higher the extrusion temperature, the better the deposited material can flow and homogenise with the adjacent material, resulting in a seamless and cohesive microstructure - a microstructure that is less likely to have air gaps or voids. This effectively improves the bond between layers, making the 3D printed FDM part less prone to shear stress and delamination. Furthermore, crystallinity of PLA might be another factor, and required further investigation. As for the coefficient of friction, it increases with increasing extrusion temperature. This is due to the potential increase in surface roughness when the tested samples are printed at higher extrusion temperatures. As the surface roughness increases, so does the coefficient of friction.

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