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Tribological Behaviour of 3D printed Polylactic Acid (PLA) Sliding Against Steel at Different Sliding Speed

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Abstract. In this study, the tribological properties of fused deposition modelling (FDM) 3D printed Polylactic Acid (PLA) is studied when it slides against a steel disk at various speeds. 3D printed pins were printed using PRUSA MINI+ 3D Printer according to recommended printing parameters. Pin on disc tribological tests were conducted at normal load of 20 N, sliding time of 20 minutes, and linear sliding speeds of 0.46, 0.58, 0.7 and 0.81 m/s. Experiment results showed that wear rate increases with the increase of sliding speed, and coefficient of friction decreases with the increase in sliding speed. Observation of worn surfaces suggested the major wear mechanisms are abrasion, adhesion, and delamination. The difference in tribological behaviour was mainly caused by hardness-temperature relationship. The main anomaly that occurred in the observed trends are that the pin melted at highest sliding speed, resulting in opposite trends. The increase in temperature at the contact point of the pin and sliding disk weakens PLA pins. Therefore, 3D printed PLA can be used in a temperature-controlled low speed sliding application such as a lubricated gear and not for applications that subjected to high sliding speeds and temperature.

1. Introduction

3D printing is a major step in revolutionising the manufacturing industry that has been known to mankind for many centuries. This method is able to surpass typical manufacturing methods such as CNC machining and plastic injection moulding in many ways. This is due to the advantages that 3D printing offers over other methods, such as complex design, rapid prototyping, on-demand printing, strong yet lightweight parts, and the lower costs associated with them. However, there are some aspects where the 3D printing method falls short, such as the limitations of total lead time in a mass production environment. For rapid prototyping in the design phase of a product, 3D printing is one of the best manufacturing methods. In 3D printing itself, there are many different techniques such as Fused Deposition Method (FDM), selective laser sintering, digital light modelling, direct metal laser sintering, electron beam melting and so on. The FDM also named as Fused Filament Fabrication (FFF) is a process involves printing layers of material that fuse together and eventually become the desired object. The filament material, such as, polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS), and etc. is heated and liquified, and then extruded from a nozzle in a pattern that builds up the object itself layer by layer. Depending on the printer, many printing conditions/parameters can be altered that ultimately affect the structural integrity of the printed part itself. These include the layer thickness, the printing temperature and infill percentage. As the use of 3D printing in the manufacturing industry greatly increases, it is important for designers and engineers to know the mechanical and tribological properties of the 3D printed polymers. In order to understand the tribological properties of 3D printed polymer, some research works were conducted previously [1–4][5]. However, it was immediately noticeable that many studies focused on 3D printing parameters and did not investigate the effect of sliding speeds on the tribological properties of 3D-printed PLA. Roy et al. [3] looked at the tribological properties of 3D printed PLA and ABS plastic parts. They performed tribological tests on 3D-printed PLA and ABS with different printing parameters such as infill angle, infill percentage, layer thickness and infill pattern. One of their main conclusions was 3D-printed PLA and ABS had very similar tribological properties. Furthermore, sliding speed, normal load, temperature and printing parameters all play a role in how the 3D-printed polymer wears. Kanakannavar et al. investigated the effects of load on the tribological behaviour of 3D-printed braided fabric PLA composite against steel disc [6]. They reported the COF of 3D printed neat PLA increases with increasing linear sliding velocity from 1 m/s to 3 m/s, especially at lower normal load (10 N and 20 N). This is due to the softening effect of sliding materials due to increased temperature at the contact point between the sample and the sliding disc.

As mentioned previously, research on the effects of sliding speed on the tribological properties of 3D printed PLA is limited. In contrast, the tribological properties of 3D-printed ABS are studied widely. Additional knowledge about the tribological properties of 3D-printed PLA would mean that it could be used for more demanding real-world applications. The aims of this research are therefore to understand the tribological behaviours of 3D printed PLA when sliding on a steel disc at different sliding speeds.

2. Materials and methods

2.1 Sample (Pin) Preparation

Pin samples have a diameter of 9.59 mm and a length of 47.8 mm. The pin is designed using the 3D modelling application Autodesk Inventor version 2021., the drawing file is exported as stp.file and uploaded to the PRUSA MINI + 3D printer. All pins were printed with in fill density of 15%, layer thickness of 0.25 mm and printing temperature of 210˚C. The same printing parameters were set for all samples. The filament used to print these sample pins are Polylactic Acid (PLA). Figure 1 shows FDM 3D printed PLA pin used in this study.

(a) **(b)**

Figure 1 (a) Top View of 3D Printed PLA Pin (b) Side View of 3D Printed PLA Pin

2.2 Tribological Experiment

Friction and wear behaviour of 3D printed PLA against ASSAB 760 steel was evaluated using a pin-on-disc tribotester, as shown in Figure 2. Tests were conducted according to procedure of ASTM 99-17 standard. The normal load of 20 N and sliding time of 20 mins were constant parameters used in the test. The experiment was conducted at sliding velocities of 120 RPM, 150 RPM, 180 RPM, 210 RPM, which are 0.46, 0.58, 0.70 and 0.81 m/s respectively. The masses of the pin before and after the test were measured using a AND FZ -500i digital scale, which has an accuracy of up to three decimal places. The pin is inserted at an 180˚ raster angle to the sliding direction, and this is kept constants for all samples to ensure that the constant sliding angle in relation to the raster angle. Disc's rotation speeds were measured by hand-held tachometer CT6 LED (Compact, UK, Lancashire). Friction forces were measured by voltmeter and recorded every 30 seconds. The sliding disc is also refreshed with abrasive papers and acetone before each test. The close-up view of worn surface was observed with 1600x digital microscope (CoolingTech, China, Shenzhen). The wear rate (mg/m) is measured by the difference in mass (mg) of the PLA pins, per total distance travelled (m) whereas the specific wear rate (mg/Nm) is the wear rate per unit load.

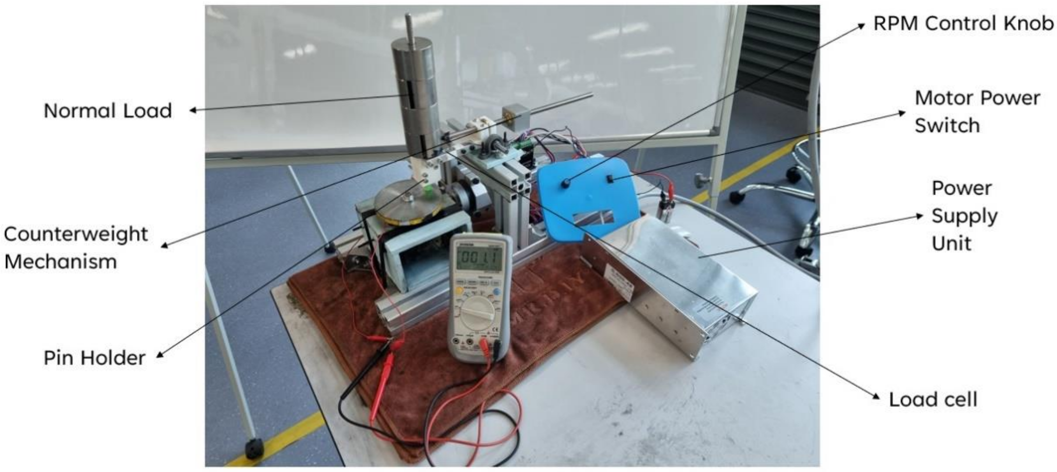


Figure 2. Set up of Pin-on-disk Tribotester for experiment

3. Results and discussion

Figure 3 shows the wear rate of the 3D printed PLA pins at different sliding speeds quantitatively and the specific wear rate of PLA samples at different sliding distance. The wear rate ranges from 1.02 x10^{-3} mg/m to 3.58 x 10^{-3} mg/m. In general, the wear rate increases with increasing linear sliding speed, from 0.46 m/s to 0.70 m/s. However, at the highest speed (0.81 m/s), there is a sharp drop in the wear rate. This phenomenon is directly related to the increasing temperature at the contact point between the pin and the sliding disc as the sliding speed increases [3]. 3D printed PLA has a glass transition temperature from 55°C to 65°C [7] and glass transition temperature T_g is the temperature where amorphous materials transit from a hard and glassy state into a viscous or rubbery state when temperature is increased [8]. Higher surface temperature softens the PLA. This phenomenon is in agreement with Archard equation [9], where the wear volume is inversely proportional to the hardness of softest contact surface. Furthermore, when polymers slide on a dry metallic surface, e.g., on a pin-on-disc tribometer, adhesive and abrasive wear occurs and some parts of the polymer stick to the metallic surface and others are thrown away as wear debris [10]. When abrasion and delamination occur on the pin, the material detaches from the pin, which also leads to a loss of mass on the pin. The increasing temperature facilitates the occurrence of delamination on the pin, which further increases the mass loss and thus the wear rate. Interestingly, as shown in Figure 3(a) and (b), the wear rate and specific wear rate at the highest speed and longest sliding distance are the lowest. At the highest speed, the contact temperature is the highest and the PLA pin failed in different mechanism. The PLA pin softened and then deformed (Figure 5d) but the less material was removed from the pin.

The coefficient of friction (COF) of 3D-printed PLA pins at different sliding velocities is presented at Figure 4. The COF ranges from 0.5243 to 0.6702. At the first 3 sliding speeds of 0.46 m/s to 0.70 m/s, the coefficient of friction decreases with increasing linear sliding speed. However, at the highest sliding speed (0.81 m/s), an anomaly is observed where the coefficient of friction is higher than at the speed before (0.7 m/s). The reason for the decreasing COF with increasing sliding velocity is due to the material weakening that occurs with increasing sliding velocity from 0.46 m/s to 0.7 m/s. As mentioned earlier, the increasing temperature at the point of contact between the steel sliding disk and the pin causes the material to weaken, making it easier to loosen. Since less force is required to detach the material, the pin can slide more easily, ultimately reducing the friction and coefficient of friction of the pin at these speeds, similar to previous observation [6]. In agreement to results of the wear rate/specific wear rate (Figure 3), the highest velocity is an anomaly compared to the trend observed at the lower velocities. At the sliding speed of 0.81 m/s, the COF is higher than the slower sliding speed tested previously. At highest sliding speed, the contact point has the highest temperature due to frictional heat. As result, PLA pin softened, deformed, and had a larger contact area (as shown in Fig 5d and Fig 7). The pins also picked up the debris rotating on the sliding disc. When the pin softened, it became sticky, and more force is required to slide the pin to compensate. This increase in the force required to slide the same pin is directly related to the increased frictional force compared to lower speeds, which ultimately leads to an increase in the coefficient of friction. The deformation of the pin is another factor, as it increases the true contact area between the pin and sliding disc. As the contact area is increased, a larger area is subjected to a higher frictional force, which ultimately increases the coefficient of friction.

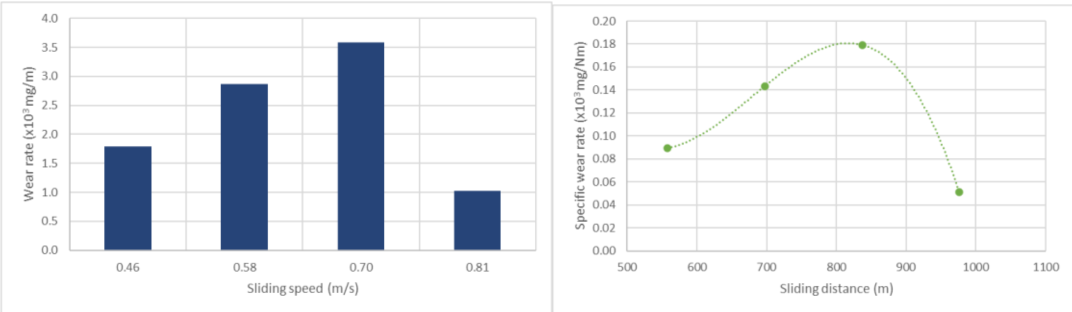


Figure 3. (a) Wear rate of 3D printed PLA at different sliding speed; (b) Specific wear rate of 3D printed PLA at different sliding distance

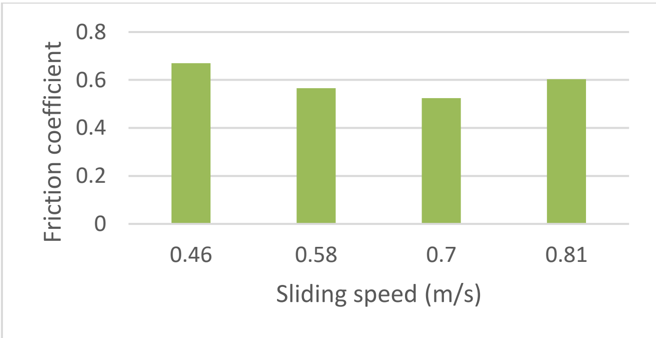
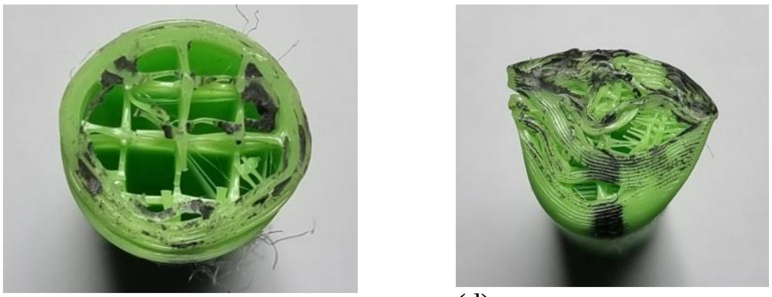
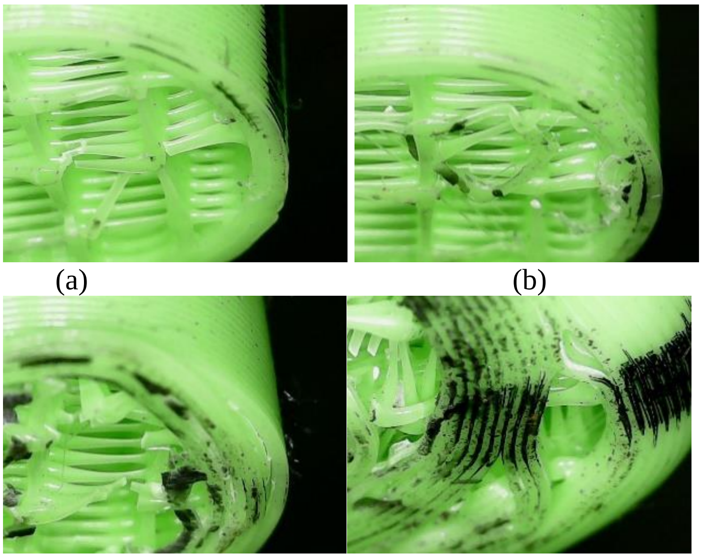


Figure 4. Coefficient of Friction (μ) of 3D printed PLA against steel at different sliding speed



(c) (d)

Figure 5. Top view of worn pins slid at (a)0.46 m/s (b) 0.58 m/s (c) 0.70 m/s (d) 0.81 m/s



(a) (b)

(c) (d)

Figure 6. Close up view of worn of pins slid at (a) 0.46 m/s (b) 0.58 m/s (c) 0.70 m/s (d) 0.81 m/s

Figure 7. Side view of worn pin slid at 0.81 m/s

Figures 5 and 6 show the top and close-up view of the pin's worn surfaces slid at different linear sliding speeds. The visible damage to the pin increases with increasing linear sliding speed. The lowest speed pin is slightly damaged and worn, while the pin slid at the highest speed is deformed and heavily worn. At the speeds of 0.46 m/s, no obvious damage was detected via visual inspection, but a close-up picture identified abrasion marks, as shown in Figure 5(a) and Figure 6(a). At a higher speed of 0.58 m/s, abrasion marks, delamination and small deformation were observed from Figure 5(b) and Figure 6(b). At speeds of 0.58 m/s and 0.70 m/s, delamination is visible as the layering of the PLA filament has begun to separate, as shown in Figures 5(b), 5(c), 7(b) and 6(c). At the highest speed of 0.81 m/s {Figure 5(d) and 6(d)}, deformation and material transfer can be observed as the pin melted and picked up the spinning debris on the sliding disc. A side view of pin slid at 0.81 m/s, is provided in Figure 7 to highlight the pin deformation.

The main wear mechanisms that can be identified are abrasion, delamination, adhesion, and deformation. PLA has different crystalline structure and yield behaviours at different temperature [11]. In general, it's yield strength decreased with an increase in temperature. Furthermore, storage modulus of PLA also decreased with an increase in temperature [12]. As result, PLA is subjected to higher wear rate at higher sliding speed. At lower speeds, the most obvious wear mechanism is abrasion. Further down the line, as the sliding speed increases, delamination of the PLA filament layers occurs. This occurs when the pin loses material down to the layers of the pin itself due to the abrasive wear. The closer the sliding disc gets to the layering of the pin, the weaker the bond between the layers of the 3D printed PLA becomes. In addition to the abrasive wear that removes material from the pin, the force eventually overcomes the bond between the layers and the pin begins to delaminate [13]. This is also helped by the increasing heat at the point of contact between the pin and the sliding disc, which makes it easier for the material to detach from the pin. However, the effect of the heat is most evident when adhesive wear and deformation occurs on the pin. As can be seen in Figure **5**(d) and Figure **7**, the pin is severely deformed at the highest sliding speed. This is because the pin exceeds the melting temperature of the PLA filament, which is around 145-160°C [6]. At this point, the pin starts to melt and deform in the sliding. As the pin is sticky, the circulating deposits on the sliding disc from the initial stages of the experiment begin to reattach to the pin at the highest speed, as the high temperature allows this to happen.

4. Conclusions

The tribological properties of 3D-printed PLA sliding against a steel disc at different sliding speeds were investigated. At linear sliding velocities from 0.46 m/s to 0.81 m/s, the relationships between wear rate, specific wear rate, coefficient of friction and sliding speed/distance were investigated, and the main wear mechanisms occurring were observed and identified. The main wear mechanisms identified were abrasion, adhesion, delamination, and deformation. The wear rate ranged from 1.02 $x10^{-3}$ mg/m to 3.58 x 10^{-3} mg/m. In general, wear rate increases as the linear sliding speed increases. This is because the increase in temperature at the contact point of the pin and sliding disc weakens the PLA filament and promotes material loss. As for COF, it ranged from 0.5243 to 0.6702. COF decreases with increasing sliding speed. The increasing temperature of the pin at the point of contact with the sliding disc leads to a weakening of the material and thus to its detachment and deformation. The anomalies in these two relationships occur when the pin slid at the highest speed, where the pin deformed and caused opposite trends as previously observed It can be concluded that 3D printed PLA can be considered for low speed -temperature controlled sliding application. Further investigations are required to investigate the possibility to replace engineering parts with 3D printed PLA, under actual working environments.

5. References

[1] Prusinowski A and Kaczynski R 2020 Tribological behaviour of additively manufactured fiber-reinforced thermoplastic composites in various environments *Polymers (Basel).* **12** 1–17
[2] Hanon M M, Marczis R and Zsidai L 2020 Impact of 3D-printing structure on the tribological properties of polymers *Ind. Lubr. Tribol.* **72** 811–8
[3] Roy R and Mukhopadhyay A 2021 Tribological studies of 3D printed ABS and PLA plastic parts *Mater. Today Proc.* **41** 856–62
[4] Amirruddin M S, Ismail K I and Yap T C 2022 Effect of layer thickness and raster angle on the tribological behavior of 3D printed materials *Mater. Today Proc.* **48** 1821–5
[5] Srinivasan R, Suresh Babu B, Udhaya Rani V, Suganthi M and Dheenasagar R 2020 Comparision of tribological behaviour for parts fabricated through fused deposition modelling (FDM) process on abs and 20% carbon fibre PLA *Mater. Today Proc.* **27** 1780–6
[6] Kanakannavar S, Pitchaimani J and Ramesh M R 2020 Tribological behaviour of natural fibre 3D braided woven fabric reinforced PLA composites: *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.* **235** 1353–64

[7] Bakar A A B A, Zainuddin M Z Bin, Adam A N Bin, Noor I S B M, Tamchek N Bin, Alauddin M S Bin and Ghazali M I B M 2022 The study of mechanical properties of poly(lactic) acid PLA-based 3D printed filament under temperature and environmental conditions *Mater. Today Proc.* **67** 652–8
[8] Shrivastava A 2018 Introduction to Plastics Engineering *Introd. to Plast. Eng.* 1–16
[9] Archard J F 1953 Contact and Rubbing of Flat Surfaces *J. Appl. Phys.* **24** 981–8
[10] Abdelbary A 2014 Sliding mechanics of polymers *Wear of Polymers and Composites* (Cambridge; United Kingdom: Woodhead Publishing) pp 37–66
[11] Zhou C, Guo H, Li J, Huang S, Li H, Meng Y, Yu D, De Claville Christiansen J and Jiang S 2016 Temperature dependence of poly(lactic acid) mechanical properties *RSC Adv.* **6** 113762–72
[12] Li Z, Zhou X and Pei C 2011 Effect of sisal fiber surface treatment on properties of sisal fiber reinforced polylactide composites *Int. J. Polym. Sci.* **2011** 803428
[13] Gebisa A W and Lemu H G 2018 Investigating Effects of Fused-Deposition Modeling (FDM) Processing Parameters on Flexural Properties of ULTEM 9085 using Designed Experiment *Mater. 2018, Vol. 11, Page 500* **11** 500