Effect of layer thickness and raster angle on the tribological behavior of 3D printed materials

Citation for published version:
Amirruddin, MS, Ismail, KI & Yap, TC 2022, 'Effect of layer thickness and raster angle on the tribological behavior of 3D printed materials', *Materials Today: Proceedings*, vol. 48, no. 6, pp. 1821-1825. https://doi.org/10.1016/j.matpr.2021.09.139

Digital Object Identifier (DOI):
10.1016/j.matpr.2021.09.139

Published In:
Materials Today: Proceedings

[Innovative Manufacturing, Mechatronics & Materials Forum 2021]

Effect of Layer Thickness and Raster Angle on the Tribological Behavior of 3D Printed Materials

Muhammad Syahmi bin Amirruddin[a,b], Khairul Izwan bin Ismail[b] , Tze Chuen Yap[b,*]

[a]*Solaris Infiniti Sdn Bhd, KL Sentral, 50470, Kuala Lumpur, Malaysia*
[b]*School of Engineering and Physical Sciences, Heriot-Watt University Malaysia, 62200 Putrajaya, Malaysia*

Abstract

Additive manufacturing (AM) is a manufacturing process which add material into a solid 3-dimensional product. Fused Deposition Modelling (FDM) or Fused filament Fabrication (FFF) is one of the most common additive manufacturing methods. Parts processed by FDM are usually serve as prototypes of concept design and unable to use a functioning part due to their mechanical and tribological properties. Material wear has been a huge problem for machines as it is the main contributor to machine failures. Tribological behavior of AM part are required to be enhanced if AM parts are purposed to be functioning parts. Due to the nature of manufacturing technique, the tribological properties are affected by the FDM printing parameters. In current work, tribological properties of 3D printed pins, printed at different raster angle and layer thickness were investigated. FDM printed Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) samples were printed at three raster angle 0°, 45° and 90° and three layer thickness of 0.127 mm, 0.254 mm and 0.33 mm. Experiments were conducted on a pin-on-disk tribometer apparatus under dry sliding condition and fixed load of 10 N and 300 rpm. Results has shown that an increase of layer thickness promotes a decrease in friction force while an angle of 45° displays the best wear resistance. ABS is proofed to have better wear resistance than PLA.

Keywords: Fused deposition modelling; fused filament fabrication; printing parameter; friction coefficient; wear.

1. Introduction

Additive manufacturing has been a revolutionary step for mankind in the manufacturing industry. Compare with traditional manufacturing processes such as the CNC machining, 3D printing provides few advantages which allows manufacturers to modify their design up to their own needs without interfering the production line and to customise the design. There are nine different additive manufacturing techniques but Fused Deposition Modelling (FDM) is the most popular 3D printing method due to its affordability and printing speed [1]. Mechanical properties of a 3D printed material are widely studied by researchers but tribological study regarding FDM 3D printed material is limited. Friction and wear in FDM 3D printed products are important factors to be considered if FDM 3D printed part are used as functional parts that involved relative motions. Tribological tests such as pin on disk test were commonly used to understand the wear and friction behavior of new polymeric materials or polymeric materials produced by new fabrication method [2]–[5].

[*] Corresponding author. Tel.: +603-88943780.
E-mail address: t.yap@hw.ac.uk

Tribological and mechanical behaviours of FDM printed parts are affected by printing parameters. Identify and understand the best process parameters that would be able to produce the desired properties would be beneficial for the users. A recent study observed the effect of five different parameters towards the tribological properties of ABS materials [3], [4]. The five parameters are raster angle, layer thickness, air gap, build orientation, and road width. This study concludes that the friction behaviour is mainly affected by the layer thickness, raster angle, build orientations and air gap [3] while the wear behaviour is affected by layer thickness, raster angle, and build orientations [4]. The results show that the coefficient of friction increases as the main parameters increase. The relationship between process parameters in FDM printed ABS and sliding wear was also investigated in another study [6]. In this study, four process parameters, layer thickness, raster angle, raster width and air gap were selected. Using microphotographs, the study showed wear is a phenomenon that occurs when a material breaks the inter-layer bond, cracks in the surface layer due to stress cycle. With the process parameters acting as the variable, it can be concluded that using the suitable process parameters would greatly improve the wear of a material. Furthermore, another study observed the effect of load, raster angle and sliding speed effecting the 3D printed pin's tribological properties [7]. The results showed an increase of loads will create cracks in the filaments, reducing its overall strength. The wear rate of the pin is heavily affected under heavy load stress, with higher load causing a lower wear rate [7]. Textured surfaces were also proposed to improve the tribological behaviour of 3D printed parts [8]. VisiJet M3 crystal specimens with four different surface textures; flat, circle-concave, circle, convex and square-concave were 3D printed. From reciprocating sliding wear experiment with low load condition, the friction and wear coefficient showed no significant difference among four textured surfaces. However, under high load, the convex textured surface showed a higher wear and friction rate than the untextured surface, but the circle-concave showed lower wear and friction rate than the untextured surface. In another reciprocating tribo- test, the roles of printing parameters on the tribological behaviours of 3D printed polybutylene terephthalate (PBT) was investigated [9]. The research proofed that printing orientation and infill density affect the tribological properties but further investigations in thermomechanical and viscoelastic properties are required to understand the tribological mechanism. In recent study, the friction and wear behaviour of 3D printed ABS and PLA printed at different layer thickness, infill angle, infill pattern, and printing orientation were investigated through block on roller tribo test [10]. They concluded that tribological behaviour of 3D printed parts are affected by plastic flow in the sliding surface, porosity of the printed parts. Tribological behaviour of 3D printed ABS was compared with PLA-carbon fibre composite [11] and PLA-carbon fibre composite was reported to have lower specific wear rate and coefficient of friction compared to ABS at high infill density and lower layer thickness.

The effect of layer thickness and raster angle in 3D printing mechanism to the mechanical properties of 3D printed PEEK was investigated in a separated study [1]. This work concluded that higher layer thickness results in a stronger strength in 3D printed material. This is due to the interlayer bonding between the layers and with less bonding involved within the layers, the stronger the outcome of the materials. Moreover, the raster angle varies with strength. In this study, the raster angle showed 45° having the strongest properties. In another study, interlayer adhesion strength of FDM printed ABS was found strongly correlated to layer thickness of printing [12]. Despite the above findings are closely related, it focuses on mechanical properties instead of tribology.

This research aims to study and understand the effect of layer thickness and raster angle on the tribological properties of a 3D printed parts. Furthermore, two commonly used FDM filaments materials, Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) will be investigated for direct comparison. Both thermoplastic materials are the most popular plastic for FDM 3D printing due to their reasonable price and strength. Understanding the effect of printing parameter to the tribological properties of ABS and PLA will be very beneficial for manufacturers and the industrial world.

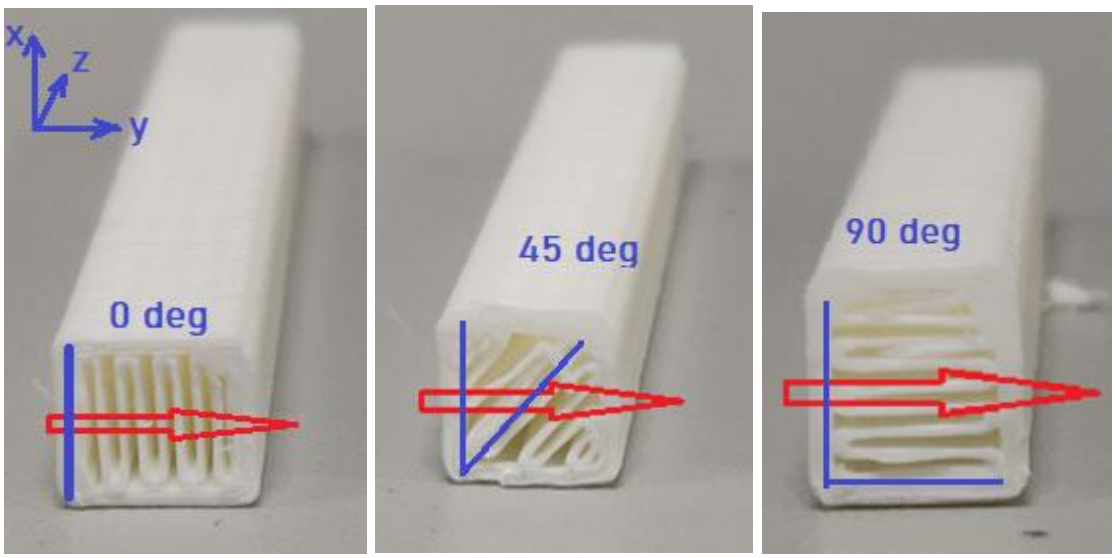
2. Methodology

2.1 FDM sample preparation

Polymeric pins were printed by Ultimaker 2+ 3D printer. The pin was created using Creo Parametric and saved as a STL format. It was then transferred to Ultimaker CURA, a software for slicing and setting of parameters. The FDM process parameters are listed in Table 1. The pins are rectangular pin with a dimension of 0.7×0.7 cm^2 square and 5 cm length. A total of 18 pins were 3D printed by using Ultimaker ABS and PLA filaments of 2.85 mm, with 9 respective pins for each material. The mechanical properties of both filaments are available on technical data sheet provided by manufacturer [13], [14]. Infill density for all specimens were set at 50%. Recommended print bed temperature and nozzle temperature by Ultimaker were applied. The pins were printed in a Z-axis orientation to ensure that the pin's raster angle texture is present on its surface. Layer thickness was measured along z axis. Fig. 1 shows pins printed at three different raster angles.

Table 1**.** Variables investigated in current works

Variables		levels	
Materials	ABS	PLA	
Layer thickness (mm)	0.127	0.254	0.32
Raster angle (°)	0	45	90



(a) (b) (c)

Fig. 1. 3D printed pin at different raster angle with printing direction x-y-z and sliding direction (red arrow)

(a) Pin with 0° raster angle, (b) Pin with 45° raster angle, (c) Pin with 90° raster angle

2.2 Tribo test

To investigate the relationship between the printing parameters and tribological properties, experiment was conducted on an in-house built pin on disc tribometer (Fig. 2), followed the procedure of ASTM G99. 3D printed polymeric pins were slide against ASSAB 760 steel disc at constant test conditions. Counter face disc was rotated at a constant speed of 300 rpm (linear speed of 0.942 m/s), normal load acted on the pin was fixed at 10 N and each experiment lasted for 20 minutes. Test parameters were selected based preliminary tests. Steel disc was cleaned using a V-Tech Metal Polish cream to refresh the surface before each test. The pin's masses before and after tribo test were measured using a AND EK-300i weighting scale with resolution of 0.01 g and the difference in masses of the pin is the mass loss. A CT6 LED HAND tachometer was used to record the rotation speed of the disc. Load cell YCL-133 with multimeter GDM 397 were used to measure friction force in the form of voltage during the tribo test. Voltage data were then converted to friction force.

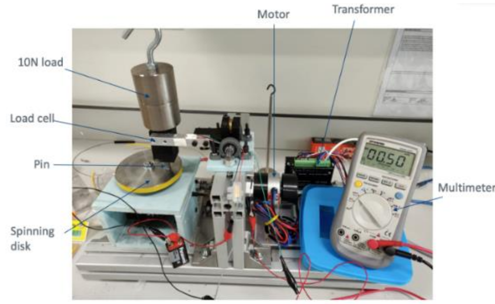
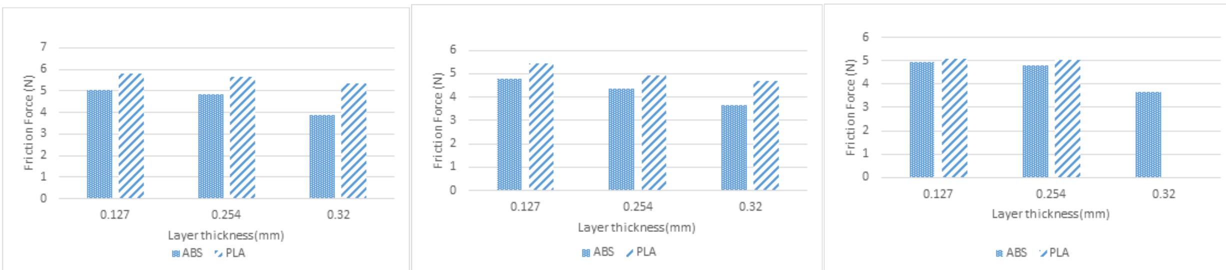


Fig. 2 Pin on disc tribometer

3. Results and Discussions

3.1 Friction Force against Layer Thickness



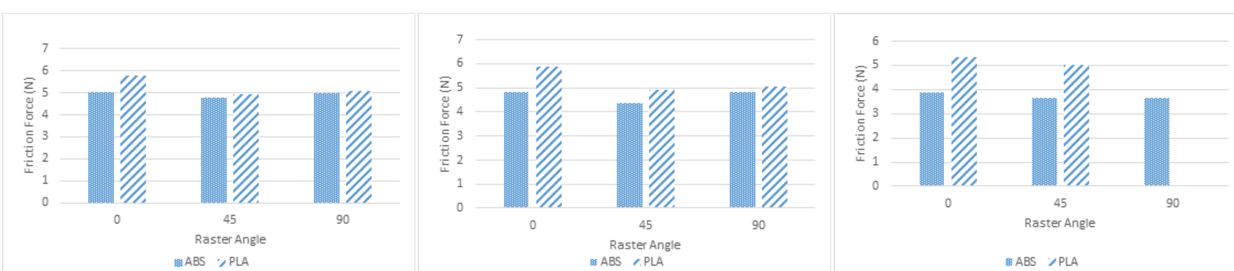
(a) (b) (c)

Fig. 3. Friction forces of ABS and PLA pins printed at three different layer thickness and constant raster angle of (a) 0° (b) 45° (c) 90°

Fig. 3 a-c shows the results of friction force against layer thickness at three fixed raster angles. At raster angle of 0°, friction force reduced with increase in layer thickness for both ABS and PLA. Similar trends can be observed in Fig. 3 b and c for raster angles of 45° and 90°. In general, higher layer thickness reduces friction force and both materials experienced similar trend. However, this finding is different from what reported by [10], where no consistent trend was observed when testing ABS pin of different layer thickness (0.007 and 0.013 inch). Furthermore, PLA has higher friction force than ABS in all investigated cases. Similar results was reported by [10], where PLA printed with 45° infill has higher friction coefficient than ABS printed with 45° infill. They also reported that for sample printed with 90° infill, PLA has higher friction than ABS at the beginning of the test, but the gap narrowed over time. The friction results of PLA at layer thickness of 0.32 mm were not available due to broke down of test rig.

3.2 Friction Force against Raster Angle

Fig. 4 presents the results of friction force against raster angle under fixed layer thickness. In general, 0° raster angle pins have the highest friction force followed by 90° raster angle pins and lastly, 45° raster angle pins. This indicated that a perpendicular pattern, 0° of the pin, against the direction of force had the highest force exerted on the pin. The textured pattern of 45° on the pin showed the least friction force exerted on its surface. On the other hand, the frictional force on the 90° raster angle pin is relatively close to the 0° raster angle pins. Similar to previous findings, PLA pins have higher frictional force than ABS pins.

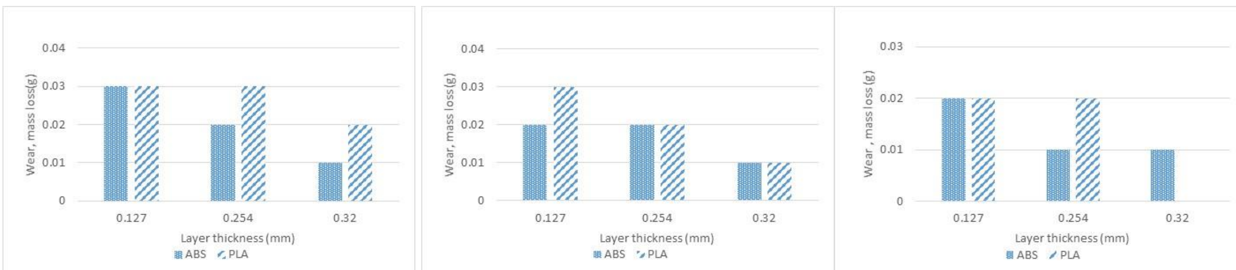


(a) (b) (c)

Fig 4. Friction forces of ABS and PLA pins printed at three different raster angle and constant layer thickness of (a) 0.127 mm, (b) 0.254 mm, (c) 0.32 mm

3.3 Wear vs Layer Thickness

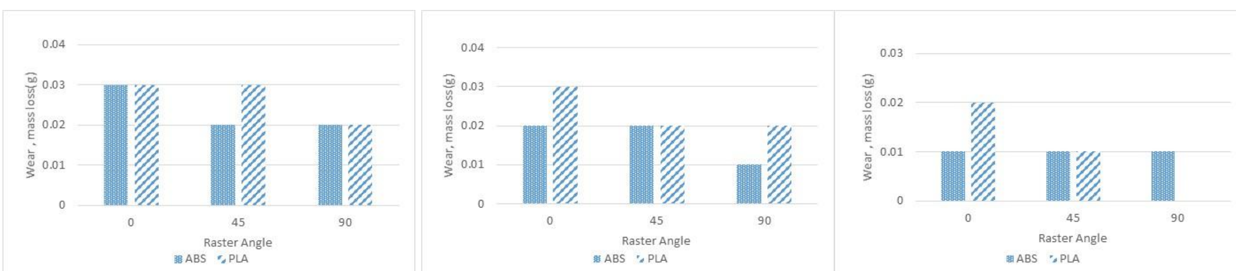
Fig. 5 shows the results of wear in term of mass loss against layer thickness under fixed raster angle. Due to limitation of experimental setup, only mass loss of 0.01g resolution can be reported and as such current work is unable to report detailed trend. In addition, the results of PLA at layer thickness of 0.32 mm were not available due to broke down of test rig. Nevertheless, Fig. 5 a-c indicates that 3D prints printed with higher layer thickness are more wear resistance. Same trend can be observed for all samples prepared at different raster angles, and different materials. In additional, ABS is better than PLA in term of wear resistance. This might be due to ABS has a higher melting temperature (225-245°C) compared to PLA (145-160°C)[13], [14]. Furthermore, ABS has a higher glass transition temperature (around 106°C) compared to PLA (around 57°C)[15]. Glass transition temperature is the temperature where polymer transitions from crystalline to fluid state [15]. In other words, friction heat generated from sliding motion changes the hardness of PLA after 57°C, whereas ABS can retain it hard state until around 106°C. The wear loss of a material is normally predicted with Archard's wear equation ($Q = {}^{KWL}/_{H}$), where the wear loss in volume (Q) is proportional to wear constant (K), normal load (W) and sliding distance (L) but inversely proportional to the hardness of the softer material (H) [16]. Thus, ABS which can retain it hardness for wider temperature range, has a better wear resistance than PLA.



(a) (b) (c)

Fig. 5. Wear of ABS and PLA pins printed at three different layer thickness and constant raster angle of (a) 0° (b) 45° (c) 90°

3.4 Wear vs Raster Angle



(a) (b) (c)

Fig. 6. Wear of ABS and PLA pins printed at three different raster angle and constant layer thickness of a) 0.127 mm, b) 0.254 mm, c) 0.32 mm

Fig. 6 shows the results of wear against raster angle under fixed layer thickness. Due to limitation in resolution of the weighing machine, only the general trend is discussed. Pin printed at 0° raster angle had the highest wear (mass loss) and pin printed at 45° showed the least wear. Similar finding was reported by [17]. In addition, Fig. 6 also indicates that at highest layer thickness of 0.32 mm. raster angle has insignificant effect on the ABS's wear.

From the above analysis, the relationship between printing parameters and friction & wear behaviors were observed. Current works indicate that, a higher layer thickness will result in a lower frictional force. This is opposite to trend reported by [3] where the average friction coefficient of PC-ABS increased with increase in layer thickness. Current work also shows that a higher layer thickness will result in a lower wear. In 3D printing process, parts are manufactured in a layer-by-layer method. Therefore, the printed part's structural & tribological behaviors are affected by the bonds between layers, and air gap between layers are always the weakness region. Printing with higher layer thickness will result in a smaller number of layers and this subsequently translate to less voids in the build. Nevertheless, the actual friction and wear mechanism at various layer thickness are complicated and requires further investigation. On the other hand, raster angle shows a different behavior and trend compared to layer thickness. Within the raster angle of 0°, 45° and 90° that was observed, 45° raster angle pins had the lowest friction force in current study. Further investigations and more tests are required to support and understand the findings. Similar trend was reported by [17] where lowest friction occurred at around 60° raster angle. Throughout the study, PLA were observed to have a higher frictional force than ABS in all experiments. Both PLA and ABS are having similar trend, where friction decreases with layer thickness and 45° raster angle pins show the best tribological behaviour. ABS is consistently better than PLA in term of wear resistance. This is consistent to previous findings[10]. Being able to withstand higher impact force and high heat resistance, ABS seems to be the better material compared to PLA in terms of wear resistance.

4. Conclusions

In conclusion, the relationship of raster angle and layer thickness against the tribological properties has been successfully identified. A higher layer thickness would result in a lower frictional force and wear experienced by it. When the layer thickness increased from 0.127 mm to 0.32 mm, reductions of 23%-26% and 7-8% were observed in friction force for ABS and PLA respectively while a reduction in mass loss of ~66.7% was noticed for both materials. Raster angle of 45° was observed to have least friction compared to 0° and 90° (4-16% lower compared to friction at 0° or 90°). In additional, ABS is a better material if compare with PLA, for application that involved relative motion. Further investigations in thermomechanical, viscoelastic behavior of 3D printed polymers under sliding motion and rheology of molten 3D printed polymer are required to further understand the sliding mechanism of 3D printed polymer.

Acknowledgements

The authors would like to acknowledge Mr. Elyas Budiman bin Rahmat (lab technician) for the help and assistance. This research work was conducted as preliminary work for a project funded by Ministry of Higher Education Malaysia (MOHE). The third author would like to acknowledge MOHE for the FRGS grant with code FRGS/1/2019/TK03/HWUM/02/1.

References

[1] W. Wu, P. Geng, G. Li, D. Zhao, H. Zhang, and J. Zhao, "Influence of Layer Thickness and Raster Angle on the Mechanical Properties of 3D-Printed PEEK and a Comparative Mechanical Study between PEEK and ABS," *Mater. 2015, Vol. 8, Pages 5834-5846*, vol. 8, no. 9, pp. 5834–5846, Sep. 2015, doi: 10.3390/MA8095271.

[2] Sivaraos *et al.*, "Friction Performance Analysis of Waste Tire Rubber Powder Reinforced Polypropylene Using Pin-On-Disk Tribometer," *Procedia Eng.*, vol. 68, no. 0, pp. 743–749, 2013, doi: http://dx.doi.org/10.1016/j.proeng.2013.12.248.

[3] O. A. Mohamed, S. H. Masood, and J. L. Bhowmik, "A parametric investigation of the friction performance of PC-ABS parts processed by FDM additive manufacturing process," *Polym. Adv. Technol.*, vol. 28, no. 12, pp. 1911–1918, Dec. 2017, Accessed: May 05, 2020. [Online]. Available: http://doi.wiley.com/10.1002/pat.4080.

[4] O. A. Mohamed, S. H. Masood, J. L. Bhowmik, and A. E. Somers, "Investigation on the tribological behavior and wear mechanism of parts processed by fused deposition additive manufacturing process," *J. Manuf. Process.*, vol. 29, pp. 149–159, Oct. 2017, doi: 10.1016/J.JMAPRO.2017.07.019.

[5] N. S. M. El-Tayeb, B. F. Yousif, and T. C. Yap, "Tribological studies of polyester reinforced with CSM 450-R-glass fiber sliding against smooth stainless steel counterface," *Wear*, vol. 261, no. 3–4, pp. 443–452, 2006, doi: 10.1016/j.wear.2005.12.014.

[6] A. K. Sood, A. Equbal, V. Toppo, R. K. Ohdar, and S. S. Mahapatra, "An investigation on sliding wear of FDM built parts," *CIRP J. Manuf. Sci. Technol.*, vol. 5, no. 1, pp. 48–54, Jan. 2012.

[7] P. K. Gurrala and S. P. Regalla, "Friction and wear rate characteristics of parts manufactured by fused deposition modelling process," *Int. J. Rapid Manuf.*, vol. 6, no. 4, p. 245, 2017, doi: 10.1504/IJRAPIDM.2017.087541.

[8] Y. Hong, P. Zhang, K.-H. H. Lee, and C.-H. H. Lee, "Friction and wear of textured surfaces produced by 3D printing," vol. 60, no. 9, pp. 1400–1406, 2017, Accessed: May 05, 2020. [Online]. Available: https://link.springer.com/article/10.1007/s11431-016-9066-0.

[9] D. Hesse, M. Stanko, P. Hohenberg, and M. Stommel, "Investigation of Process Control Influence on Tribological Properties of FLM-Manufactured Components," *J. Manuf. Mater. Process. 2020, Vol. 4, Page 37*, vol. 4, no. 2, p. 37, Apr. 2020, doi: 10.3390/JMMP4020037.

[10] R. Roy and A. Mukhopadhyay, "Tribological studies of 3D printed ABS and PLA plastic parts," *Mater. Today Proc.*, vol. 41, pp. 856–862, Jan. 2021, doi: 10.1016/J.MATPR.2020.09.235.

[11] R. Srinivasan, B. Suresh Babu, V. Udhaya Rani, M. Suganthi, and R. Dheenasagar, "Comparision of tribological behaviour for parts fabricated through fused deposition modelling (FDM) process on abs and 20% carbon fibre PLA," *Mater. Today Proc.*, vol. 27, pp. 1780–1786, Jan. 2020, doi: 10.1016/J.MATPR.2020.03.689.

[12] N. Aliheidari, J. Christ, R. Tripuraneni, S. Nadimpalli, and A. Ameli, "Interlayer adhesion and fracture resistance of polymers printed through melt extrusion additive manufacturing process," *Mater. Des.*, vol. 156, pp. 351–361, Oct. 2018, doi: 10.1016/J.MATDES.2018.07.001.

[13] Ultimaker, "Technical data sheet ABS," 2018. [Online]. Available: https://support.ultimaker.com/hc/en-us/articles/360012759139-Ultimaker-ABS-TDS.

[14] Ultimaker, "Technical data sheet PLA," 2018. [Online]. Available: https://support.ultimaker.com/hc/en-us/articles/360011962720-Ultimaker-PLA-TDS.

[15] E. Sirjani, P. J. Cragg, and M. K. Dymond, "Glass transition temperatures, melting temperatures, water contact angles and dimensional precision of simple fused deposition model 3D prints and 3D printed channels constructed from a range of commercially available filaments," *Chem. Data Collect.*, vol. 22, p. 100244, Aug. 2019, doi: 10.1016/J.CDC.2019.100244.

[16] K. C. Ludema, "Friction, Wear, Lubrication : A Textbook in Tribology," *Frict. Wear, Lubr.*, Jun. 1996, doi: 10.1201/9781439821893.

[17] M. Dawoud, I. Taha, and S. J. Ebeid, "Effect of processing parameters and graphite content on the tribological behaviour of 3D printed acrylonitrile butadiene styrene," *Materwiss. Werksttech.*, vol. 46, no. 12, pp. 1185–1195, Dec. 2015, doi: 10.1002/MAWE.201500450.