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Friction Behavior of 3D-printed Polymeric Materials Used in Sliding Systems

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Abstract: *Recently, 3D-printed polymeric materials have been successfully replacing the usual ones especially used in sliding systems like couplings. Among the polymeric materials, Acrylonitrile Butadiene Styrene (ABS) and Poly Lactic Acid (PLA) can be the competitive materials in such application after 3D-printing. In this study, 3D printing was used to produce samples from ABS and PLA via fused deposition modelling (FDM) technology. Then friction behavior of 3D-printed samples was investigated depending on printing orientation of the samples. Ultra High Molecular Polyethylene Weight (UHMWPE), as a well-known industrial polymer, was also used for comparing the friction behavior of 3D-printed ABS and PLA polymers. Friction tests were conducted using a pin-on-plate type tribometer according to ASTM G133 under different applied loads and sliding speeds at room temperature. It was found that printing orientation of all ABS and PLA samples has a considerable effect on their friction behavior. Transverse direction (T.D) of the 3D-printed samples shows higher coefficient of friction (COF) values than the longitudinal direction under all applied loads and sliding speeds. On the other hand, COF values obtained in both 3D-printed samples increase as the load and speed increase regardless of the printing direction. When both 3D-printed materials are compared, PLA samples exhibit lower COF values than ABS samples in both printing directions and under all loads and speeds. However, the UHMWPE sample produced with traditional method shows much lower COF values and stable change in friction behavior under all conditions compared to 3D-printed PLA and ABS samples.*

Keywords*: 3D-printed polymer, friction behavior, PLA, ABS, printing orientation*

1. Introduction

In some practical applications, the couple of metal/polymeric materials is often used to reduce the friction that occurs in the sliding conditions as in the case of Figure 1. In such applications, many polymeric materials are commonly used because of their good self-lubricated properties [1]. Ultra High Molecular Polyethylene Weight (UHMWPE) is one of the most widely used polymeric materials in friction applications. Many techniques or processing procedures have been utilized for manufacturing of parts or hybrid structures from the polymeric materials. In recent years, three-dimensional (3D) printing technology has been widely used especially for complex shaped parts. As known, this technology is an additive manufacturing (AM) process that enables the fabrication of different shaped parts by adding layers of materials on top of each other successively [2]. The most well-known 3D printing technology is FDM-Fused Deposition Modeling, also called as Fused Filament Fabrication (FFF) based on extrusion [3,4]. The process proceeds by melting the filament of thermoplastic polymer and then solidifying into final parts (Figure 2). 3D printed materials generally have anisotropic properties due to the layer by layer processing procedure.

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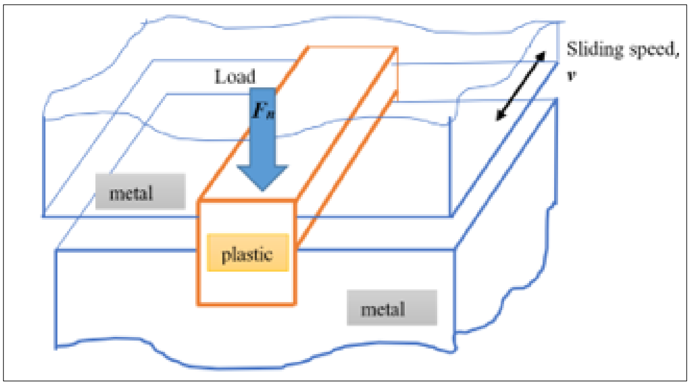

Figure 1. A representative sliding system including both metallic and polymeric materials and intersections

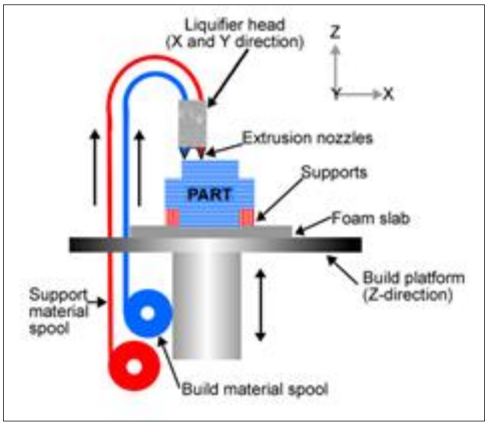

Figure 2. A schematic showing a 3D printing based on fused deposition modelling [4]

Sliding systems are commonly used in many applications like food packaging, aerospace industry, automotive manufacturing, and biomedical engineering. In such systems, some complex shaped parts can easily be produced in net-shaped forms using 3D printing technology at a relatively low cost without wasting materials. Polymeric materials can achieve good frictional and wear properties for bearings and bushing applications in such areas due to the ability of forming a thin film transfer on the metal counterface which assists in reducing the friction coefficient [5].

There are many studies on structural and mechanical properties of 3D printed polymeric materials [6-8]. However, limited studies have been performed on their tribological behaviors which are especially used in sliding application with metal counterparts like couplings. Muammel *et al.* [9] examined the friction behavior of 3D printed ABS with different colors and PLA under alternative movements on cylindrical pairs of flat plastic plates. They found that static and dynamic friction factors were different. Dagnan *et al.* [10] studied the friction behavior of AM polymers using UMT Tribo Lab with the linear reciprocating module in a ball-on-plate configuration under dry sliding conditions. They used Polyjet D photopolymer technique for manufacturing the parts from AM polymers. The frictional performance was shown to be strongly dependent on the surface orientation under 1 N load where surface asperities are seen to play a major role during the reciprocating sliding. However, it was shown that bulk mechanical properties affect the coefficient of friction values rather to a greater degree than surface roughness under higher loads of 5 and 10 N. Roy *et al.* [11] also studied tribological behavior of 3D printed (Stratasys F170) ABS and PLA polymers using block-on-roller configuration. They analyzed the effects of the printing parameters on tribological behavior of 3D printed ABS and PLA samples. In another study, Pawlak W. [12] obtained a COF value of about 0.48 in coupling PLA/metal pair. A composite structure of 50% graphite and 50% of poly lactide was created which allowed to decrease both coefficient of friction and linear wear.

Influence of the surface roughness of 3D printed parts on their friction behavior was reported by Nedić *et al.* [13]. They utilized a tribometer with block-on-disc configuration and found relatively higher COF values from 3D printed ABS samples than that from PLA samples.

On the other hand, the parts produced by AM technologies like FDM technique may have dependence on printing direction due to the nature of 3D printing technology. Therefore, the 3D printed parts may have anisotropic behavior, and friction coefficient values may change depending on printing direction [14]. As looking at the literature, very limited studies have been undertaken on this issue [1] and further investigations need to be able to establish a general conclusion especially for 3D-printed polymeric materials.

In view of the above, the main purpose of this paper is to investigate friction behavior of different 3D-printed polymeric materials depending on printing orientations. For this purpose, two polymeric materials of Acrylonitrile Butadiene Styrene (ABS), Poly Lactic Acid (PLA) are created by Fused Deposition Modelling (FDM) technology. Also, UHMWPE, as a well-known industrial polymer, was also used for comparison. Friction test were conducted using a pin-on-plate type tribometer according to ASTM G133 under different loads and sliding speeds at room temperature.

2. Materials and methods

In this study, three polymeric materials of Acrylonitrile Butadiene Styrene (ABS), Poly Lactic Acid (PLA) and Ultra High Molecular Polyethylene Weight (UHMWPE) are used. The PLA is a biodegradable thermoplastic derived from renewable resources (corn) with good properties. This polymer has relatively high strength and high elastic modulus which makes it a suitable candidate for producing different components used in either the industrial packaging field or automotive industry [15]. PLA filaments used for this work was extruded at 190℃, with printing speed as 23 mm/s. As known, PLA has been used in 3D printing applications for a long time. If the mechanical and tribological properties of that polymer can be improved more, further possible applications like housings or structural interior of automobiles or other vehicles can be realized. The ABS is an opaque engineering thermoplastic widely used in electronic housings, auto parts and consumer products [11]. It is an ideal material of choice for various structural applications due to its good physical properties. This polymeric material has a good resistance of abrasion and it is hard in nature and thus delivers good impact strength. ABS Filament in this work is operated at the temperature of 230℃.

In this paper, 3D- printed samples from the PLA and ABS were manufactured using Fused Deposition Modeling (FDM) (Figure 2) technique via a WANHAO Duplicator 4s plus printer. This 3D printer can produce a model with dimensions of 200 mm x 200 mm x 180 mm with a positioning accuracy of 12 μm for X and Y axes and 0.4 μm for Z axis. The PLA and ABS samples produced by 3D printing and traditionally produced UHMWPE sample are shown in Figure 3. The process parameters of the 3D printing process are given in Table 1. The mechanical properties for the polymeric materials tested are gathered from the literature [8, 15, 16] and presented in Table 2.

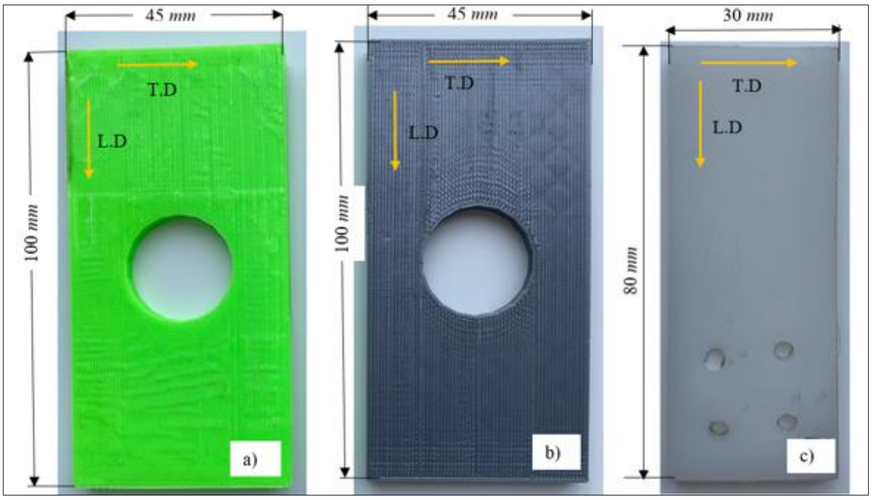

Figure 3. The samples used in friction tests: a) 3D printed PLA sample and (b) 3D printed ABS sample. L.D and T.D represent the longitudinal direction ad the transverse direction, respectivally. (c) Conventially produced UHMWPE sample

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Table 1. 3D printing parameters

Parameters	Polymeric Materials	
	PLA	ABS
Layer thicknesses, *mm*	1	1
Fill density, %	20%	20%
Print speed, *mm/s*	23	23
Printing temperature, ºC	190	230
Bed temperature, ºC	70	50

Table 2. Mechanical properties of the samples tested [8,15,16]

Mechanical Properties	Polymeric materials		
	PLA	ABS	UHMWPE
Poisson's ratio	0.36	0.43	0.46
Tensile modulus of elasticity (MPa)	3500	1700-3200	915±423
Tensile yield strength (MPa)	70	29.8-43	25.6±3.3
Tensile ultimate elongation (%)	7	10-50	317±140

Sliding friction tests of the samples were performed with the UMT 2 tribometer CETR (Campbell, CA, USA) (Figure 4 (a)). A schematic diagram of the pin-on-plate friction set-up is shown in Figure 4 (b). This set-up has been used extensively in many studies reported in the literature and this configuration has been shown to be appropriate for UHMWPE-on-hard (metal or ceramic) combinations [17]. This equipment can accurately control and measure the applied loads, displacements and velocities of the pin. It is connected to a computer that can record the horizontal and normal forces. A cylindrical metallic pin (5 mm in diameter) made of CoCr alloy with the hardness of 260 HB was used. The normal force applied to the pin can be exerted onto the sample surfaces along two printing directions: longitudinal direction L.D (0°) and transverse direction T.D (90°) (Figure 3ab).

A series of sliding friction tests were carried out on two types of 3D printed polymeric materials of PLA and ABS. Also, the UHMWPE was used as a good reference polymeric material. Dimensions of 3D-printed polymeric samples were 100 mm x 45 mm x 5 mm while those of UHMWPE sample were 80 mm x 30 mm x 5 mm (Figure 3).

The sliding friction tests were performed at the room temperature under dry sliding condition for sliding speeds of 1 mm/s and 0.5 mm/s. Applied load values were 50 N, 75 N and 100 N. These test conditions were determined considering the literature and the real working conditions. Before conducting the tests, the pin and the surfaces of the samples are cleaned with ethanol. The surface profile and average roughness (Ra) values of the samples were measured with the 2D Profilometer SJ301 (Mitutoyo, Japan).

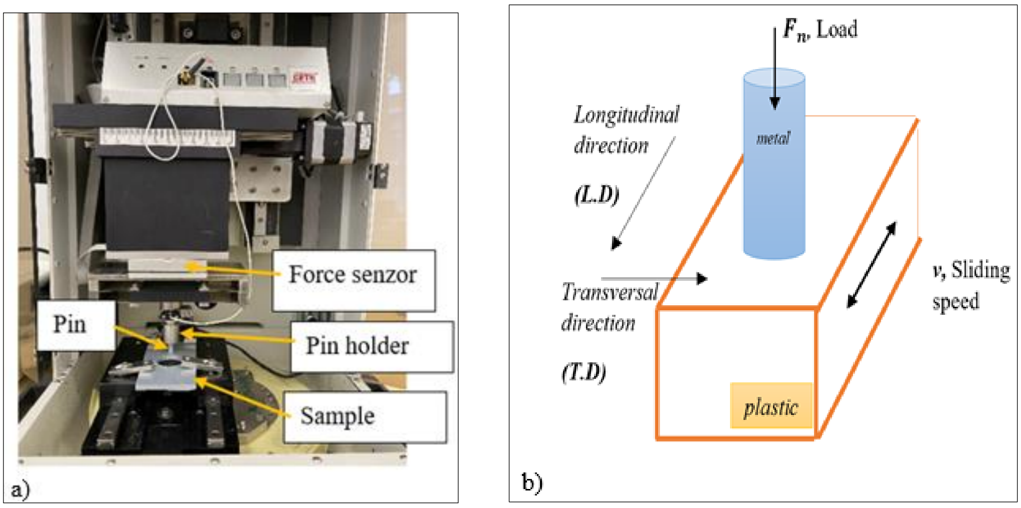

Figure 4. a) A picture of UMT sliding test set-up used for evaluation of friction behavior of the samples produced and b) a schematic showing the pin-on-plate test configuration

3. Results and discussions

The surface profiles of 3D-printed ABS and PLA and conventionally produced UHMWPE samples are shown in Figures 5-6 along both longitudinal direction (L.D) and transverse direction (T.D). It is seen from the graphs that the conventionally produced UHMWPE sample shows surface texture with more frequent and shorter spacing surface roughness fluctuations. The 3D-printed samples exhibit surface texture with a relatively wider range of roughness fluctuations. The average surface roughness (Ra) values of 3D-printed ABS and PLA samples and conventionally produced UHMWPE sample are given in Table 3 depending on printing directions. Through the L.D, Ra values of 3D-printed PLA and ABS samples and conventionally produced UHMWPE sample are 1.40±0.24 μm, 0.69±0.20μm and 1.40±0.15 μm, respectively. Through the T.D, they are 2.77±0.10 μm, 6.58±0.10μm and 1.39±0.15 μm, respectively. Along the L.D, the lowest Ra value was found from the 3D-printed ABS sample as 0.69±0.20 μm. In this direction, the PLA and UHMWPE samples showed almost the same Ra value of 1.40 μm. Along the T.D, the UHMWPE sample showed the lowest Ra value of 1.39±0.15 μm, which is as almost the same with that obtained along the L.D. In the T.D direction, 3D-printed PLA and ABS samples exhibited much higher Ra values than those in L.D. The PLA and ABS samples showed 2.77±0.10 μm and 6.58±0.10 μm Ra values, respectively.

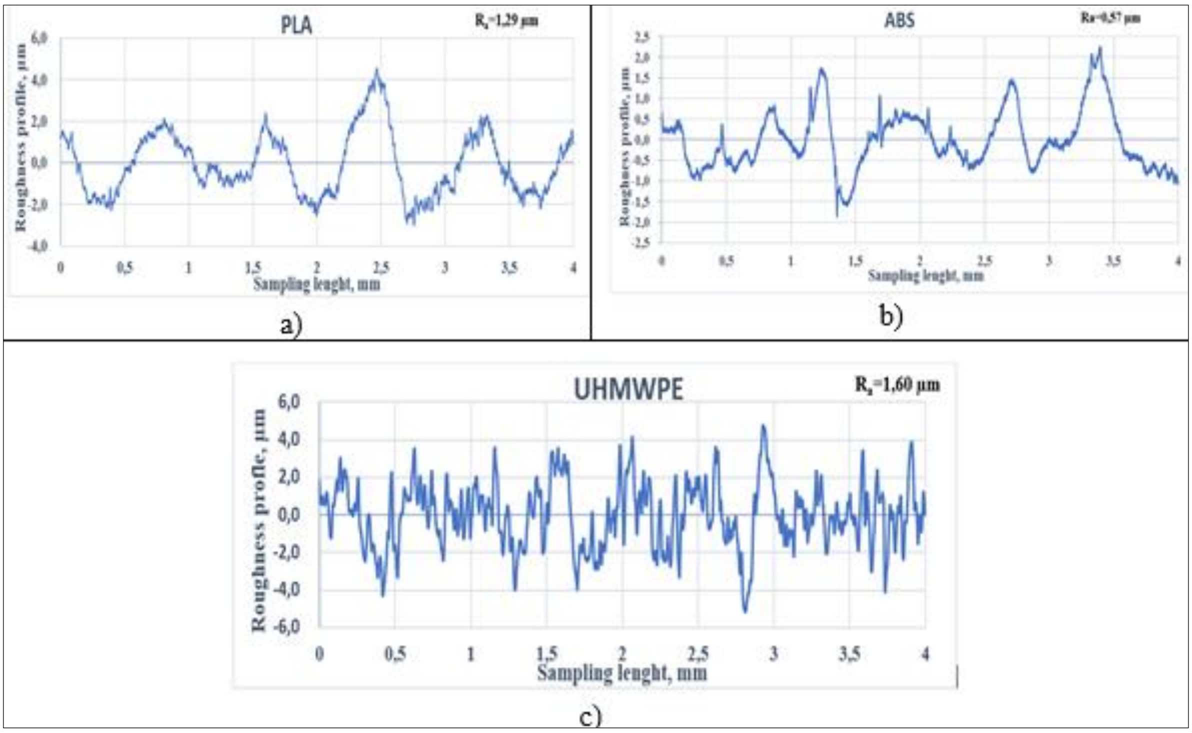

Figure 5. Surface texture showing 2D profiles of the deviation of roughness along the L.D: a)3D-printed PLA sample, b) 3D-printed ABS sample and c) UHMWPE sample

The variations of the coefficient of friction (COF) with displacement along the longitudinal direction for all samples at speeds of 0.5 mm/s and 1 mm/s and under normal loads of 50 N, 75 N and 100 N are shown in Figures 7 and 8. The figures show a sharp increase in COF during the initial transient-state sliding period with steady-state levels for all samples under all working conditions. 3D-printed PLA and ABS samples exhibit more scattering during the steady state region compared to conventionally produced UHMWPE sample. Also, this scattering in COF values decrease as increasing the sliding speed from 0.5 mm/s to 1 mm/s. It is also noteworthy that when the sliding speed increases, the friction coefficient curves are also slightly shifted upward for both 3D-printed samples. Both results may be due to the increase in sliding temperature generated between the polymeric sample and metallic pin surfaces

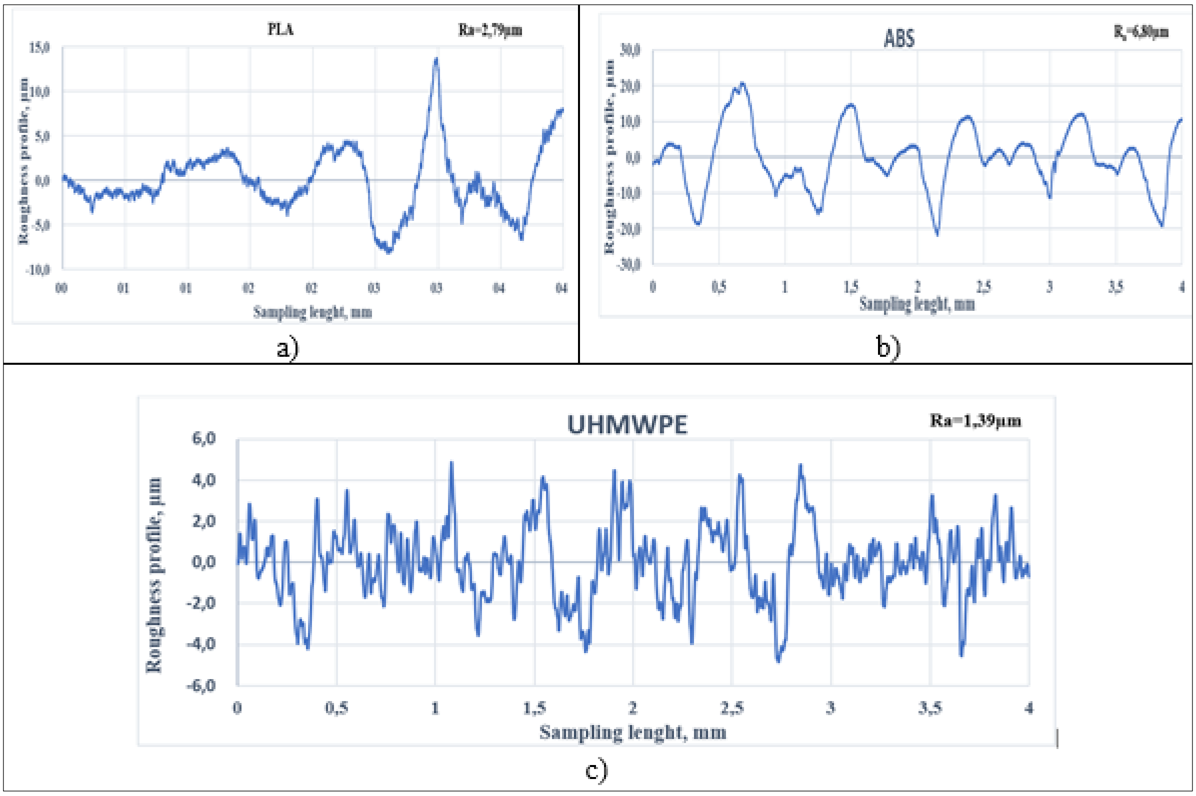

Figure 6. Surface texture showing 2D profiles of the deviation of roughness along the T.D:
a) 3D-printed PLA sample, b) 3D-printed ABS sample and c) UHMWPE sample

Table 3. Average roughness (Ra) values for both orientations of all samples

Printing direction	Longitudinal direction (L.D)			Transversal direction (T.D)		
Samples	PLA	ABS	UHMWPE	PLA	ABS	UHMWPE
Ra [μm]	1.40±0.24	0.69±0.20	1.40±0.15	2.77±0.10	6.58±0.10	1.39±0.15

during sliding at relatively high speed under the same loads. Furthermore, the COF curves shifts upward for both 3D-printed samples as the applied load increases at both sliding speeds as expected from the friction's laws. On the other hand, traditionally produced UHMWPE samples exhibit almost constant COF values after initial sharp increase. Also, no scattering was seen during the sliding period for that sample.

Figures 9 and 10 show the variation of COF with displacement along the transverse direction for all samples at speeds of 0.5 mm/s and 1 mm/s and under the normal loads of 50 N, 75N and 100N. The COF for 3D-printed samples quickly reaches a value that is approximately constant for all samples under all working conditions as in the case for longitudinal direction. However, in this direction, the coefficient of friction exhibits more unstable change/oscillation during sliding for 3D printed samples.

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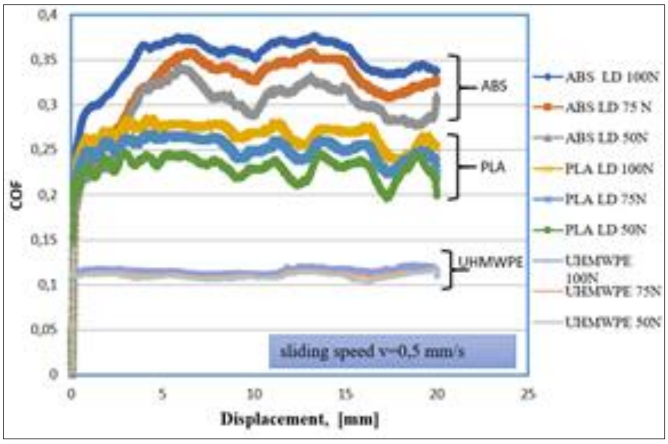

Figure 7. The variation of coefficient of friction (COF) for all samples as a function of sliding displacement along the longitudinal direction under different applied loads of 50 N, 75 N and 100 N at a sliding speed of 0.5 mm/s

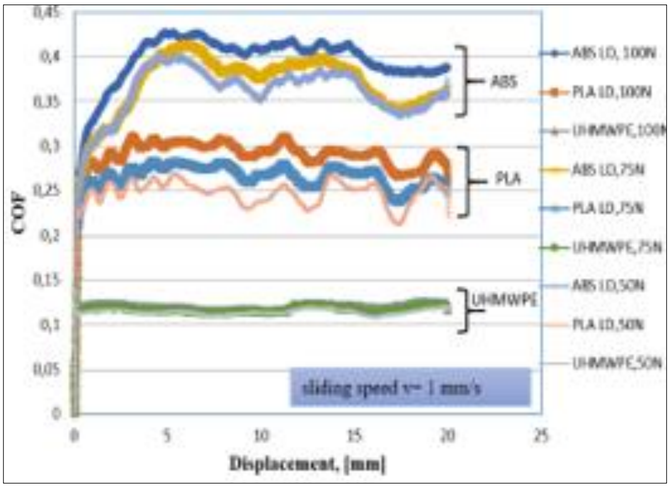

Figure 8. The variation of coefficient of friction (COF) for all samples as a function of sliding displacement along longitudinal direction under different applied loads of 50 N, 75 N and 100 N at a sliding speed of 1 mm/s

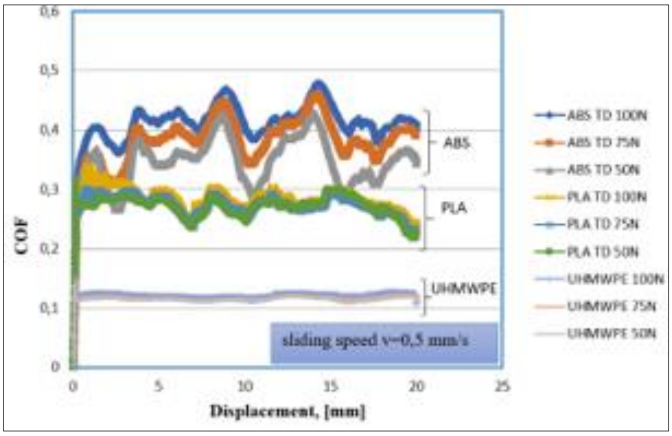

Figure 9. The variation of coefficient of friction (COF) for all samples as a function of sliding displacement along the transverse direction under different applied loads of 50 N, 75 N and 100 N at a sliding speed of 0.5 mm/s

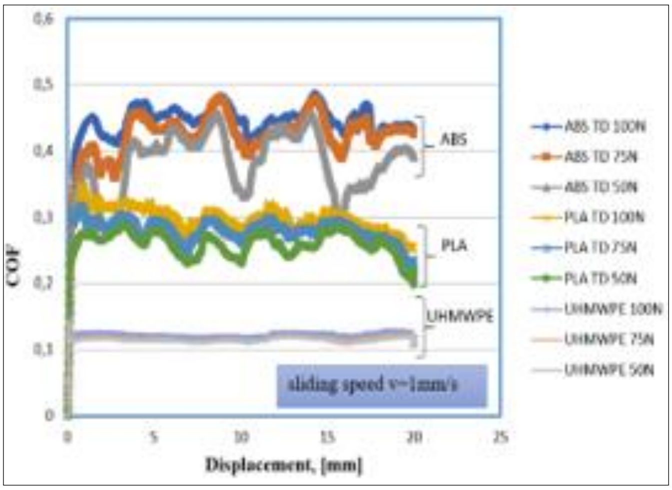

Figure 10. The variation of coefficient of friction (COF) for all samples as a function of sliding displacement along transverse direction under different applied loads of 50 N, 75 N and 100 N at a sliding speed of 1 mm/s

That instability in COF values may be because of relatively high surface roughness values. The Ra values along the T.D are higher than those along the L.D (Table 3). But the friction coefficient curves are also slightly shifted upward (to higher friction coefficient values) with increasing sliding speed and applied load.

The average COF values for the whole duration of the test were also calculated from the graphs in Figures 7-10, and their changes for both longitudinal and transverse directions are shown in Figure 11 and Figure 12, respectively. Also, the average COF values of all samples for both directions under different sliding conditions are shown in Table 4. In general, it can be said that the COF of 3D printed ABS and PLA samples slightly changes depending on the printing direction. The COF values of 3D printed ABS sample for the longitudinal direction are 0.297 and 0.375 at 0.5mm/s and 1mm/s, respectively, under 50 N load. These COF values increases to about 0.319 and 0.366, respectively, along the transversal direction. This trend is also valid under all loads (Figures 11-12 and Table 4). Regarding the 3D printed PLA samples, it can be said that the change in the COF values is almost the same with those obtained from 3D printed ABS samples. Thus, it is noteworthy that the COF values slightly increase along transverse direction for all samples due to increased Ra roughness value. Interestingly, the conventionally produced UHMWPE samples exhibit very low and stable COF values under all sliding conditions compared to 3D printed ABS and PLA samples. UHMWPE samples show almost the same COF values around 0.110 under all loads and sliding speeds (Table 4).

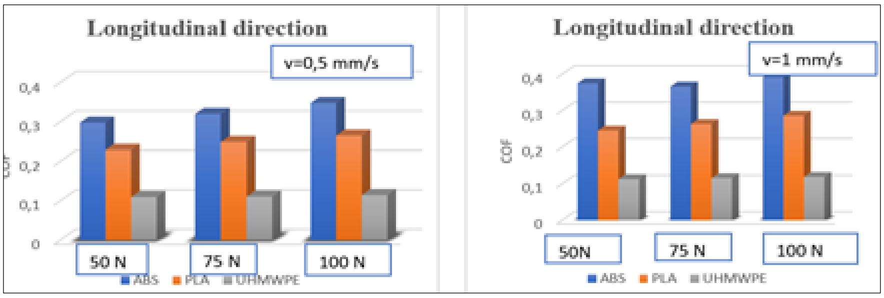

Figure 11. The variation of COF values for all samples along the longitudinal direction depending on applied loads of 50 N, 75 N and 100 N and at sliding speeds of: (a) 0.5 mm/s and (b) 1 mm/s

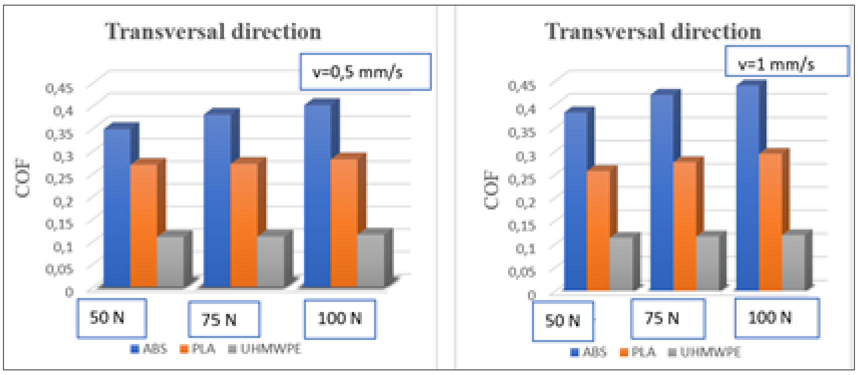

Figure 12. The variation of COF values for all samples along the transverse direction depending on applied loads of 50 N, 75 N and 100 N and at sliding speeds of: (a) 0.5 mm/s and (b) 1 mm/s

Table 4. The average COF values for all samples along both directions under different sliding conditions

Material	Sliding direction	Applied load [N]	Sliding speed [mm/s]	
			0.5	1
3D-printed ABS	L.D	50	0.297	0.375
		70	0.319	0.366
		100	0.347	0.392
	T.D	50	0.348	0.383
		70	0.38	0.42
		100	0.401	0.44
3D-printed PLA	L.D	50	0.228	0.245
		70	0.248	0.263
		100	0.264	0.286
	T.D	50	0.269	0.257
		70	0.271	0.276
		100	0.281	0.294
Conventionally produced UHMWPE	L.D	50	0.109	0.113
		70	0.11	0.116
		100	0.114	0.119

4. Conclusions

This paper investigates the friction behavior of two different 3D-printed polymeric materials (Acrylo-nitrile Butadiene Styrene (ABS), Poly Lactic Acid (PLA)) depending on printing orientations at different sliding speeds and under different applied loads. For comparison, conventionally produced Ultra High Molecular Polyethylene Weight (UHMWPE) was also used. The main findings and conclusions of this study can be summarized as follows:

-the samples from ABS and PLA polymeric materials were successfully produced by 3D printing using fused deposition modelling (FDM) technology;

-3D Printing orientation of all ABS and PLA samples has an effect on their friction behavior. Transverse direction (T.D) of the 3D-printed samples shows higher coefficient of friction (COF) values than the longitudinal direction under all applied loads and sliding speeds;

-COF values obtained in both 3D-printed samples increase with increasing applied loads and sliding speeds regardless of the printing direction;

-3D-printed PLA samples exhibit lower COF values than ABS samples along both longitudinal and transverse directions of the samples under all loads and sliding speeds;

-UHMWPE sample produced by traditional method shows much lower COF values and exhibits more stable friction behavior under all sliding conditions compared to 3D-printed PLA and ABS samples;

-it can be concluded in the light of the findings that 3D printing direction and types of polymeric materials have a considerable effect on their friction behavior. This research is a step forward in this area and further studies are needed. More detailed comparative studies including wear behavior and atmospheric conditions can be performed including more polymeric materials having different surface roughness values. Also, research may be extended to include the effect of microstructure and mechanical properties on the friction and wear behaviors of 3D-printed polymeric materials working with metallic counter faces.

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