Sliding surface structure comparison of 3D printed polymers using FDM and DLP technologies

M M Hanon and L Zsidai

1 Institute for Mechanical Engineering Technology, Mechanical Engineering Doctoral School, Szent István University, H-2100 Gödöllő, Hungary
2 Baquba Technical Institute, Middle Technical University (MTU), Baghdad, Iraq

E-mail: *harba.Muammel.M.Hanon@phd.uni-szie.hu*

Abstract. This study aims to review the surface structure of the parts that are manufactured using various techniques of 3D printing. Particularly, two different methods were employed in the current work: Fused Deposition Modelling (FDM) and digital light projection (DLP). The output of both technologies regarding the surface construction aspects was evaluated and compared. For determining the features of the surfaces, an optical microscope was utilised for taking the pictures from the cross-sectional area (upper and lower edges) and the outer face of the samples. Various magnification values have been investigated to find the best sights at the surface structure of the printed bodies. Surface roughness was examined due to its relevance to the texture properties of the fabricated pieces. The tribology of the workpieces has been tested as well. The results show that the products of the FDM technique have been characterised with a rough surface and anisotropic properties which were reflected on the examined measurements. In contrast, the DLP method has revealed objects with a very smooth surface and approximately homogeneous structure.

1. Introduction
Three-dimensional (3D) printing technology has become very popular in the recent decade. It turned into a robust alternative for building many parts which are involved in attractive applications [1], [2]. The products in the 3D printing are created as a layer by layer. Thus, manufacturing of components with a complex structure is enabled [3], [4]. Fused Deposition Modeling (FDM) is one of the 3D printing techniques based on extrusion principle. With FDM, thermoplastic material is extruded. The molten material layer is printed on top of the previous layer (see figure 1), then almost merges and hardens immediately when the printing nozzle leaves.

The FDM technique is an inexpensive 3D printing method and the most commonly utilised in home 3D printers [5], [6]. Nowadays, the most often materials used are ABS-Acrylonitrile butadiene styrene (oil-based plastic) [7], [8] and PLA-Polylactic acid (bio-based plastic) [9], [10].

Digital Light Processing (DLP) is a 3D printing technology based on the Photo-polymerization mechanism. This technique uses a projector UV-light for hardening of liquid photo-curable resins as layer by layer. The whole layer will be exposed with UV-light at once through a mask, which makes this technology basically faster than FDM. The process contains a vat filled with a light-curable liquid resin. The platform rises, and a layer of the resin distributes evenly as shown in figure 2. This process is iterated up to the object is created [12].
The surface properties are considered a critical issue for certain implementations. Hence, studying the surface structure of the produced objects is an essential matter. The surface morphology of the printed parts has a key role in enhancing their performance in terms of lowering friction and wear. There are many researchers studied the microstructure of 3D printed bodies, e.g. glass for bone scaffolds [14], tissue engineering [15], microfluidic chips [16], and fibre-reinforced polymer composites [17]. However, still there is a lack in the literature about the surface construction of the printed bulks of polymers with different methods.

In the present work, Fused Deposition Modelling (FDM) and Digital Light Projection (DLP) techniques of 3D printing have been used. Numerous cylindrical tribology test specimens were fabricated with diverse printing options and prepared for the experiment. The resulting of both technologies (FDM and DLP) concerning the surface construction aspects was examined and compared. An optical microscope was employed to determine the features of the surfaces of the samples. The tribological behaviour and surface roughness of the fabricated pieces were evaluated. This research forms the basis for a prospective series of tribological studies with basic knowledge of surface morphology.

2. Materials and methods

2.1. The employed FDM and DLP 3D printers

The printed test pieces were manufactured using two different 3D printers work according to the FDM and DLP technologies. The models of the used 3D printers are WANHAO duplicator 6 for the FDM and WANHAO D7 for the DLP, which are exhibited in Figures 3 and 4 respectively.

For the FDM 3D printer WANHAO duplicator 6, the G-Code of the 3D model can be incorporated directly from the SD card. The model could be designed using any CAD software, which is in this case Solid work software. The file must be saved as "stl" format due to it is compatible with most slicing programs. Cura (Wanhao edition v16.01) software was used as a slicer for this work. The FDM printing technology utilises the materials in a filament form.

Regarding the DLP 3D printer WANHAO D7, all parameters and commands could be given from a supplement controller supplied with the printer (Shown in figure 4). For the slicing purpose, CreationWorkshop software used which is the recommended and prepared for the same printer. “cws” format is the file extension that can be recognisable by the controller. The model file can be uploaded to the controller using a pen drive. The material that employed for the DLP printing is the so-called resin which is a chemical liquid curable by light. The Technical specifications of both 3D printers (FDM WANHAO duplicator 6 and DLP WANHAO D7) are listed in table 1.
2.2. Printing options

Once the STL file of the model completed, it is imported to the previously mentioned slicing programs. Hence, different settings can be examined when printing the test pieces using the FDM and DLP printers. These settings are expected to affect the properties of the finished object. The primary investigated option is the print orientation (horizontally “X”, 45° angle, and vertically “Z”) which are shown in figure 5 (a). In the FDM, raster direction means, the orientation of the extruder head when filling the printing material within the contour of the printed part. The angle of the raster directions of the test piece with the longitudinal axis can be adjusted to any value. Also, successive layers may have different orientations. So, there is a possibility of variation, e.g. if the raster direction angle of the first layer is 45° the second could be built at 135° (see figure 5 (b)). For the present work, while varying the print orientation, the raster direction was set as crossed 45/135°. Layer thickness is also one of the parameters that can be varied in the printing process. These parameters are expected to influence the results of the subsequent tests (Tensile, tribology, bending, impact, and surface roughness). Table 2 summarises all the examined parameters of the current study.

Table 2. The employed options for printing the tribology test specimens

| Parameter          | FDM                | DLP            |
|--------------------|--------------------|----------------|
| Raster angle       | Crossed 45/135°    | **-            |
| **Orientation**    | *X, 45°, Z         | *X, 45°, Z     |
| Thickness          | 200μm              | 100μm          |

*The variables of each examined set.
**Where X, 45°, Z refer that the orientations of printing are: horizontally, 45° angle, and vertically consecutively.
**No raster direction in the DLP technology, since every layer is built once after it exposes to the UV light.
2.3. The achieved tests

The printed specimens were examined by three tests which are tribology, surface structure (optical microscope) and surface roughness. The tribological measurement was performed at tribology laboratory in Szent István University under the laboratory conditions. The first step in the measurement process is to connect the measuring circuit, which consists of a computer, Spider 8 measuring converter, a tribotester, and an inverter. Spider 8 is a strain gauge measurement device for measuring load, force, and wear. The indispensable part of the measuring system is the tribotester, which is in this case compatible with polymers. Figure 7 displays the structure of the used PLINT TE 77 tribotester (High-Frequency Tribotest), employed by Zsidai and Kalácska in previous research [18].

Before starting the measurement, some parameters must be defined which are given in Table 3. A computerised microscope (ZEISS brand) with a high quality camera and four magnification lenses (10x, 20x, 50x and 100x) was used to study the surface structure of the samples before and after the tribology test (displayed in figure 8).
Table 3. Parameters of tribology test

| Parameter                                      | Value |
|-----------------------------------------------|-------|
| Surface roughness of steel counterpart, Ra [μm] | 0.8   |
| Load, F [N]                                    | 200   |
| Alternating motion frequency, f [Hz]           | 10    |
| Stroke length, [mm]                            | 6     |
| Relative humidity, Rh [%]                      | 50    |
| Ambient temperature (°C)                       | 23    |

3. Results and discussion

3.1. Tribology measurements

The friction and wear are the most critical values to be obtained for the tribological measurements. The attitude of the coefficient of friction as a function of the sliding distance has been represented in Figure 9. During the test, both static and dynamic friction coefficient were evaluated. The value of the static friction coefficient (blue line) is always higher than the relative dynamics (red line). The behaviour of wear versus the sliding distance is shown in Figure 10 for one of the inspected test pieces (PLA printed in 45° orientation by FDM method).

A number of measurements with the given materials have been carried out. For each material (printed with FDM and DLP technologies) and print orientation (horizontal, 45°, and vertical), three identical specimens were prepared and subjected to the same tribology test parameters. A comparison among the average results of the examined samples is exhibited in figures 11 and 12 concerning the static and dynamic friction coefficient, and the wear depth respectively.
In the current work, the materials that were used in the FDM and DLP 3D printing methods are the PLA filament (white and grey colours) and WANHAO resin (red colour) consecutively. In figure 11, the red column represents the maximum value of the dynamic friction coefficient, while the blue column is complemented by the maximum static friction coefficient measured during the experiment. It can be clearly seen that the static max value of the specimens printed in the X orientation (Horizontally) is greater than those of the other orientations. The highest value of the dynamic max friction coefficient was observed at the X oriented sample (printed with the FDM method) on an average about 0.79. Whereas the lowest is noticed at the test pieces printed with FDM in 45° angle orientation, averaging 0.49, representing a 38% difference in comparison with the greatest value. Regarding the static friction coefficient, the maximum value was 0.86 for DLP technique specimens in X orientation. While the minimum value was measured at FDM printed in 45° orientation on an average of 0.53, which also brings 38% difference between the highest and lowest static max values. The biggest variation between static and dynamic friction coefficient has been measured in DLP test specimens, which indicates the high tendency of these materials for the stick-slip phenomenon.

![Figure 11](image1.jpg)  **Figure 11.** Comparison of friction coefficient among tested specimens regarding print method and orientation

![Figure 12](image2.jpg)  **Figure 12.** Comparison among the average wear values of specimens concerning print method and orientation

The comparison among the average wear for the specimens printed with various methods and orientations is illustrated in figure 12. The values of average wear have been calculated from three identical specimens’ measurement. The maximum wear values belong to the specimens printed with DLP method. The highest measured wear is 0.0110 mm at the DLP X oriented samples. The smallest value was measured at the FDM specimens printed in 45° orientation with an average of 0.0103 mm. It is clear from Figures 11 and 12 that similar attitudes are observed between the behaviour of the coefficient of friction and wear among the tested samples regarding the rise and drop of the values.

### 3.2. Surface roughness measurements

Taking a glance by the naked eye on the samples printed using FDM and DLP methods, it is easy to realise the obvious difference in their surface roughness (see Figure 13). To study it accurately, surface roughness test was accomplished for the specimens manufactured in the three orientations (X, 45°, and Z) by both mentioned printing technologies. The measurements were examined from the upper side and the perimeter of each tested cylinder.

Figure 14 illustrates the values of the surface roughness ($R_a$). The surface roughness of the worn area after the tribology test (at the cylinder perimeter) was checked. It is apparent from the overall results that surface roughness of the worn area after the tribology test is much lower than other surfaces due to abrading the rough layers from the previous surface. Figure 15 (a) displays the R profile diagram of the most distinguished rough area which was recognised in the upper side of the 45°
oriented specimens fabricated by the FDM technology. While figure 15 (b) presents the R profile of the lowest surface roughness value that was measured in the upper side of the DLP samples printed at Z orientation.

**Figure 13.** Examined areas in surface roughness test

**Figure 14.** Comparison among the average surface roughness values in the tested specimens

**Figure 15.** R profile diagram of the highest and lowest surface roughness values

### 3.3. Surface morphology

**Figure 16.** Surface texture of the upper and lower faces in samples printed using FDM and DLP methods
The surface structure of the lower (the face that is in contact with the platform) and upper faces of the cylindrical test pieces which printed in FDM and DLP methods has been demonstrated in figure 16. In general, it can be clearly seen that DLP technology has displayed much more smooth surfaces than the FDM. The lower side of the FDM exhibited very rough texture due to the contact with the raft layer (the layer between the built sample and the platform of the 3D printer). Spaces among the lines have been revealed at the upper side which indicates the anisotropy of the FDM method. On the other hand, it is apparent that DLP specimens have demonstrated relatively smooth surfaces in comparison with the FDM. Resolidified materials were noticed with the DLP products which arise from the unremoved resin spots when cleaning by alcohol after the printing and then cured and resolidified during the postprocessing with UV light. The perimeter surface morphology of the FDM and DLP samples has been shown in Figures 17 and 18 respectively. The essential points related to the surface morphology of the perimeter were illustrated at the mentioned Figures. These Figures represent the surface structure before and after the tribology test for different oriented specimens (X, Z, and 45°).

**Figure 17.** Surface morphology of FDM specimens printed in X, 45°, and Z orientation before and after tribology test

**Figure 18.** Surface morphology of DLP specimens printed in X, 45°, and Z orientation before and after tribology test
4. Conclusions
In this research, the surface structure, tribological properties, and surface roughness of specimens fabricated using two of the 3D printing technologies (FDM and DLP) have been examined. With each method, three different orientations (X, 45°, and Z) as a print parameter were investigated. The tribological measurements were carried out under dry condition utilising cylindrical plane in the reciprocating tribotest system. The measured wear as well as the static and dynamic friction coefficient among the tested samples was compared. After evaluating the results, the following can be concluded:

- Altering the 3D printing method and the print options (particularly print orientation) has revealed a significant effect on the surface structure and the tribological properties of the manufactured objects;
- Concerning the surface roughness test, very smooth surfaces were observed for the bodies' printed utilising DLP technology in comparison with the FDM method;
- The specimens fabricated using DLP 3D printing method have shown a huge tendency to stick-slip phenomenon especially those who were built in 45° and Z orientations. While the parts printed in 45° orientation by the FDM technique has reflected the lowest trend for this phenomenon;
- The products which are made employing FDM technology is more appropriate for the tribological applications since the DLP samples exhibited considerable wear and friction values during the tribology test due to the fast surface melting behaviour of its materials.

For further work, studying the effect of changing other parameters and print settings on the surface morphology and tribological properties is worthwhile. In addition, different 3D printing technologies (not those used in this work) could also be involved in manufacturing the suggested objects.

Acknowledgements
This work was supported by the Stipendium Hungaricum Programme and by the Mechanical Engineering Doctoral School, Szent István University, Gödöllő, Hungary.

References
[1] Berman B 2012 3-D printing: The new industrial revolution Bus. Horiz. 55 pp.155-162
[2] Bhushan B and Caspers M 2017 An overview of additive manufacturing (3D printing) for microfabrication Microsyst. Technol. 23 pp.1117-1124
[3] Ngo T D, Kashani A, Imbalzano G, Nguyen K T Q, Hui D 2018 Additive manufacturing (3D printing): A review of materials, methods, applications and challenges Compos. Part B Eng. 143 pp.172-96
[4] Wu P, Wang J, Wang X 2016 A critical review of the use of 3-D printing in the construction industry Autom. Constr. 68 21-31
[5] Turner B, Strong R, Gold S 2014 A review of melt extrusion additive manufacturing processes: I. Process design and modeling Rapid Prototyp J. 20 pp.192-204
[6] Parandoush P and Lin D 2017 A review on additive manufacturing of polymer-fiber composites Compos. Struct. 182 pp.36-53
[7] Sun Q, Rizvi G M, Bellehumeur C T, Gu P 2008 Effect of processing conditions on the bonding quality of FDM polymer filaments Rapid Prototyp J. 14 pp.72-80
[8] Torrado A R, Shemelya C M, English J D, Lin Y, Wicker R B, Roberson D A 2015 Characterizing the effect of additives to ABS on the mechanical property anisotropy of specimens fabricated by material extrusion 3D printing Addit. Manuf. 6 pp.16-29
[9] Tymrak B M, Kreiger M, Pearce J M 2014 Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions Mater. Des. 58 pp.242-246
[10] Senatov F S, Niaza K V, Zadorozhnny Y M, Maksimkin A V, Kaloshkin S D, Estrin Y Z 2016 Mechanical properties and shape memory effect of 3D-printed PLA-based porous scaffolds
[11] WIJK A V and WIJK I V 2015 3D Printing with Biomaterials: Towards a Sustainable and Circular Economy (Amsterdam: IOS Press)

[12] Redwood B, Schöffer F, Garret B 2017 The 3D printing handbook : technologies, design and applications (3D Hubs B.V.)

[13] Stansbury J W and Idacavage M J 2016 3D printing with polymers: Challenges among expanding options and opportunities Dent. Mater. 32 pp.54-64

[14] Kolan K C, R, Leu M C, Hilmas G E, Brown R F, Velez M 2011 Fabrication of 13-93 bioactive glass scaffolds for bone tissue engineering using indirect selective laser sintering Biofabrication 3 025004

[15] Mironov V, Boland T, Trusk T, Forgacs G, Markwald R R 2003 Organ printing: computer-aided jet-based 3D tissue engineering Trends Biotechnol. 21 pp.157-161

[16] Lee J M, Zhang M, Yeong W Y 2016 Characterization and evaluation of 3D printed microfluidic chip for cell processing Microfluid Nanofluidics 20 5

[17] Invernizzi M, Natale G, Levi M, Turri S, Griffini G 2016 UV-Assisted 3D Printing of Glass and Carbon Fiber-Reinforced Dual-Cure Polymer Composites Materials (Basel) 9 583

[18] Zsidai L and Kalácska G 2014 “Stick-slip” PA és PEEK kompozitok sírlódásánál henger/sik modell vizsgálati rendszerben Műanyag és Gumi 51 pp.462-470