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THE EFFECTS OF INFILL PATTERNS ON THE MECHANICAL PROPERTIES OF 3D PRINTED PLA PARTS FABRICATED BY FDM

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Abstract. The purpose of this study is to analyze the effect of the infill pattern on the mechanical properties of 3D printed PLA parts. Polylactic acid (PLA) parts were fabricated by fused deposition modeling (FDM) at various infill patterns at 30% infill density. Five different infill patterns (stars, 3D honeycomb, honeycomb, gyroid, Hilbert curve) have been investigated. The results have shown that the honeycomb infill pattern exhibited the highest mechanical properties with 29.43 MPa and 2.04 mm elongation due to the improved strength of the strut junctions in this pattern. In the case of the Hilbert curve pattern, compared to the other patterns, though they have the same infill density, tensile strength was lowest because of the presence of large air gaps in the pattern that induced rapid fracture during the test. The optical microscope images of the fracture surfaces were compatible with the tensile strength results. Also considering the build time and the spent filament, it can be said that the honeycomb infill pattern is very promising. Lastly, the results showed that the tensile strength and elongation of 3D printed PLA parts increased 43.4% and 32%, respectively, under optimum infill pattern conditions. The findings of this study will help manufacturing firms and researchers to decide on the appropriate infill pattern, so that FDM parts can be fabricated with minimal production cost and good mechanical properties.

Keywords: fused deposition modeling, 3D printing, infill pattern, tensile strength, PLA.

Introduction

Additive manufacturing (AM) creates 3D parts by adding layer-upon-layer of material for a wide variety of industrial and other applications. Contrary to the traditional production technique in which the material is removed until the desired part is obtained, AM is used in variety applications in defense, aircraft, medical, automobile industries etc. There are many different AM techniques, including Stereolithography (SLA), Selective Laser Sintering (SLS) or Laminated Object Manufacturing (LOM), etc. Among these AM techniques, Fused Deposition Modeling (FDM) stands out and is frequently used around the world [1–3]. A wide variety of materials are available in the FDM technique which has low maintenance cost, low fabrication cost even for complex parts and is environmentally friendly [4]. G-codes files are generated directly from CAD files, usually in STL format. In this technique, parts are produced by adding layer upon layer of material until the shape of the part is formed. Filament is heated to a semi-liquid state and G-code controls the movement of the nozzle as shown in Fig. 1 [5].

Many process parameters in FDM have great influence on the component properties and production efficiencies. Layer thickness, raster angle, build orientation, infill density, printing speed, infill pattern, raster width, etc. can be listed as some of the important process parameters. Researchers are still working hard to obtain the best parameter settings. Hence, a deeper understanding of the FDM process is required to enhance the mechanical properties of the 3D printed PLA parts by setting optimal process parameters. Infill pattern is one of the key FDM process parameters and provides built-in support for the 3D print as the printer builds each layer. Therefore, different infill patterns have been examined by some researchers [1, 2]. Hedayati et al. [6] worked on octagonal honeycomb patterns. Mishra et al. [7] examined various infill patterns and found that line, zigzag and concentric showed improved energy absorption ability over other infill patterns. Srinivisan et al. [2] studied influence of the infill patterns such as grid, triangular, cubic on 3D printed PETG parts. Parab and Zaveri [8] investigated the effects of the infill on the compressive strength of 3D printed PLA parts. Aloyaydi et al. [9] and Dezaki et al. [10] investigated the effect of infill patterns (such as honeycomb, wiggle, grid, and rectilinear) on the mechanical properties of 3D printed parts. Studies on the effects of infill patterns in FDM process are ongoing. Because different patterns are able to provide better results for mechanical properties. Until now, little attention has been paid to the complex infill patterns in 3D printed PLA parts. Grid, rectilinear and triangular infill patterns are often chosen as infill patterns for the studies. Hence, this study tends to investigate the effect of different infill patterns (stars, 3D honeycomb, honeycomb, gyroid, Hilbert curve) on mechanical properties of 3D printed PLA parts. The findings of this study will help manufacturing firms and researchers to decide on the appropriate infill pattern, so that FDM parts can be fabricated with minimal production cost and good mechanical properties.

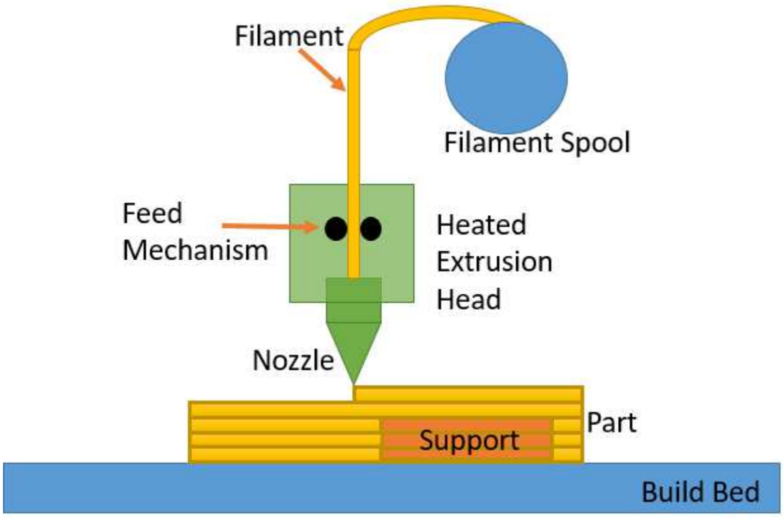


Fig. 1. Schematic diagram of FDM process

Experimental Approach

Material and method. 1.75 mm diameter commercial polylactic acid (PLA) filament was used as feedstock for a Creality Ender 3D Pro 3D Printer with 0.4 mm diameter nozzle, as shown in Fig. 2. The data of the samples were all in STL format and then translated into G-code sliced with slic3r. Slic3r is an open-source slicer software. In this study, infill pattern has been changed while preserving other parameters such as infill density, print speed, layer width, raster angle, build orientation, printing and bed temperature. The infill patterns selected for this study were stars, 3D honeycomb, honeycomb, gyroid, and Hilbert curve, shown in Figs. 3 (*a–e*) and 4 (*a–e*).

The parts were fabricated according to the American Society for Testing and Materials (ASTM) D638 type IV standard shown in Fig. 5. The dog bone type PLA parts were built (Fig. 6) according to the process parameters given in Table 1. Build time to produce the parts was taken from the 3D machine.

Table 1

Parameters of printer settings

Items	Value	Items	Value
Nozzle diameter (mm)	0.4	Infill Density (%)	30
Wall thickness (mm)	0.8	Printing Temperature (°C)	200
Layer height (mm)	0.2	Build Plate Temperature (°C)	60
Wall line count	3	Print Speed (mm/s)	60

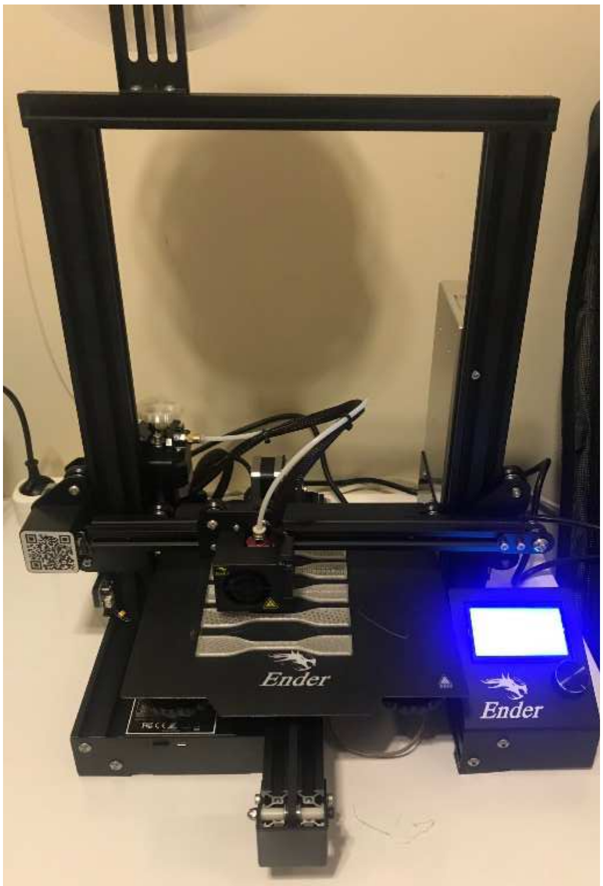


Fig. 2. Ender 3 pro 3D printer

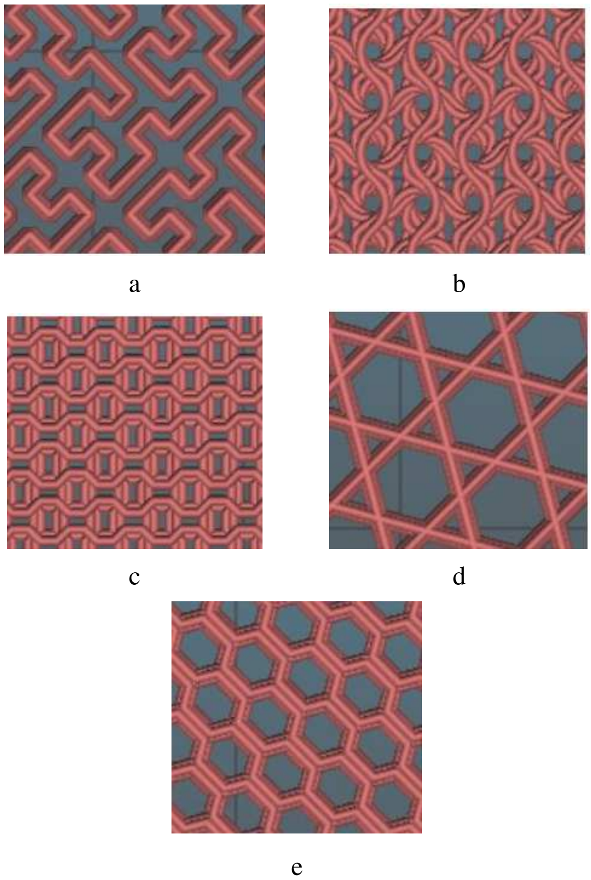


Fig. 3. Schematic diagram of infill pattern with infill density of 30%: a – Hilbert curve; b – gyroid; c – 3D honeycomb; d – stars; e – honeycomb

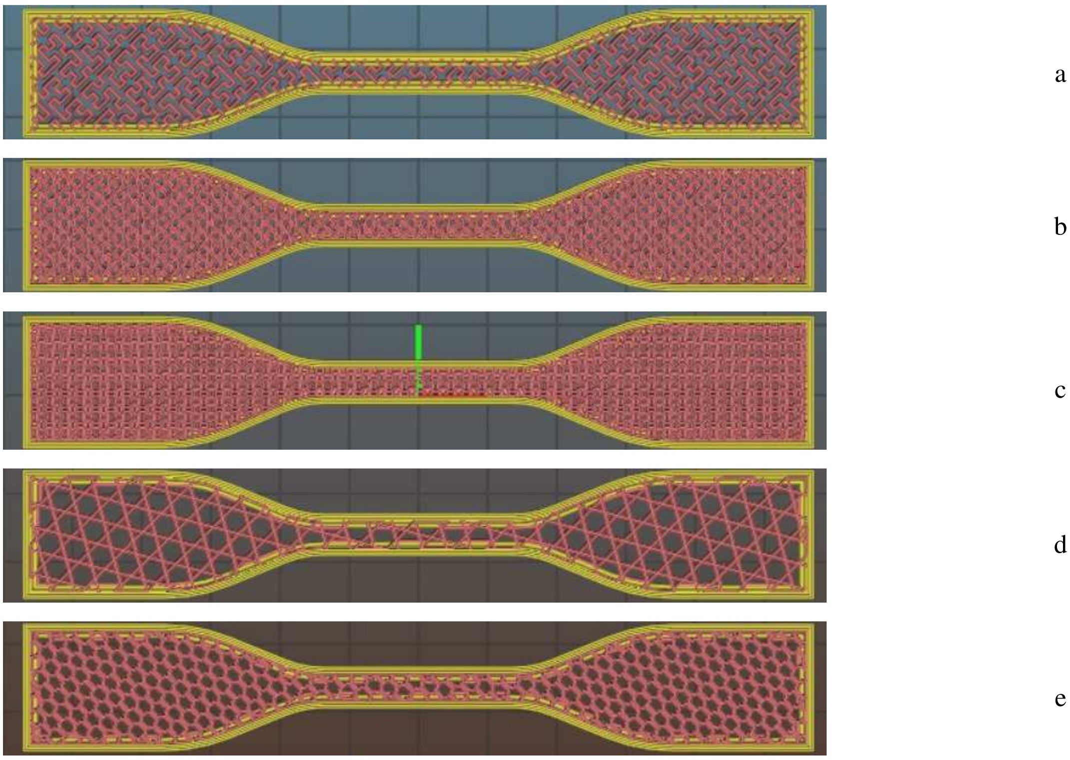


Fig. 4. Schematic diagram of FDM parts: a – Hilbert curve; b – gyroid; c – 3D honeycomb; d – stars; e – honeycomb

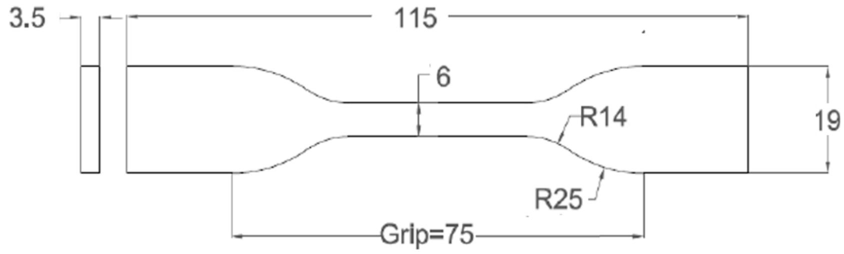


Fig. 5. CAD model of the specimen (dimensions in mm)

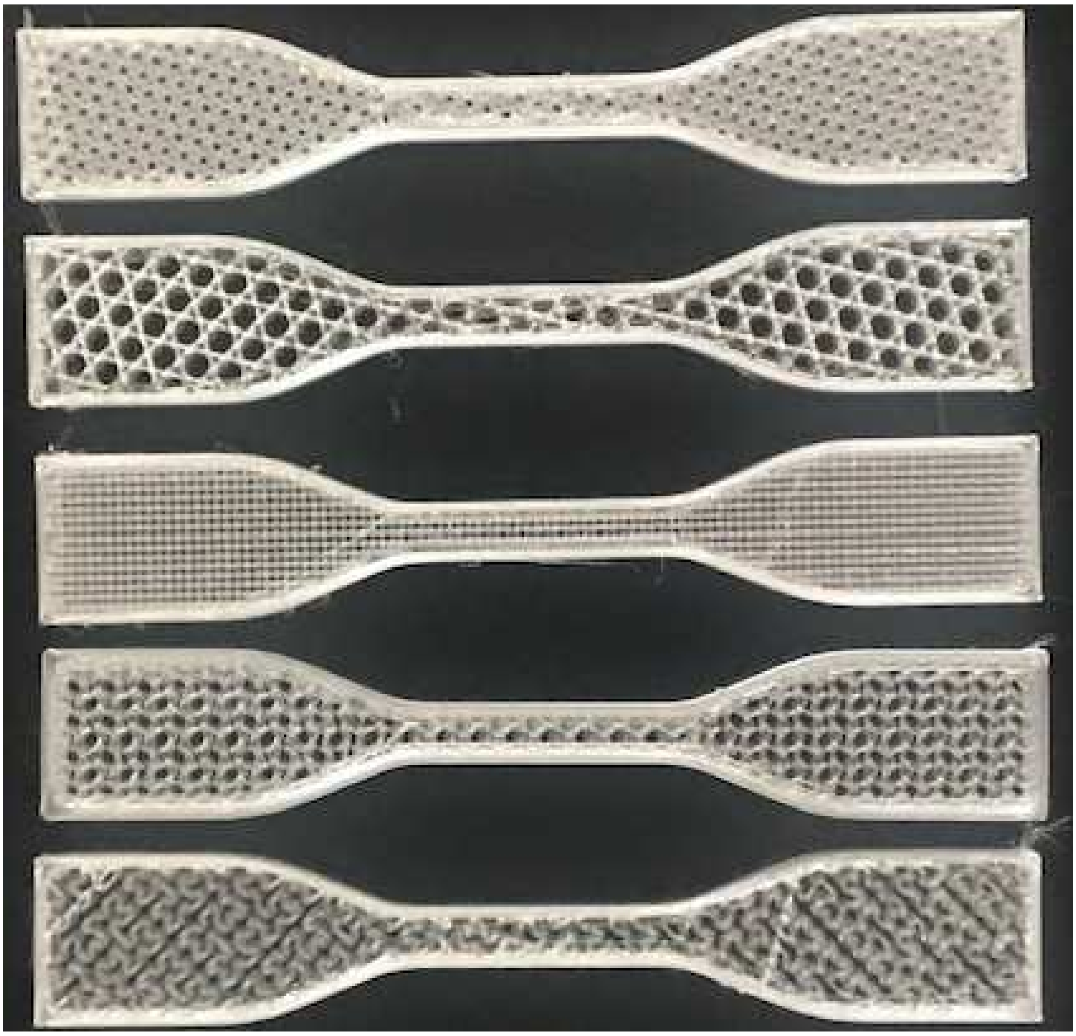


Fig. 6. Fabricated 3D printed PLA parts

The tensile strengths of the 3D printed PLA parts were examined on a universal testing machine, (Instron 8872) with a 25 kN load cell at a test speed of 1 mm/min at room temperature. The fracture surface morphologies of the samples were examined using Zeiss Axio Zoom.V16 optical microscope.

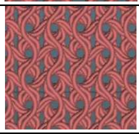
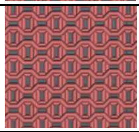
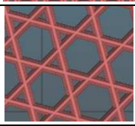
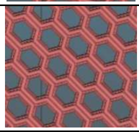
Results and Discussion

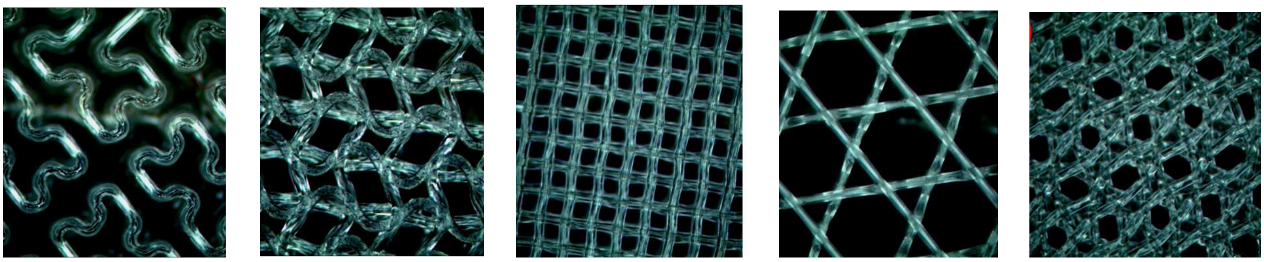
The optical microscope images of the infill patterns are shown in Fig. 7, and the tensile strengths of the specimens are listed in Fig. 8 and Table 2.

According to the results, under the same process parameters, in this study, honeycomb and 3D honeycomb gave better tensile strength as compared to others. Honeycomb and 3D honeycomb had 29.43 MPa and 26.35 MPa of tensile strength, respectively, while the rest of the patterns had tensile strength between 16–24 MPa (Table 2). This was because there was an enormous amount of short line segments in the honeycomb pattern [2]. It has been observed that the infill pattern in FDM part manufacturing seriously affects the mechanical strength. In the honeycomb pattern, a higher amount of struts junctions design behaved like columns and this increased the tensile strength of the parts [11, 12].

Table 2

Tensile strength, material weights, spent filament, build time according to infill patterns

	Patterns	Material Weights (g)	Build Time (sec)	Tensile Strength (MPa)	Elongation (mm)
Hilbert Curve		2.483	400	16.66	1.389
Gyroid		3.134	744	21.12	1.802
3D Honeycomb		3.245	765	26.35	1.834
Stars		3.086	497	24.09	1.528
Honeycomb		3.787	854	29.43	2.04



a b c d e

Fig. 7. Optical microscopic images of the infill of the 3D-printed parts: a – Hilbert curve; b – gyroid; c – 3D honeycomb; d – stars; e – honeycomb

Fig. 8 shows the stress-strain curve for various patterns. According to Fig. 8, the highest tensile strength and elongation were obtained for the honeycomb infill pattern (Fig. 7 *e*), while the lowest tensile strength and elongation were obtained for Hilbert Curve (Fig. 7 *a*) at 30% infill density. This showed that, infill patterns determine the influential cross-sectional area in the tensile direction and interlayer bonding strength of the 3D printed PLA parts, thereby affects the mechanical properties of the parts. it has been known that as the infill density increases, the air gaps in the parts decrease and the influential cross-sectional area increases. Thus, in the case of the Hilbert curve pattern as shown in Fig. 7 *a*, compared to the other patterns (Fig. 7 *b–e*), though they have the same infill density, tensile strength decreased because the solid cross-section of sample was minimum. Additionally, sharp bends were present in the Hilbert curve infill pattern that served as a concentrator stress region. The 3D printed PLA parts with Hilbert curve infill pattern were subjected to more stress because of the presence of stress concentration zones, resulting in less tensile strength and elongation compared to other infill patterns [2].

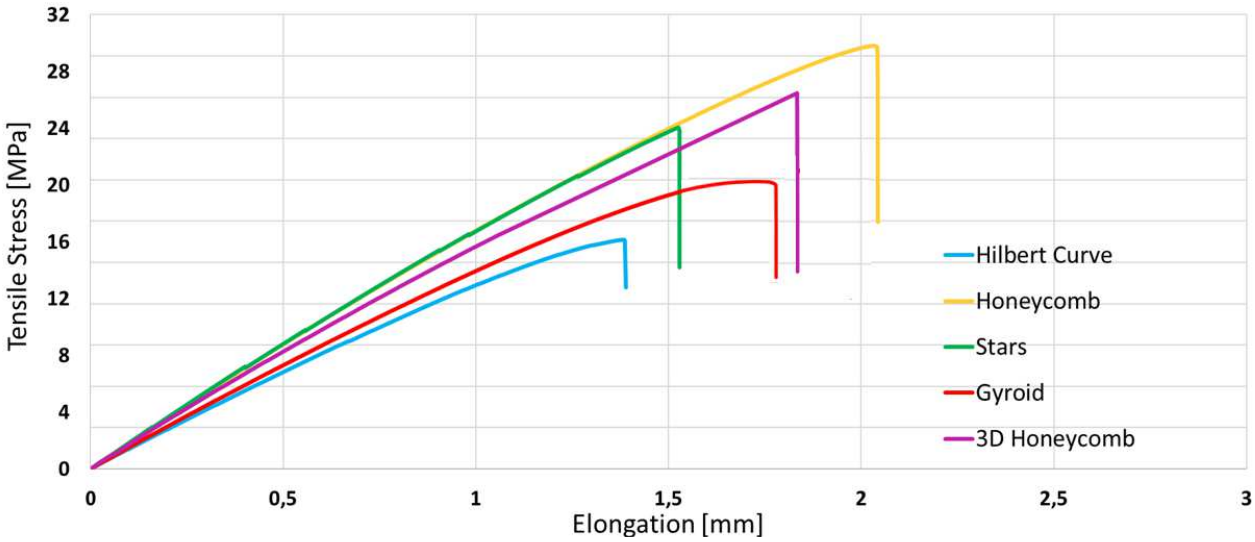


Fig. 8. Stress-Strain curve for various patterns at 30% infill density

For validation of obtained mechanical properties, it is important to examine the fracture of the 3D printed PLA parts after the tensile tests. Fig. 9 shows the optical microscopic images of the fractured surfaces. The reduction of mechanical properties was also attributed to the presence of air gaps in the Hilbert Curve pattern that induced rapid fracture during the test. As shown in Fig. 9, due to different infill patterns in the cross-sectional area of 3D printed PLA parts, the infill ratio of the cross-section area differs and causes a difference in mechanical properties [13, 14]. The presence of air gaps and layer bonding strength of 3D printed PLA parts could affect the mechanical properties [9]. In the case of the honeycomb infill pattern, air gaps in the 3D parts are reduced, allowing the material layers and filaments to bond more tightly and increase the resistance of the PLA molecular chain. Larger air gaps and delamination observed in Fig. 9 *a*, thus resulting in lower tensile strength. On the other hand, better adhesion between layers without delamination and less air gaps observed in Fig. 9 *e* which yielded the highest tensile strength by increasing the bonding area between layers.

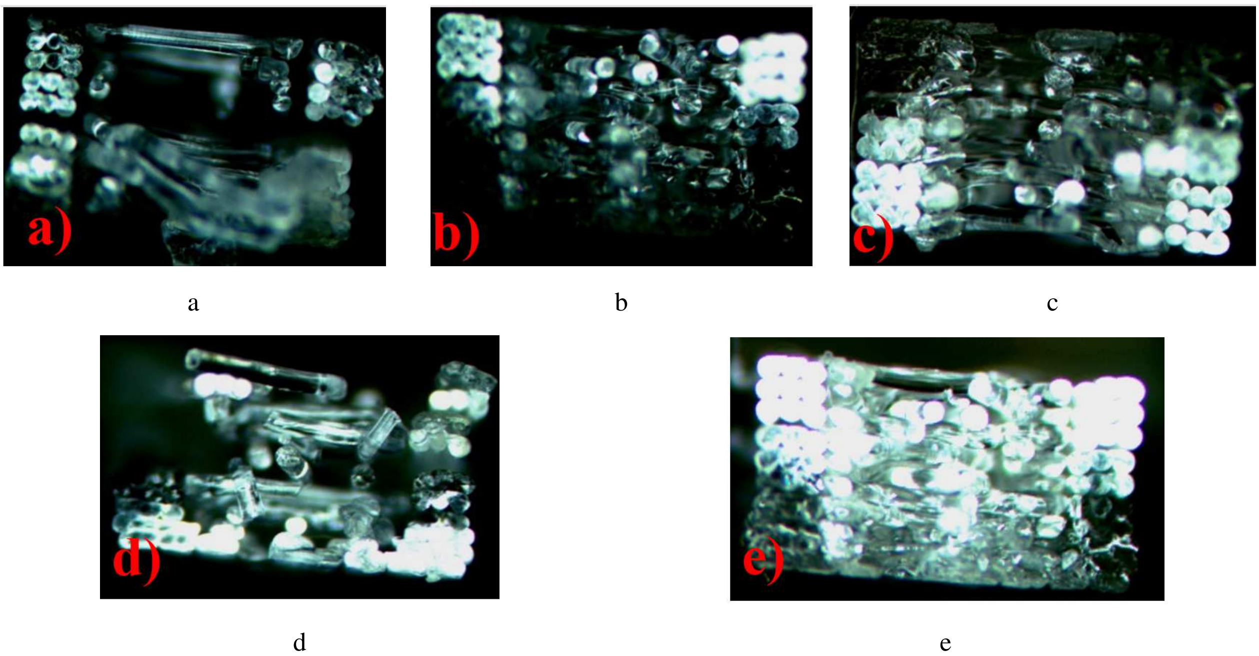


Fig. 8. Optical microscopic images of the fractured surfaces of different patterns: : a – Hilbert curve; b – gyroid; c – 3D honeycomb; d – stars; e – honeycomb (100x magnification)

Furthermore, it has been known that when the build time becomes longer, a higher amount of material is used, energy usage increases and this leads to higher energy costs [15]. Thus, considering the build time and the spent filament, it can be said that the honeycomb infill pattern is very promising with a tensile strength of 29.43 MPa, an elongation of 2.04 mm, a build time of 497 minutes and a filament spent of 1.29 m.

Conclusions

Polylactic acid 3D parts with different infill patterns with 30% infill density were fabricated by the FDM method. The pattern design has been found to have a serious impact on the mechanical strength of 3D printed PLA parts. It has been concluded that the honeycomb infill pattern gave the highest mechanical properties with 29.43 MPa and 2.04 mm elongation. This was due to the improved strength of the strut junctions in the honeycomb pattern. The tensile strengths were in agreement with the optical microscope images of the fracture surfaces. The infill pattern significantly affected the amount of air gap in the 3D printed parts. With the reduction of the air gaps, tensile strength was increased. Also considering the build time and the spent filament, it can be said that the honeycomb infill pattern is very promising. As a result, in this study 29.43 MPa of tensile strength could be achieved and this showed that, for future studies, enhanced mechanical properties of the 3D printed PLA parts would be achieved by the optimization of the infill pattern.

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