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Effect of Infill Patterns and Print Orientation on the Mechanical Properties of Manufactured Polylactic Acid Parts

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ABSTRACT
The fused deposition modeling (FDM) technique produces function models of various thermoplastic polymers and is one of the most commonly utilized additive manufacturing (AM) technologies. The purpose of this research is to study how combining infill pattern (CIP) and printing orientation affects tensile characteristics and building time. Polylactic acid (PLA) was chosen as a material for the specimen's fabrication. The print orientations were the on-long-edge and flat orientations. Because the product is built along the z-axis, the short-edge (up-right) orientation was not considered, resulting in minimal strength. The combinations of the infill patterns called Concentric, Cross, Triangle, Zigzag, Rectilinear, Cubic, Honeycomb, and Grid were investigated with 70% infill density and 0.15 mm layer thickness with a layer-by-layer strategy. The result indicates that the printing orientation significantly affected the tensile strength, especially in CIP specimens. The on-long edge orientation of the CIP specimen had higher tensile strength. The specimen Concentric/Triangle has the highest tensile strength in flat and on-long edge orientations of 30 MPa and 33 MPa, respectively. Still, the building time in flat orientation was long (25 min.) while the printing time in on-long orientation was short (29 min.). The honeycomb/Triangle combination represents lower tensile strength in both orientations of 19 MPa for flat and 20 MPa for on-long edge, but the building time in both orientations was long (14 min and 35 min, respectively). As a result, the specimen with the CIP has greater tensile strength than the single-infill pattern specimen. It was additionally found that when the Triangular pattern was combined with other patterns, the tensile strength of those patterns improved. CIP specimens built in an on-edge orientation had a higher tensile strength than those built in a flat orientation. In the triangle infill pattern, when combined with other patterns, the tensile strength of some samples enhanced while the others improved, while others decreased.

Keywords: Fused deposition modeling (FDM), additive manufacturing (AM), Polylactic acid (PLA), layer-by-layer, printing orientation, Combined infill patterns (CIP), build orientation.

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Introduction

The additive manufacturing (AM) techniques are known as three-dimensional printing (3DP) technology. This method produces 3D objects with lightweight and complicated structures [1]. 3D printers have been used in various applications in recent years such as architectural configurations, prototype manufacturing, and medical applications. The AM techniques include FDM, digital light processing, laminated object manufacturing, and stereo lithography which depend on the material's types, the production tolerances, and the product's application [2]. The main disadvantage of these techniques is their longer production time and low part strength compared to other traditional manufacturing techniques. That is why they cannot be used for mass production. FDM technology is one of the greenest and most economical 3D printing processes since it produces functional prototypes that use different thermoplastic filaments as a starting material [3]. There are various types of thermoplastic filaments such as Acrylonitrile Butadiene Styrene (ABS), Polylactic acid (PLA), Nylon, Thermoplastic elastomer (TPE), High-Impact Polystyrene (HIPS), polypropylene (PP), and other thermoplastic polymer materials are available for

FDM method for different purposes. These filaments have been used as synthetic polymer components due to their processability, mechanical flexibility, physicochemical capabilities, and ability to withstand significant deformations [4]. In this way, the filaments are heated in the nozzle and are then dispensed on the printing plate layer-by-layer to produce the desired 3D structure [5]. This enables the manufacturing of complex products that are difficult to be modeled by subtractive processes. Such techniques are now used in industries to shorten the time and cost involved in product development [[6], [7]]. However, the FDM draws some significant disadvantages including poor mechanical qualities, surface finish, and inferior dimensional quality [8]. The quality of the product is attributed to process parameters such as layer thickness, infill pattern, infill density, nozzle temperature, build orientation, print speed, and raster angle [9]. Notably, various works studied the FDM specimen properties in association with the parameters of the printing process [10]. Chacon et al. investigated the impact of layer thickness, building orientations, and rate of feed on the PLA specimens' tensile strength with the FDM process [11]. They found that as the layer thickness of the specimen decreased, the resulting strength increased, while the strength varied significantly for the sample with a flat orientation. In addition, Durgun et al. explored the improvement of production cost and mechanical properties for the FDM process [12]. It had been concluded that the build orientation had a greater impact on surface roughness and the ABS polymer's strength than the raster orientations. Aloyaydi et al. studied how infill patterns affect FDM parts' compression strength [13]. The Grid type pattern showed the greatest compressive strength, while the Triangular pattern had higher impact energy. Further, Mishra et al. investigated the influence of FDM printing variables and the thickness of layers on the strength [14]. It was found that the strength of FDM parts increases as the wall layer increases. The influence of printing variables such as the air gap and raster angle on FDM's specimen strength has been examined by Ahn et al. [15]. They discovered that the air gap and raster angle significantly affect the strength. Wang et al. studied the PLA specimen's mechanical properties under various printing parameters using the 3D-printing process [16]. They concluded that the height of the layer influences the layer bonding of 3D-printed samples' strength. Yang et al. investigated five printing parameters to find out their effect on building time, strength, and surface roughness utilizing the analysis of variance test (ANOVA) [17]. They showed that the layer thickness and the nozzle diameter had the most impact on tensile strength and surface roughness. Sukindar et al. examined the nozzle diameter and the impact of pressure drop on product quality by comparing different extruder angles and diameters using finite element analysis (FEA) and testing procedures. In their work, the low strength in FDM-printed samples is considered a drawback that results from poor layer binding [18]. In addition, poor adhesion between layers is caused by temperatures or parameters that are not optimized. Furthermore, Moradi et al. worked on 3D-printed Honeycomb internal pattern samples with FDM technology [19]. Compared with other infill patterns, Honeycomb patterns showed a higher mechanical resistance. Besides, Akhoundi et al. examined the effect of binding and adhesion after printing, regarding various patterns such as concentric, rectilinear, Honeycomb, and Hilbert curves, on the strength of the final product [20]. The research focused on the infill pattern and infill percentage of 3D-printed PLA parts. Accordingly, Hanon et al. investigated the strength of PETG (polyethylene terephthalate-glycol) and PLA, comparing the two materials in a variety of building orientations (from +45° to -45°) using Honeycomb and Straight patterns [21]. Better elongation results were indicated by PETG which enhances the highest tensile strength possible value in Y orientation with a 0° raster direction. Also, they improve the flexural rigidity by decreasing its value below 10%. Moreover, Samykano et al. analyzed the parameters of the FDM utilizing an improved mathematical model [22]. Their findings indicated that the optimized parameters for ABS material were 80% density, 65° raster angle, and 0.5 mm thickness of layer. Li et al. proved that layer height is the main factor influencing the strength of bonding, followed by deposition velocity [23]. It was noticed that the infill rate has a negligible effect. The mechanical characteristics of the FDM parts employing standard laminate theory were explored by Casavola et al. [24]. Both Young's modulus and Ultimate Tensile Strength (UTS) decreased when the raster's angle increased from 0° to 90°, while samples at 45° showed mediate mechanical behaviors. Studying the effect of the raster angle on the strength, Rajpurohit et al. verified that a lower layer height and a 0° raster angle provide higher strength [25]. As well as the tensile strength increased as the raster width increased up to a point at which the tensile strength decreased. In the same manner, Dave et al. noticed higher tensile strength of samples that were built into on-long edge and flat orientations with rectilinear and concentric infill patterns as compared to upright orientations [26]. Also, they confirmed that parts with Hilbert's curve infill patterns performed improved when oriented along the short edge compared to the long edge. In comparison with the strength of ABS monofilaments, Rodrigues et al. viewed degradation in the FDM specimens' strength due to the existence of losses and void of molecule's orientation throughout the extrusion procedure [27]. However, Lederle et al. performed material extrusion in an inert gas atmosphere and found that both ABS and nylon copolymer materials had been mechanically enhanced [28]. Utilizing different materials, Wu et al. compared various parameters of a specific material with those of the ABS specimen [29]. They utilized the polyether-ether-ketone (PEEK) specimens to be examined. The results ensure that the PEEK had good strength performance comparable with the ABS specimen as it recorded 114% higher compressive strength, 115% higher bending strength, and 108% higher tensile strength. Ziemian et al. reported greater fatigue life for 0° and + 45°/− 45° raster orientations under tension-tension fatigue testing when compared to transverse (90°) and diagonal (45°) raster orientation [30]. Witkin et al. investigated how the building orientations affected the thermal and mechanical properties of polyetherimide (ULTEM) specimens that were printed using FDM and found that the thermal expansion coefficient varied according to the orientation [31]. Alvarez et al. found that for hexagonal infill patterns, infill percentages ranging from 50% to 98% resulted in longer printing times and lower tensile strength [32]. Furthermore, Shih et al. found that PLA specimens, which were treated with cold plasma, had a higher strength of interlayer bonding than PLA samples that were left untreated. They also observed that the bonding strength had been adversely affected by the treatment time [33]. Lee et al. examined forced air cooling's effects on PLA specimens manufactured [34]. They concluded that using the FDM method and at greater airflow velocities conditions (5 m/s), a trade-off between the dimensional quality and the strength had occurred since the dimensional quality was improved while the mechanical strength was decreased. Bin Ishak et al. used material deposition for various building orientations in a single product in several planes [35]. For the upright printed samples, they observed developments in yield strength, modulus of elasticity, and (UTS). Currently, research has been presented about the impact of the combined infill pattern on the mechanical behavior of parts. In this line, Mohd Ariffin et al. combined (MIP) multiple infill patterns in a sample with different build orientations and found the effect on mechanical properties, as shown in Fig. 1 [36]. To design the patterns, they used CAD software which indicated that the FDM process was unable to combine patterns on its own. As a result, the Grid and Honeycomb patterns have the maximum ultimate tensile strength with the lightest weights, while the build orientation had significant effects on the mechanical characteristics.

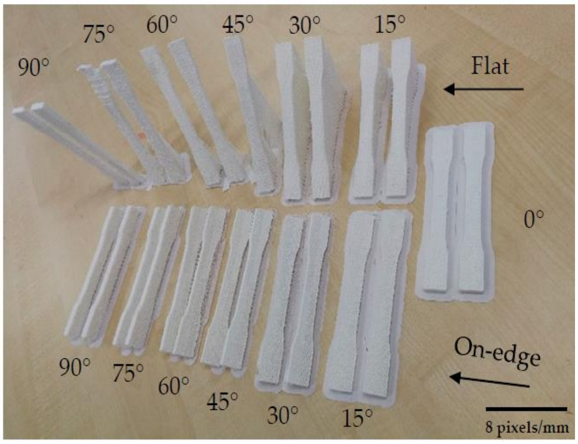


Fig. 1 - Set of classified layers and 3DP printed PLA samples

Similarly, Patel et al. studied the part's ultimate tensile strength with a combined infill pattern with different infill densities, and sequences of layer staking for various raster's orientations using the FDM technique, as shown in Fig. 2 [37]. While compared to single infill pattern samples, the results showed that the arrangements of combined infill and stacking of layer had a significant impact on the strength for the 45° raster's orientation.

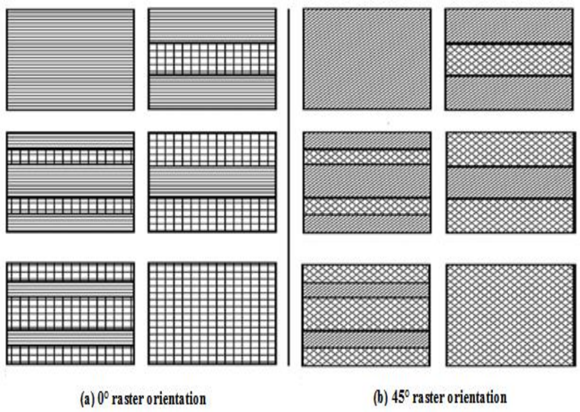


Fig. 2 - Various staking of layers for different infill densities and raster orientations.

However, Roger et al. used topological optimization in such a way the structural design of the 3D-built printed parts had been optimized, as shown in Figs. 3 and 4 [38]. They combined the heterogeneous infill types while printing the sample using the FDM technique to achieve their targeted properties.

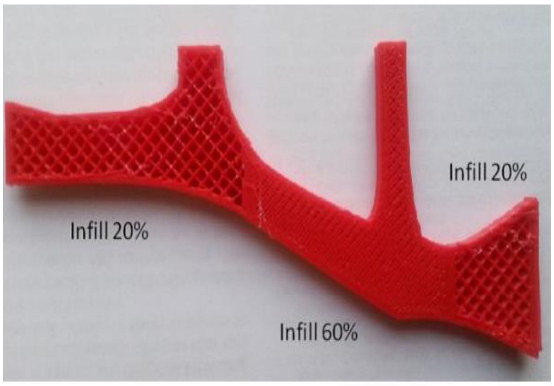


Fig. 3 - Inner rectilinear filling of the optimized structure with different densities

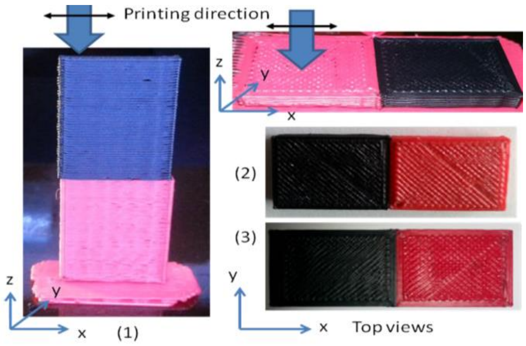
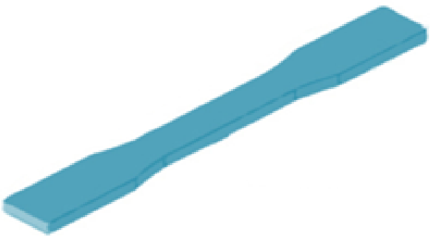
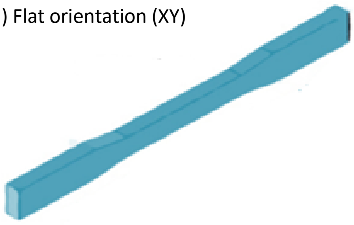


Fig. 4 - Bimaterial samples: (1) vertical printing, (2) horizontal printing with side-by-side parts, and (3) horizontal printing with side-by-side and interpenetrated layers at the interface



(a) Flat orientation (XY)

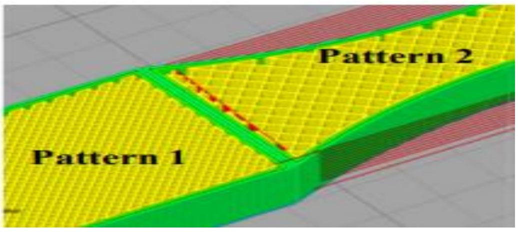


(b) On-long orientation (ZX)

Fig. 5 - 3DP printed tensile parts with different build orientations

Moreover, Naik et al. investigated the effects of raster angles on the UTS of multiple infill patterns (MIP) items produced with the FDM technique (Fig.5) [39]. The findings indicated that single-infill pattern samples had less tensile strength than MIP parts. Also, they found that MIP parts built-in on long orientation had high UTS/mass ratios and UTS.

Finally, Sajjad, R et al. examined the influence of combined infill strategies on the structural strength of single-build samples using FDM technology, as shown in Fig. 6 [3]. The experimental results have shown that the combinations of triangular and rectangular patterns led to 20%, 13%, 27%, and 4% increments in ratio of strength-to-weight compared with Triangular type, Rectilinear type, Rectangular type, and Honeycomb type single infill, respectively. In addition, along with minimal production cost, the rectangular infill combination with the Triangle patterns possessed the optimum strength-to-weight ratio.



Individual infills	Possible combinations of filling patterns			
	Pattern 1	Pattern 2	Pattern 1	Pattern 2
Rectilinear	Rectilinear	Honeycomb	Honeycomb	Rectilinear
Triangle	Triangle	Rectangular	Rectangular	Triangle
Rectangular	Triangle	Honeycomb	Honeycomb	Triangle
Honeycomb	Rectangular	Honeycomb	Honeycomb	Rectangular

Fig. 6 - Printing of combinations of chosen infill patterns with various types of infill patterns

To the best of the author's knowledge, few studies have been accomplished on the effect of the combined infill patterns and some printing variables like building orientation on the tensile properties and 3D printing time of FDM products. There are requirements for a study on the effect of single and CIP on the tensile properties of FDM-printed PLA parts. Hence, in this study, experimental investigations were carried out to understand the impact of a CIP at different building orientations and infill patterns on the strength of FDM-printed PLA parts. To fabricate the specimens, a customized G-code file was prepared to print CIP specimens, and the uniaxial tensile tests were carried out to investigate mechanical responses in terms of tensile strength. It was noticed that the tensile strength for some CIP specimens has been increased as well as the printing time has been decreased.

Experimental part

FDM-based printer and material

In this study, an open-source 3DP with the FDM technique was utilized for the samples' fabrication. The 3D printer had a print-bed of 500 × 500 × 500 mm^3. As shown in Fig. 7, the 3D printer may use several different thermoplastic materials such as PLA, ABS, and PEEK. In our work, the PLA material was selected because of its high modulus and strength. Also, the manufacturer specifications of the PLA filament and the 3DP parameters are presented in Table 1 and Table 2.

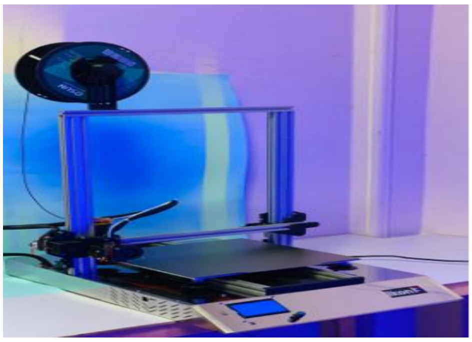


Fig.7 - Open source FDM 3D printer

Table 1 - PLA material properties by the manufacturer

Description	Typical value
Filament diameter	1.75 mm
Tensile Strength at Yield	65 MPa
Flexural modulus	2102 MPa
Flexural strength	75 MPa
Elongation at break	12 %
Density	1.25 g/cm^3
Printing temperature	205-225 ˚C
Melting temperature	115 ± 35 ˚C

Table 2 - Main printing parameters of the 3DP machine

Description	Value
Nozzle diameter	0.4 mm
Layer height	0.15 mm
Wall thickness	0.7 mm
Infill density	100 %
Print speed	60 mm/s
Printing temperature	200 ˚C
Build plate temperature	60 ˚C
Line width	0.35 mm

Experimental design for fabrication of specimens

Print orientations are the most significant process parameters affecting the quality of CIP products, among other printing parameters. The CIP specimens were designed and fabricated as dog bone shapes according to the ASTM D638 standard for tensile test measurement, as shown in Fig. 8. The build orientations of the part are defined by placing the specimen models concerning the x-axis. There were two print orientations were considered (flat and on-edge) with 70% infill density and 0.15 mm layer thickness using the layer-by-layer (LBL) printing strategy, as shown in Fig. 9. Since the part in the upright orientation is built along the z-axis, resulting in the minimum strength, this orientation was not considered. The CIP models were created using the Cura 3DP software, version 5.1.0, as shown in Fig 10. It consists of different layers of single infill patterns, which involve Concentric, Cross, Triangle, Zigzag, Rectilinear, Cubic, Honeycomb, and Grid pattern types, respectively, as shown in Fig 11.

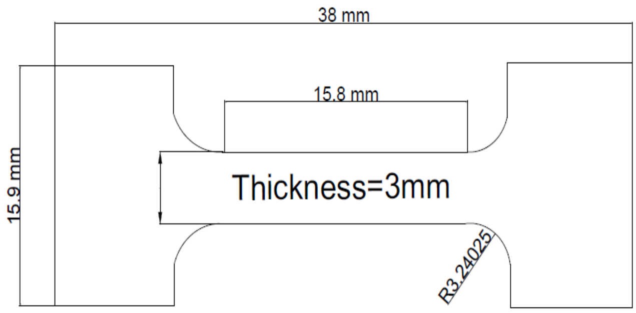


Fig.8 - Tensile specimen with dog bone shape (Dimensions were in mm)

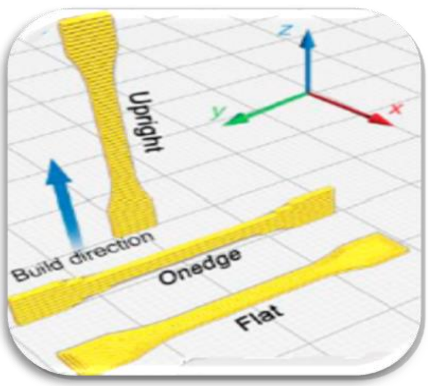


Fig. 9 - 3D-printed tensile specimens with different orientations

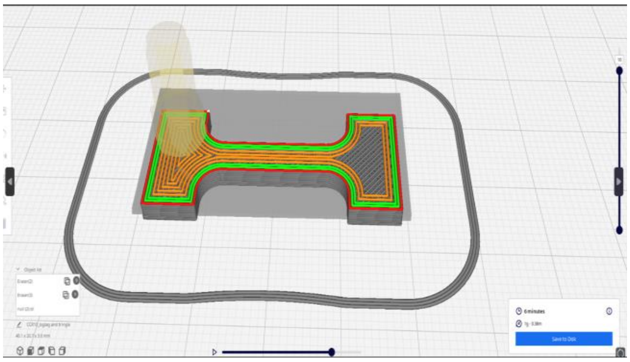


Fig. 10 - FDM 3D printer on Cura software

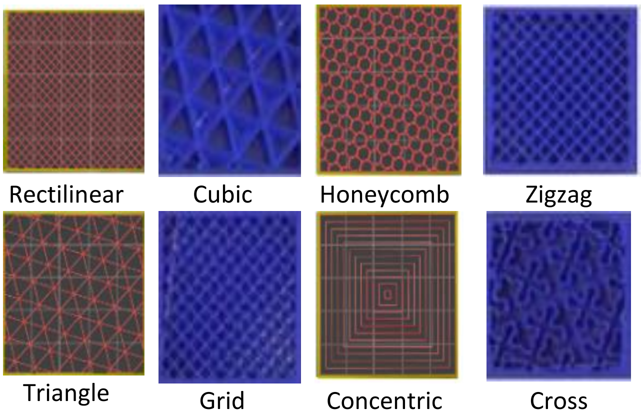


Fig. 11 - Infill patterns of the 3D printed PLA

Specimen fabrications

Based on the ASTM D638 standard, 3D models of the tensile specimen were designed in Solid Works. The models are exported in STL files format and transferred to the slicer software, where the whole cross-sections of the 3D models are converted to individual layers of a specific layer thickness with the adjustment of the process parameters then the files are exported in G-Code format which is assigned to a 3DP using PLA filaments. By considering CIP, the shell feature is used for printing the boundary of the parts, while for the inner sections.

Tensile test

Each specimen is tested using a Zwick/Roell Z010 tensile testing machine by the ASTM D638 standard; this machine is shown in Fig. 12. This machine has a load cell that can measure loads up to 10 kN. Additionally, it has built-in software that enables the recording, control of measured data, and monitoring. Between the two jigs, the tensile specimen (a dog bone) is gripped and tightened. To monitor and record the material deformation until the specimen fractures, the speed's crosshead is retained at 2 mm/min during the entire test. After that, the test is stopped, and the crosshead motion resumes, returning to its starting point. Through the data acquisition system, data test is collected from the software. The 3D-printed dog-bone specimens after mechanical testing are shown in Fig. 13.

Fig. 12 - 3D printed dog-bone specimens during testing using mechanical testing machine Zwick/ Roell Z010 according to ASTM D638.

Fig. 13 - The fractured 3D printed dog-bone specimens after testing using mechanical testing machine Zwick/ Roell Z010 according to ASTM D638

Results and Discussion

Results

In the present work, investigations were carried out to study the tensile behavior of CIP printed parts of different orientations. All of the experiments are carried out by the previously discussed experimental design and tested. In this section, the results obtained through the tensile test of the FDM samples with CIP are discussed.

Effect of the combined infill patterns and printing orientation on tensile strength

For studying the effect of the combined infill pattern on the strength and printing or building time of PLA samples, four samples were printed as a single infill pattern (Concentric, Cross, Triangle, and Zigzag), and then each two types of these patterns were combined. The six combined samples (Concentric/Cross, Concentric/Triangle, Concentric/Zigzag, Cross/Triangle, Cross/Zigzag, and Triangle/Zigzag) were obtained via the layer-by-layer printing strategy, which means layer infill type by layer of different infill types with flat and on-long edge orientations. Table 3 and Table 4 represent the results of tensile strength for different orientations of single and combined infill patterns. It was noted that the Triangle pattern improved significantly the strength of the sample. Thus, four other different patterns (Rectilinear, Cubic, Honeycomb, and Grid) were printed and combined with the Triangle pattern. Accordingly, four combined samples were obtained (Rectilinear/Triangle, Cubic/Triangle, Honeycomb/Triangle, and Grid/Triangle), and the effect of the Triangle pattern after combining them with on the tensile strength was studied as presented in Table 5.

Table 3 - Tensile strength of PLA samples printed with different types of single infill patterns

Infill type	Tensile strength (MPa)	
	Flat	On-long edge
Concentric	21	31
Triangle	25	28
Cross	15	25
Zigzag	29	30
Grid	10	25
Cubic	10	26
Honeycomb	12	29
Rectilinear	15	32

Table 4 - Tensile strength of combined PLA samples using different infill patterns

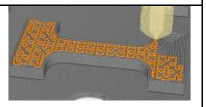
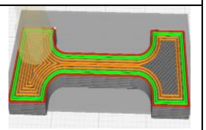
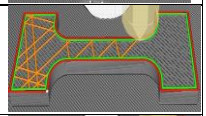
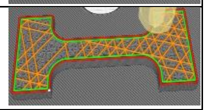
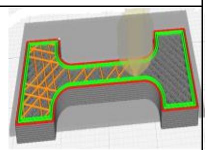
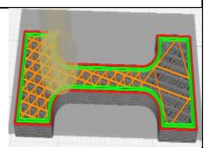
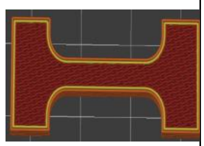
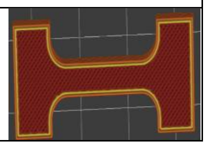
Combined infill type	Tensile strength (MPa)		3D printing infill
	Flat	On-long	
Concentric /Cross	25	28	
Concentric /Zigzag	27	30	
Concentric /Triangle	30	33	
Triangle /Zigzag	22	31	
Triangle / Cross	23	29	
Cross / Zigzag	26	27	

Table 5 - Tensile strength of PLA samples printed with Triangle pattern combined with different infill patterns

Combined infill type	Tensile strength (MPa)		3D printing infill
	Flat	On-long	
Triangle / Grid	21	24	
Triangle /Cubic	26	30	
Triangle /Honeycomb	19	20	
Triangle /Rectilinear	23	24	

On the other hand, Fig. 14 shows the effect of different types of single infill patterns on the tensile strength of the PLA-printed samples at different orientations. In the case of the on-long orientation, a higher strength is observed for all samples than for the other orientations. It is obvious that in the on-long edge orientation of the PLA samples printed with the single pattern, the Rectilinear infill pattern possessed the highest tensile strength (32 MPa), while in the flat orientation of the single pattern, the Zigzag pattern possessed the highest tensile strength (29 MPa), as shown in Fig. 14. On the other hand, the effect of different types of combined infill patterns on the tensile strength of the PLA-printed samples at different orientations is shown in Fig. 15. It was found that when some different patterns were combined, the strength of both infill patterns increased, such as Concentric/Triangle, Cubic/Triangle, and Concentric/Cross in the flat orientations, and Concentric/Triangle, Zigzag/Triangle, Cubic/Triangle, and Cross/Triangle in the on-long orientations. It was also found that the pattern that has high strength improves the pattern that has low strength when combining them, such as Concentric/Triangle, Concentric/Cross, Concentric/Zigzag, Cross/Zigzag, Cross/Triangle, Rectilinear/Triangle, Honeycomb/Triangle, Grid/Triangle, and Cubic/Triangle samples in flat orientations and Concentric/Triangle, Zigzag/Triangle, cubic/Triangle, Concentric/Cross, and Cross/Zigzag in on-long orientations, as shown in Fig. 15. It was also noted that when the Triangle infill pattern was combined with some patterns, some patterns improved while others decreased the tensile of the sample, as it was in Zigzag/Triangle with flat orientations and Grid/Triangle, Honeycomb/Triangle, and Rectilinear/Triangle with on-long orientation, as shown in Fig. 16.

Effect of the infill patterns and printing orientation on the building time of the PLA samples

Building time is an important parameter for the production of 3D-printed materials in industry. In this regard, the impact of printing orientations and the infill pattern of the FDM part on the building time was studied. Tables 6, 7, and 8 represent the results of the building time test for different orientations of single and combined infill patterns.

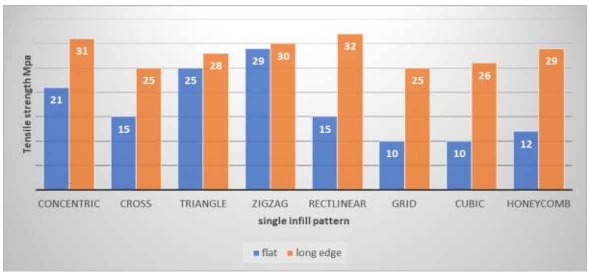


Fig. 14 - Effect of printing orientation on the tensile strength of PLA samples printed with different types of single infill patterns

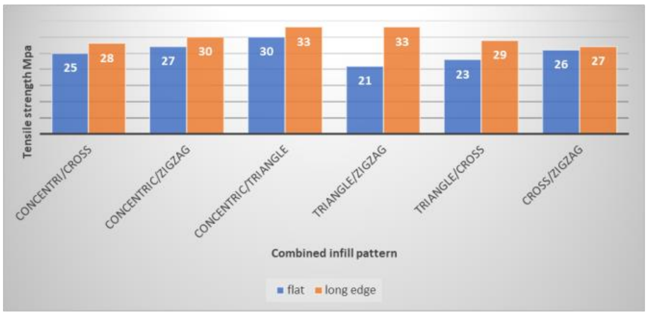


Fig. 15 - Effect of printing orientation on the tensile strength of PLA samples printed with different types of combined infill patterns

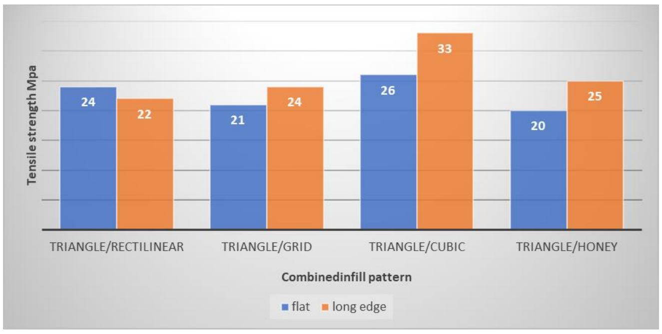


Fig. 16 - Effect of printing orientation on the tensile strength of PLA samples printed with Triangle combined with different types of infill patterns

Table 6 - Building time (min) of single PLA samples using different infill patterns printed orientation

Infill type	Building time (min)	
	Flat	On-long edge
Concentric	20	32
Triangle	18	31
Cross	22	33
Zigzag	18	30
Grid	13	25
Cubic	15	26
Honeycomb	12	29
Rectilinear	15	25

Table 7 - Building time (min) of combined PLA samples using different infill patterns printed orientation

Infill type	Building time (min)	
	Flat	On-long edge
Concentric/Cross	25	30
Concentric/Zigzag	26	28
Concentric/Triangle	25	29
Triangle/Zigzag	18	31
Cross/Triangle	20	32
Zigzag/Cross	17	32

Table 8 - Building time (min) of combined PLA samples using Triangle with different infill patterns printed orientation

Infill type	Building time (min)	
	Flat	On-long edge
Triangle/Grid	12	35
Triangle/Cubic	12	29
Triangle/Honeycomb	14	35
Triangle/Rectilinear	13	36

In the case of on-long orientation, a longer printing time is observed for all samples than for the other orientations. As seen from Fig. 17, for single infill patterns in the flat orientation, the Cross pattern had a longer time and the Honeycomb had a shorter time in the on-long orientation. As shown in Figs. 18 and 19, for the combined pattern, the Concentric/Zigzag pattern had a longer time in the flat orientation and Triangle/Rectilinear in the on-long orientation. Here it is interesting to note that there are samples that, when combined, the building time less than printing them individually, such as Concentric/cross, Concentric/Zigzag, Concentric/Triangle, Zigzag/Triangle, Cross/Triangle, and in on-long orientation, and Zigzag/Cross, Cubic/Triangle, Rectilinear/Triangle, and Grid/Triangle in flat orientation.

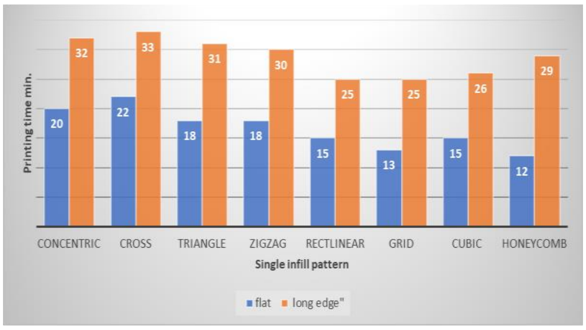


Fig. 17 - Effect of printing orientation of different single infill patterns on the building time of the PLA printed samples

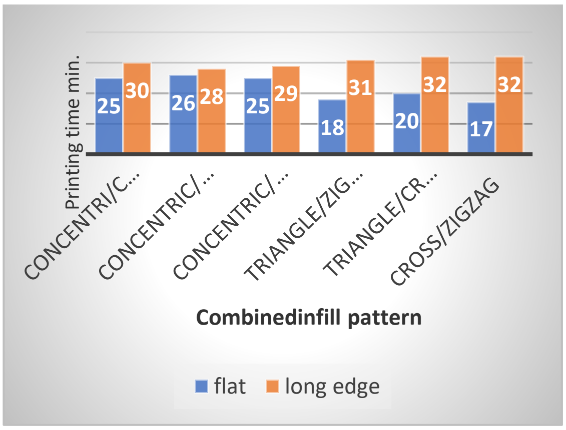


Fig. 18 - Effect of printing orientation of different combined infill patterns on the building time of the PLA printed samples

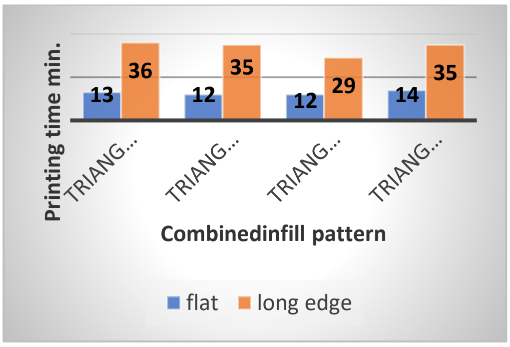


Fig. 19 - Effect of printing orientation of Triangle with different types of infill patterns on the building time of the PLA printed samples

Discussion

After deep research, it was found that not much research has been accomplished on the effect of the combined infill patterns and some printing variables like building orientation on the tensile properties and 3D printing time of FDM products. There are requirements for a study on the effect of single and CIP on the tensile properties of FDM-printed PLA parts. Hence, in this study, experimental investigations were carried out to understand the impact of a CIP at different building orientations and infill patterns on the strength of FDM-printed PLA parts.

In the case of the on-long orientation, a higher strength is observed for all samples than for the flat orientation due to vertically stacked layers and these layers are perpendicular to the applied force during the tensile test and have good adhesion of layers because each layer acts as a reinforcing element for the layers below and above it additionally it provides better structural integrity. In flat orientation, the applied force is parallel to the layers leading to weaker interlayer bonding, and interlayer boundaries may act as stress concentrators, making failure of the product.

In the on-long edge orientation of the single pattern, the Rectilinear infill pattern possessed the highest tensile strength because it offers good structural integrity and efficient material usage.

While in the flat orientation of the single pattern, the Zigzag pattern possessed the highest tensile strength. This is because of its interlocking Structure, increased Contact Area, and improved Layer Adhesion.

The PLA samples printed using a combination of Concentric and Triangle patterns possessed the highest strength in both orientations (flat and on-long) compared to their single counterparts. The synergistic improvement in the strength of the two samples can be due to several factors: enhanced interlayer adhesion, increased surface area, improved load distribution, and structural integrity.

Moreover, its printing time decreased, particularly in the on-long orientation, and increased in the flat orientation as compared to its single counterparts.

When the Triangle and Cubic samples were combined and printed in the flat orientation, the strength of the two single samples improved because these patterns were regular and repetitive, they helped to distribute stress uniformly throughout the print, minimizing the concentration of stress points that could cause failure and the building time was the shortest in the combined sample. Similarly, printing on the on-long orientation.

In the case of combined Concentric and Cross samples, an improvement in the strength of the two singular samples was found since it maximizes the print strength in both the X and Y axes when printed on a flat orientation. This is important because forces acting on a flat surface are usually distributed in both directions, making reinforcement in both directions required to prevent deformation, twisting, and bending, however, the building time was longer in the combined sample. Whereas, in the on-long orientation, an improvement was found in the Cross sample only, but the building time of the combined sample was the shortest.

After combining the Triangle and Cross patterns, an improvement in the strength of the two samples was found, in the case of on-long orientation by creating an interlocking structure, promoting better layer adhesion, offering directional strength, optimizing material usage, ensuring uniform stress distribution, enhancing rigidity, and simplifying the printing process, and the building time of the combined sample was the shortest. However, in a flat orientation, the strength of the cross pattern was improved due to its combination with the concentric pattern, the building time was longer in the combined sample.

When the Triangle and Zigzag samples were combined, an improvement in the strength of the two samples was found, this is because the Zigzag infill design adds support in multiple directions and increases overall strength, while the Triangle infill pattern helps with stability and resistance to bending., in the case of on-long orientation, and the printing time of the combined sample was the shortest.

So we can conclude from these results that when combining the Triangle infill pattern with other patterns, the effect on tensile strength can depend on several factors:

i. Complementary Patterns: Some infill patterns may complement the Triangle infill pattern, resulting in improved tensile strength. For example, combining the Triangle infill with a perpendicular or diagonal pattern can enhance the overall structural integrity by providing additional reinforcement and reducing stress concentration points.

ii. Conflicting Patterns: When the Triangular infill pattern is combined with some other patterns that may not distribute the material effectively or provide adequate support, it could lead to decreased tensile strength. The interaction between these patterns can result in weak points or inconsistencies in the structure, reducing its overall mechanical performance.

Conclusions

In this study, the impact of combined infill patterns and printing orientations has been examined, concerning the tensile and building time characteristics of PLA-based 3D-printed objects. Based on the experimental findings, the following major conclusions are drawn:

The results showed that CIP specimens built in an on-edge orientation had a higher tensile strength than those built in a flat orientation.

The PLA samples printed using a combination of Concentric and Triangle patterns possessed the highest strength in both orientations (flat and on-long) compared to their single counterparts. The synergistic improvement in the strength of the two samples was found to be 30% and 16.7%, respectively, in the case of the flat orientation and 6% and 15%, respectively, in the case of the on-long orientation. Moreover, its printing time decreased, particularly in the on-long orientation, and increased in the flat orientation as compared to its single counterparts.

When the Triangle and Cubic samples were combined and printed in the flat orientation, the strength of the two single samples improved by 3.8% and 61.5%, respectively, and the building time was the shortest in the combined sample. Similarly, printing on the on-long orientation, both samples improved by 6.7% and 3%, respectively, and the building time was the shortest in the combined sample.

In the case of combined Concentric and Cross samples, an improvement in the strength of the two singular samples was found to be 16% and 40%, respectively, when printed on flat orientation, however, the building time was longer in the combined sample. Whereas, in the on-long orientation, an improvement was found in the Cross sample only by 10.7%, but the building time of the combined sample was the shortest.

After combining the Triangle and Cross patterns, an improvement in the strength of the two samples was found to be 3.4% and 13.7%, respectively, in the case of the on-long orientation, and the building time of the combined sample was the shortest. However, in a flat orientation, improvement was found in the Cross sample only by 34.7%, but then again, the building time was longer in the combined sample.

When the Triangle and Zigzag samples were combined, an improvement in the strength of the two samples was found to be 9.7% and 3.2%, respectively, in the case of on-long orientation, and the printing time of the combined sample was the shortest.

The Triangle infill pattern, when combined with some other patterns, the tensile strength of some samples enhanced while the others improved, while others decreased.

The printed PLA samples with the combined patterns Zigzag/Triangle and Concentric/Zigzag in the flat orientation and Grid/Triangle, Honeycomb/Triangle, and Rectilinear/Triangle in the on-long orientation have the lowest tensile strength and the highest building time. So, it is not recommended for future work.

Research recommendations. With PLA material, the present work is only valid for uniaxial loading. The way forward of this research may include the implementation of the proposed strategies for combined loading, shear, and flexural by using the same or different printing materials.

CRediT author statement. All authors contributed to this study. **M. Hamoud**: Conceptualization, Methodology, Software. **O. Abdal-Aziz**: Data curation, Writing draft preparation. **A. Barakat**: Visualization, Investigation. **A. Gad**: Supervision, Software, Validation, Reviewing and Editing.

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Өндірілетін полилактикалық қышқыл бөліктерінің механикалық қасиеттеріне толтыру үлгілері мен басып шығару бағытының әсері

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ТҮЙІНДЕМЕ
Балқытылған тұндыру арқылы модельдеу (FDM) әдісі әртүрлі термопластикалық полимерлердің функционалдық үлгілерін шығарады және ең жиі қолданылатын қоспаларды өндіру (AM) технологияларының бірі болып табылады. Бұл зерттеудің мақсаты толтыру үлгісі (CIP) мен басып шығару бағытын біріктіру созылу сипаттамаларына және құрастыру уақытына қалай әсер ететінін зерттеу болып табылады. Үлгіні жасау үшін материал ретінде полилактикалық қышқыл (PLA) таңдалды. Баспа бағдарлары ұзын жиекті және жалпақ бағыттарда болды. Өнім z осі бойымен салынғандықтан, қысқа жиекті (жоғары оң жақ) бағдары ескерілмеді, бұл ең аз беріктікке әкеледі. «Концентрлік», «Крест», «Үшбұрыш», «Зигзаг», «Түз сызықты», «Кубтық», «Бал ұясы» және «Тор» деп аталатын толтыру үлгілерінің комбинациялары толтыру тығыздығы 70% және 0,15 мм қабат қалыңдығымен қабатты стратегиямен зерттелді. Нәтиже басып шығару бағытының, әсіресе CIP үлгілеріндегі созылу беріктігіне айтарлықтай әсер еткенін және CIP үлгісінің ұзын жиегі бағытының созылу беріктігі жоғары екенін көрсетеді. Concentric/Triangle (Концентрлік/Үшбұрыш) үлгісі сәйкесінше 30 МПа және 33 МПа кезінде жазық және ұзын жиек бағдарларында ең жоғары созылу беріктігіне ие болды, бірақ тегіс бағыттағы жинақтау уақыты ұзағырақ болды (25 минут), ал ұзын жиек бағдарында басып шығару уақыты қысқа болды (29 минут). Бал ұясы/үшбұрыш комбинациясы екі бағытта да төмен созылу беріктігін қамтамасыз етті: тегіс

жиек үшін 19 МПа және ұзын жиек үшін 20 МПа, бірақ құрастыру уақыты екі бағытта да ұзағырақ болды (тиісінше 14 минут және 35 минут). Нәтижесінде, CIP үлгісі бір рет толтырылған үлгіге қарағанда үлкен созылу беріктігіне ие. Сонымен қатар, үшбұрышты өрнекті басқа өрнектермен біріктіргенде, сол өрнектердің созылу күші жақсарғаны анықталды. Шеттік бағдармен құрастырылған CIP үлгілері тегіс бағдармен жасалған үлгілерге қарағанда жоғары созылу беріктігіне ие болды. Кейбір басқа үлгілермен біріктірілген үшбұрышты толтыру үлгісінде кейбір үлгілердің созылу беріктігі жоғарылады, ал басқалары жақсарды, ал кейбіреулері төмендеді.

Түйін сөздер: Балқытылған тұндыру арқылы модельдеу (FDM), қоспаларды өндіру (AM), полилактикалық қышқыл (PLA), қабат-қабат, басып шығару бағыты, аралас толтыру үлгілері (CIP), құрастыру бағыты.

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Влияние рисунков заполнения и ориентации печати на механические свойства деталей, изготовленных из полимолочной кислоты

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АННОТАЦИЯ

Метод моделирования наплавленным осаждением (FDM) позволяет создавать функциональные модели различных термопластичных полимеров и является одной из наиболее часто используемых технологий аддитивного производства (АП). Целью данного исследования является изучение того, как сочетание рисунка заполнения (CIP) и ориентации печати влияет на характеристики растяжения и время строительства. В качестве материала для изготовления образцов была выбрана полимолочная кислота (PLA). Ориентация печати была длинной и плоской. Поскольку изделие построено вдоль оси Z, ориентация короткого края (вверх-правая) не рассматривалась, что приводит к минимальной прочности. Комбинации рисунков заполнения под названием «Концентрический», «Крест», «Треугольник», «Зигзаг», «Прямолинейный», «Кубический», «Соты» и «Сетка» были исследованы с плотностью заполнения 70% и толщиной слоя 0,15 мм с послойной стратегией. Результат показывает, что ориентация печати оказала значительное влияние на прочность на разрыв, особенно в образцах CIP, а ориентация образца CIP вдоль длинной кромки имела более высокую прочность на разрыв. Образец Концентрик/Треугольник имеет самую высокую прочность на разрыв при плоской ориентации и ориентации по длинной кромке - 30 МПа и 33 МПа соответственно, но время наращивания при плоской ориентации было большим (25 минут), в то время как время печати при ориентации по длинной стороне был коротким (29 мин.). Комбинация «сота/треугольник» обеспечивает меньшую прочность на разрыв в обеих ориентациях: 19 МПа для плоской и 20 МПа для длинной кромки, но время сборки в обеих ориентациях было большим (14 минут и 35 минут соответственно). В результате образец с CIP имеет большую прочность на разрыв, чем образец с одним заполнением. Кроме того, было обнаружено, что при сочетании треугольного рисунка с другими узорами прочность на разрыв этих узоров улучшалась.

Образцы CIP, построенные с ориентацией по краю, имели более высокую прочность на разрыв, чем образцы, построенные с плоской ориентацией. В шаблоне заполнения «Треугольник» в сочетании с некоторыми другими шаблонами прочность на разрыв некоторых образцов увеличилась, в то время как у других улучшилась, а у других снизилась.

Ключевые слова: Моделирование наплавлением (FDM), аддитивное производство (AM), полимолочная кислота (PLA), послойное ориентация печати, комбинированные шаблоны заполнения (CIP), ориентация сборки.

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References

[1] Ryan KR, Down MP, Hurst NJ, Keefe EM, & Banks CE. Additive manufacturing (3D printing) of electrically conductive polymers and polymer nanocomposites and their applications. EScience. 2022; 2(4):365-381. https://doi.org/10.1016/j.esci.2022.07.003

[2] Gross BC, Erkal JL, Lockwood SY, Chen C, & Spence DM. Evaluation of 3D printing and its potential impact on biotechnology and the chemical sciences. 2014. https://pubs.acs.org/doi/full/10.1021/ac403397r

[3] Sajjad R, Butt SU, Saeed HA, Anwar MT, & Rasheed T. Impact of multiple infill strategy on the structural strength of single build FDM printed parts. Journal of Manufacturing Processes. 2023; 89:105-110. https://doi.org/10.1016/j.jmapro.2023.01.065

[4] Poojitha G, Talari P, Banoth S, & Kumar A. Effects of combined infill angle with a honeycomb pattern on the mechanical properties of HIPS and polypropylene in FDM process. Materials Today: Proceedings. 2023. https://doi.org/10.1016/j.matpr.2023.09.219

[5] Gohar S, Hussain G, Ali A, & Ahmad H. Mechanical performance of honeycomb sandwich structures built by FDM printing technique. Journal of Thermoplastic Composite Materials. 2023; 36(1):182-200. https://doi.org/10.1177/0892705721997892

[6] Bellini A, & Güçeri S. Mechanical characterization of parts fabricated using fused deposition modeling. Rapid Prototyping Journal. 2003; 9(4):252-264.

[7] Ismail KI, Yap TC, & Ahmed R. 3D-printed fiber-reinforced polymer composites by fused deposition modeling (FDM): fiber length and fiber implementation techniques. Polymers. 2022; 14(21):4659. https://doi.org/10.3390/polym14214659

[8] Karalekas D, & Antoniou K. Composite rapid prototyping: overcoming the drawback of poor mechanical properties. Journal of Materials Processing Technology. 2004; 153:526-530. https://doi.org/10.1016/j.jmatprotec.2004.04.019

[9] Farashi S, & Vafaee F. Effect of printing parameters on the tensile strength of FDM 3D samples: a meta-analysis focusing on layer thickness and sample orientation. Progress in Additive Manufacturing. 2022, 1-18.

[10] Torres J, Cole M, Owji A, DeMastry Z, & Gordon AP. An approach for mechanical property optimization of fused deposition modeling with polylactic acid via the design of experiments. Rapid Prototyping Journal. 2016; 22(2):387-404.

[11] Chacón J M, Caminero M A, García-Plaza E, & Núnez P J. Additive manufacturing of PLA structures using fused deposition modeling: Effect of process parameters on mechanical properties and their optimal selection. Materials & Design. 2017; 124:143-157. https://doi.org/10.1016/j.matdes.2017.03.065

[12] Durgun I, & Ertan R. Experimental investigation of FDM process for improvement of mechanical properties and production cost. Rapid Prototyping Journal. 2014; 20(3):228-235. https://doi.org/10.1108/RPJ-10-2012-0091

[13] Aloyaydi B, Sivasankaran S, & Mustafa A. Investigation of infill patterns on the mechanical response of 3D printed poly-lactic acid. Polymer Testing. 2020; 87:106557. https://doi.org/10.1016/j.polymertesting.2020.106557

[14] Mishra S B, & Mahapatra S S. Improvement in tensile strength of FDM-built parts by parametric control. Applied Mechanics and Materials. 2014; 592:1075-1079. https://doi.org/10.4028/www.scientific.net/AMM.592-594.1075

[15] Ahn S H, Montero M, Odell D, Roundy S, & Wright P K. Anisotropic material properties of fused deposition modeling ABS. Rapid prototyping journal. 2002; 8(4):248-257.

[16] Wang S, Ma Y, Deng Z, Zhang S, & Cai J. Effects of fused deposition modeling process parameters on tensile, dynamic mechanical properties of 3D printed polylactic acid materials. Polymer testing. 2020; 86:106483. https://doi.org/10.1016/j.polymertesting.2020.106483

[17] Yang L, Li S, Li Y, Yang M, & Yuan Q. Experimental investigations for optimizing the extrusion parameters on FDM PLA printed parts. Journal of Materials Engineering and Performance. 2019; 28:169-182.

[18] Sukindar N A, Ariffin MKA, Baharudin BHT, Jaafar CNA, & Ismail MIS. Analyzing the effect of nozzle diameter in fused deposition modeling for extruding polylactic acid using open-source 3D printing. J. Teknol. 2016; 78(10):7-15. https://doi.org/10.3390/polym12122792

[19] Moradi M, Meiabadi S, & Kaplan A. 3D printed parts with honeycomb internal pattern by fused deposition modeling; experimental characterization and production optimization. Metals and Materials International. 2019; 25:1312-1325.

[20] Akhoundi B, Behravesh AH. Effect of filling pattern on the tensile and flexural mechanical properties of FDM 3D printed products. Exp. Mech. 2019; 59:883-897.

[21] Hanon MM, Marczis R, Zsidai L. Anisotropy evaluation of different raster directions, spatial orientations, and fill percentage of 3D printed PETG tensile test specimens. Key Eng. Mater. 2019; 821:167-173. https://doi.org/10.4028/www.scientific.net/KEM.821.167

[22] Samykano M, Selvamani SK, Kadirgama K, Ngui WK, Kanagaraj G, Sudhakar K. Mechanical property of FDM printed ABS: Influence of printing parameters. Int. J. Adv. Manuf. Technol. 2019; 102:2779-2796. https://doi.org/10.1007/s00170-019-03313-0

[23] Li H, Wang T, Sun J, Yu Z. The effect of process parameters in fused deposition modeling on bonding degree and mechanical properties. Rapid Prototype J. 2018; 24:80-92. http://dx.doi.org/10.1108/RPJ-06-2016-0090

[24] Casavola C, Cazzato A, Moramarco V, Pappalettere C. Orthotropic mechanical properties of fused deposition modeling parts described by classical laminate theory. Mater Des. 2016; 90:453-458. https://doi.org/10.1016/j.matdes.2015.11.009

[25] Rajpurohit SR, Dave HK. Effect of process parameters on tensile strength of FDM printed PLA part. Rapid Prototyp J. 2018; 24:1317-1324. http://dx.doi.org/10.1108/RPJ-06-2017-0134

[26] Dave HK, Patadiya NH, Prajapati AR, Rajpurohit SR Effect of infill pattern and infill density at varying part orientation on tensile properties of fused deposition modeling-printed poly-lactic acid part. P I Mech Eng C-J Mec. 2019. https://doi.org/10.1177/0954406219856383

[27] Rodriguez JF, Thomas JP, Renaud JE. Mechanical behavior of acrylonitrile butadiene styrene (ABS) fused deposition materials: Experimental investigation. Rapid Prototyp J. 2001; 7:148-158.

[28] Lederle F, Meyer F, Brunotte GP, Kaldun C, Hübner EG. Improved mechanical properties of 3D-printed parts by fused deposition modeling processed under the exclusion of oxygen. Prog Addit Manuf. 2016; 1:3-7. https://doi.org/10.1007/s40964-016-0010-y

[29] Wu W, Geng P, Li G, Zhao D, Zhang H, Zhao J. Influence of layer thickness and raster angle on the mechanical properties of 3D-printed PEEK and a comparative mechanical study between PEEK and ABS. Materials. 2015; 8:5834-5846. https://doi.org/10.3390/ma8095271

[30] Ziemian S, Okwara M, Ziemian CW. Tensile and fatigue behavior of layered acrylonitrile butadiene styrene. Rapid Prototyp J. 2015; 21:270-278. http://dx.doi.org/10.1108/RPJ-09-2013-0086

[31] Zaldivar RJ, Witkin DB, McLouth T, Patel DN, Schmitt K, Nokes JP. Influence of processing and orientation print effects on the mechanical and thermal behavior of 3D-Printed ULTEM® 9085 Material. Addit Manuf. 2017; 13:71-80. https://doi.org/10.1016/j.addma.2016.11.007

[32] Alvarez C, Kenny L, Lagos C, Rodrigo F, Aizpun M. Investigating the influence of infill percentage on the mechanical properties of fused deposition modeled ABS parts. Ing Invest. 2016; 36:110-116. http://dx.doi.org/10.15446/ing.investig.v36n3.56610

[33] Shih CC, Burnette M, Staack D, Wang J, Tai BL. Effects of cold plasma treatment on interlayer bonding strength in FFF process. Addit Manuf. 2019; 25:104-111. https://doi.org/10.1016/j.addma.2018.11.005

[34] Lee CY, Liu CY. The influence of forced-air cooling on a 3D printed PLA part manufactured by fused filament fabrication. Addit Manuf. 2019; 25:196-203. https://doi.org/10.1016/j.addma.2018.11.012

[35] Bin Ishak I, Fleming D, Larochelle P. Multiplane fused deposition modeling: a study of tensile strength. Mech Based Des Struct Mach. 2019; 47:1-16. https://doi.org/10.1080/15397734.2019.1596127

[36] Lalegani Dezaki M, & Mohd Ariffin M K A. The Effects of Combined Infill Patterns on Mechanical Properties in FDM Process. Polymers. 2020; 12(12):2792. https://doi.org/10.3390/polym12122792

[37] Dave H K, Patel B H, Rajpurohit S R, Prajapati A R, & Nedelcu D. Effect of multi-infill patterns on tensile behavior of FDM printed parts. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2021; 43(1). https://doi.org/10.1007/s40430-020-02742-3

[38] Roger F, Krawczak P. 3D-printing of thermoplastic structures by FDM using heterogeneous infill and multi-materials: An integrated design-advanced manufacturing approach for factories of the future. CFM 2015 - 22ème Congrès Français de Mécanique. 2015.

[39] Naik M, Thakur D, & Chandel S. An insight into the effect of printing orientation on tensile strength of multi-infill pattern 3D printed specimen: Experimental study. Materials Today: Proceedings. 2022; 62:7391. https://doi.org/10.1016/j.matpr.2022.02.305