# Impact of infill pattern and infill density on mechanical properties of FDM 3D printed parts: a review

## Impact du motif de remplissage et de la densité de remplissage sur les propriétés mécaniques des pièces 3D imprimées par FDM : une revue

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**ABSTRACT.** Fused Deposition Modeling (FDM) process is widely used for various applications as it offers many benefits. Mechanical properties of parts manufactured using FDM technique are very critical. For that reason, it is important to understand how different values of process parameters affect these properties. The purpose of this research is to provide information related to the influence of various infill pattern and infill density. A literature review is carried out based on the current researches that investigate FDM 3D printing process of polymer materials. The results show that infill percentage then layer thickness are the most influential process parameter on most of the material's mechanical properties. In addition, this work identifies gaps in existing studies and highlights opportunities for future research.

**RÉSUMÉ.** Le procédé FDM (Fused Deposition Modeling) est largement utilisé pour diverses applications car il offre de nombreux avantages. Les propriétés mécaniques des pièces fabriquées en utilisant la technique FDM sont très critiques. Pour cette raison, il est important de comprendre comment différentes valeurs de paramètres de processus affectent ces propriétés. Le but de cette recherche est de fournir des informations relatives à l'influence de divers motifs de remplissage et de densité de remplissage. Une revue de la littérature est effectuée sur la base des recherches actuelles qui étudient le processus d'impression 3D FDM des matériaux polymères. Les résultats montrent que le pourcentage de remplissage et l'épaisseur de la couche sont les paramètres de processus les plus influents sur la plupart des propriétés mécaniques du matériau. En outre, ce travail identifie les lacunes dans les études existantes et souligne les possibilités de recherche future.

**KEYWORDS.** Infill patterns, Infill density, Layer thickness, Mechanical properties, Impact, Fused Deposition Modeling.

**MOTS-CLÉS.** Modèles de remplissage, Densité de remplissage, Épaisseur de couche, Propriétés mécaniques, Impact, Modélisation par dépôt de fil fondu.

### 1. Introduction

Additive manufacturing (AM) (or 3D printing) is known as a process used to synthesize a three-dimensional object in which successive layers of material are formed under computer control to create an object. There are many different technologies being used in 3D printing, which include selective laser sintering (SLS), fused deposition modeling (FDM) (Figure 1), stereolithography (SLA), and inkjet 3D printing [LI 18]. These technologies can print various materials like ceramics, metals, and polymers. 3D printing has advantages in various domains such as medical, automotive, aerospace, and consumer goods. The adoption of 3D printing is increasing day by day due to advanced research and development in this field. 3D printing of polymers is involved in printing the most complicated parts or samples within a few hours. Among the different types of 3D polymer printing, the most commonly used type is FDM due to its low cost and simple procedure. As a result, this technology is expected to deliver excellent performance and good part quality.

There is the number of input parameters influencing the performance of the FDM machine which directly reflects the characteristics of the printed part. The various independent input parameters are the printing temperature, printing speed, infill density, infill pattern, Layer thickness, etc. In certain applications, it is required to investigate the characteristic of 3D printed parts in terms of mechanical properties.

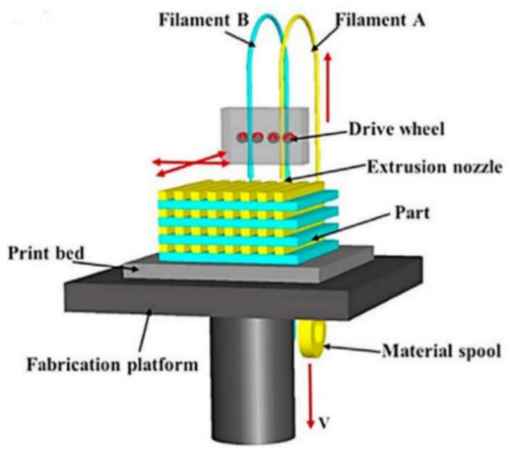



**Figure 1.** *FDM machine [WAN 17]*

The paper's objective is to present the effect of infill pattern and infill density on the mechanical properties of the 3D printed parts developed by the FDM technique. The literature selection is based on process parameters comprising infill density and infill patterns. If any other parameters are considered, it is also discussed along with it. To achieve the purpose, first, this research summarizes important research in FDM printing process. Then, this research identifies important process parameters and their influences to the mechanical properties of 3D printed part.

## 2. FDM Process

### 2.1. *FDM Process Parameters*

Process parameters play a vital role in controlling the physical behavior, including part strength, surface quality and accurateness of the FDM printed part. The parameters control the size, shape, build time and interior structure. The user needs to set the parameters before creating the slicing of the STL file. The primary process parameters include layer thickness, model build temperature, infill pattern, infill density, raster width, raster air gap, shell thickness, raster angle, and build orientation, etc. (Figure 2).

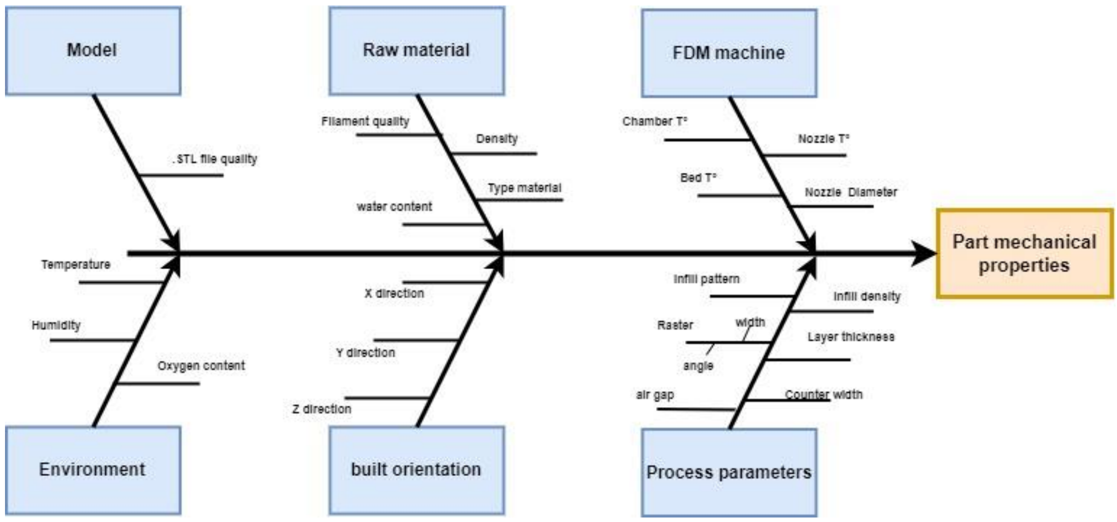



**Figure 2.** *Process parameters of FDM.*

- *Layer thickness*

Layer thickness can be defined as the slice height of the STL model for the part building. Layer thickness controls the motion of the nozzle or platform in the z-direction to build the next adjacent layer. The surface quality and accuracy are inversely dependent on the layer thickness.

- *Infill density*

Infill density is the amount of material used to fill the layer's inner area. This setting can make a part either fully or partially solid. The setting of the infill density is fed in the form of percentages like 25%, 50%, 75% or 100%. It again affects the build time, amount of raw material and strength of the FDM part.

- *Infill pattern*

The term infill refers to the pattern printed inside the part, typically grid or triangular, used to support the top layers and provide internal strength to a part. Changing the infill pattern and density can have a noticeable effect on the mechanical properties of a printed part. There are a wide variety of infill patterns available for use in slicing software. The (Table 1) shows same common infill patterns used in FDM.

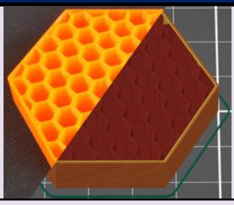
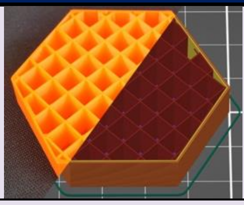
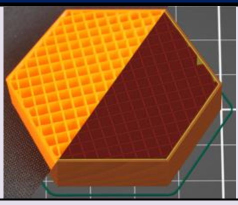
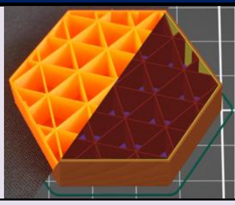
| | **Honeycomb** | **Grid** | **Rectilinear** | **Triangular** |
|---|---|---|---|---|
| **Form** |  |  |  |  |
| | Features hexagonal patterns. | Consists of a simple grid pattern | Employs a pattern of straight lines in the XY directions. | Utilizes a pattern of interconnected triangles. |
| **Characteristics** | Offers good strength and material efficiency. | Balances strength and print speed. | Provides good strength and is easy to print. | Offers excellent strength-to-weight ratio. |
| | Reduces material consumption while maintaining structural integrity. | Often used for prototypes and functional parts. | Common choice for quick prints. | Suitable for parts requiring high strength and rigidity. |

**Table 1.** Common Infill Patterns.

### 2.2. *The Strength of FDM Parts*

The influenced mechanical properties are tensile strength and yield strength, compression strength, flexural strength, ductility, elasticity or young modulus, and stiffness. In addition, the parameters also have influences on the failure mode, accuracy and repeatability, specific strength, part weight, and build time of the printed part.

The evaluation of the mechanical characteristics of Additive Manufacturing (AM) parts is governed by the standards set by the American Society for Testing and Materials (ASTM). Specific test samples are produced based on the type of force exerted on the part. The illustration in (Figure 3) displays the standardized samples utilized for assessing the tensile, flexural, and impact resilience of the components. Subsequent to the fabrication of the samples, the assessment is carried out in compliance with the established protocol until the component fails, enabling the determination of the load-strain correlation for each component. This correlation facilitates the identification and further exploration of the mechanical attributes of the component necessary for a particular application.

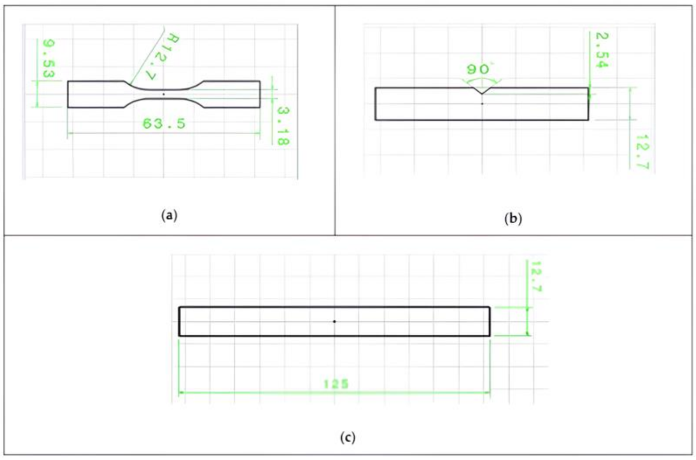



**Figure 3.** *Standard specimens for: (a) Tensile test; (b) Impact test; (c) Flexural test.*

## 3. Results and discussion

This section gives details and describes current work investigating changes in mechanical properties by varying FDM process parameters.

The research of [ALO 20] evaluated the effect of the infill pattern on the compressive strength of the part. It was found that triangular, grid and hexagonal infilled parts resulted in similar ultimate tensile strength (56–72 MPa), while the quarter cubic infill exhibited a significantly lower strength of 27 MPa. It was also found that the grid pattern had the highest tensile strength. As there is an offset between the layers in the quarter cubic design, this was not seen. This offset region behaved like a cantilever in bending when the part was loaded because it was not supported by the layers that came before it. Overall strength thus decreases to 27 MPa.

[YAD 21] investigated the compressive strength of PLA specimens made with FDM with different infill patterns and infill densities. The Hilbert curve showed the maximum compressive strength (121.35 MPa), Line (73.84 MPa), Rectilinear (78.88 MPa), Honeycomb (62.56 MPa), Octagram spiral (60.01 MPa), Archimedean (70.07 MPa), at 80% infill density. It showed that the compressive properties of PLA printed specimens increase with a higher infill percentage. The roughness of the surface decreases for rectilinear patterns. Compared to other patterns, the rectilinear pattern shows the least roughness value at 20% infill density.

Similar results were reported by [CHA 19] who studied how grid, triangular and honeycomb infill patterns perform under the flexural and tensile loadings. In both bending and tensile, the triangular pattern was found to exhibit the highest strength, followed by the grid pattern and finally the honeycomb pattern. SEM images of the fracture surfaces indicated that in the case of the grid pattern, printed filaments did not change its circular cross-section. This means that those filaments did not experience any necking, which might be the evidence of the brittle fracture. However, honeycomb and triangular patterns failed in a ductile manner and their filaments' cross-section became oval due to the necking.

on the contrary, the work of [SU 24] presented a comparison between honeycomb and triangular infill patterns within rCF/rPA coupons via the FDM recycling was performed under the various relative densities of 10%, 30%, 50%, 70%, and 90%. The best performance of rCF/rPA coupons occurred in honeycomb infill patterns with 90% relative infill densities. The tensile strength and modulus of those specimens were 76.5 GPa ± 3.5 MPa and 4.8 GPa ± 0.1 GPa, respectively.

Infill strategy impacts density and mechanical performance differently. Gyroid pattern enhances tensile strength in the studies of [GUE 22] and [KAD 23] showed the highest Young Modulus at 1108 MPa. Also [BIR 22] investigated that Gyroid offer better mechanical resistance in bending test.

For PLA material, concentric infill pattern exhibits the highest tensile strength at 32.174 MPa, while triangles show the lowest at 20.934 MPa [JAS 22]. Similar results were reported by [AGR 23] for ABS material, the best results were obtained with a concentric infill pattern, along with 80% infill density and 100 µm layer thickness. These conditions resulted in 123% and 115% higher tensile strength and 168% and 80% higher impact strength compared to line and triangle patterns, respectively.

In the comparison of materials, the PLA parts can reach a higher mechanical strength than those printed with ABS, [ROD 18] examined the manufacturing parameter of FDM for PLA and ABS concerning the mechanical properties like infill pattern and layer thickness. The result revealed that while increasing the layer height (0.1 to 0.02), the strength decreases by 75% for ABS and 11% for PLA. The tensile strength increases due to incremented infill pattern (50%) by 25% for ABS and 27% for PLA. So, the infill percentage is the most influential process parameter on materials' properties [TAN 19], decreasing infill percentage reduces UTS and increases surface roughness [ALG 21].

[SAM 19] examined three process parameters: raster angle, layer height, and infill density, which have been considered to affect the mechanical properties of ABS. It was revealed that the elastic modulus, yield strength, ultimate tensile strength, fracture strain and toughness with 80% infill percentage, 0.55 mm layer thickness and 650 raster angle are 31.57 MPa, 774.50 MPa, 19.95 MPa, 0.094 mm/mm and 2.28 J/m3, respectively. This phenomenon happens because the strength composition is correlated with the specimen to oppose the tensile strength. Due to this raster angle shows the maximum value. The layer thickness is an essential factor to reach the maximum tensile strength because this creates less distortion on the specimen. Layer height indirectly improves the mechanical strength due to temperature gradient. In a similar context [STO 23] found that Layer height has a significant impact on tensile strength in FDM printing materials like PLA, PETG, and PETGCF. Optimal parameters vary for each material to achieve best strength results.

In a recent study [LOL 23] , Machine learning techniques used to predict optimal infill pattern, the goal of this research is to find the best infill pattern settings for a polylactic acid(PLA)-based ceramic material with a universal testing machine. Cross and tri-hexagon infill patterns are efficient. Machine learning improves precision and efficacy.

In the study of [MAN 20] 33 specimens were produced along with the validation specimen for the tensile test in Universal testing machine. The test results were incorporated in MINITAB and MATLAB tools for the prediction of tensile strength using RSM, ANOVA and ANN techniques. The percentage deviation was determined for these methods, gives RSM value of percentage in error as 2.13, ANOVA value of percentage in error as 2.18 and ANN value of percentage in error as 1.10. Among these, the ANN method is considered to be the best solution as it sets out the least value of percentage in error.

Table 2 presents a comparative analysis of various studies on the mechanical properties of materials used in 3D printing, particularly tensile strength. Each source explores different materials, test methods, and results, highlighting the influences of various parameters such as infill patterns and densities.

| Source | Material | Test | Method | Remarks |
|---|---|---|---|---|
| (Su, Zhu, & Chen, 2024) [SU 24] | rCF/ rPA | Tensile | Experimental | Honeycomb infills performed better than triangular infills. Tensile strength and modulus increased with higher infill densities. |
| (Manoharan, Chockalingam, & Ram, 2020) [MAN 20] | PLA | Tensile | ANN, RSM, and ANOVA | Predicted tensile strength using ANN, RSM, and ANOVA with low error. The error percentage for ANN, RSM, and ANOVA were computed individually, and |

| | | | | |
|---|---|---|---|---|
| | | | | ANN was chosen as it showed the least error (1-2%). |
| (Algarni & Ghazali, 2021) [ALG 21] | PLA, ABS, PEEK, PETG | Tensile | ANOVA analysis to quantify and rank the influence of process parameters. | Infill percentage is the most influential process parameter on materials' properties. Decreasing infill percentage reduces UTS and increases surface roughness. |
| (Lolla et al., 2023) [LOL 23] | PLA - Based Ceramic | Tensile | X-ray diffractometer and energy-dispersive X-ray spectroscopy | Machine learning techniques used to predict optimal infill pattern; Cross and tri-hexagon infill patterns are efficient. Machine learning improves precision and efficacy. |
| (Kadhum, Al-Zubaidi, & Abdulkareem, 2023) [KAD 23] | PLA, PLA+ and PETG | Tensile and surface roughness | Experimental | Best infill patterns for mechanical properties: cubic, Gyroid. Better surface roughness were achieved with Cross. |
| (Guessasma & Belhabib, 2022) [GUE 22] | PLA–carbon composites | Tensile performance. | Finite element | Infill strategy impacts density and mechanical performance differently. Gyroid pattern enhances mechanical strength, zigzag and cross promote stretching. |
| (Jasim, Abbas, & Huayier, 2022) [JAS 22] | PLA | Tensile, Stress and strain | Experimental | Different infill patterns in FDM printing significantly impact strength. For PLA material, concentric infill pattern exhibits the highest tensile strength at 32.174 MPa, while triangles show the lowest at 20.934 MPa. |
| (Agrawal et al., 2023) [AGR 23] | ABS | Tensile strength and impact strength | Experimental | The best results were obtained with a concentric infill pattern. |
| (Stojković et al., 2023) [STO 23] | PLA, PETG, and PETGCF | Tensile strength | Regression model | Layer height has a significant impact on tensile strength in FDM printing materials like PLA, PETG, and PETGCF. Optimal parameters vary for each material to achieve best strength results. |
| (Tanveer, Haleem, & Suhaib, 2019) [TAN 19] | PLA | Tensile strength and impact strength | Experimental | higher infill density gave a higher impact strength |
| (Ganeshkumar et al., 2022) [GAN 22] | PLA | Tensile | Experimental and finite element | Hexagonal infill structure exhibits superior tensile properties. Increasing infill ratio enhances yield strength. |
| (Rodríguez-Panes, Claver, & Camacho, 2018) [ROD 18] | PLA and ABS | Tensile yield stress, tensile strength, nominal strain at break, and modulus of elasticity | Experimental | the infill percentage is the manufacturing parameter of greatest influence on the results, although the effect is more noticeable in PLA than in ABS. The test specimens manufactured using PLA perform more rigidly and they are found to have greater tensile strength than ABS. |
| (Samykano et al., 2019) [SAM 19] | ABS | UTS, elastic modulus, yield strength | RSM experimental | It was found that the optimum parameters for 3D printing using ABS are 80% infill percentage, 0.5 mm layer thickness, and 65° raster angle. |

**Table 2.** *Impact of infill patterns on Tensile strength of 3D-printed parts.*

Table 3 summarizes the findings of several studies investigating the effect of infill patterns on the bending properties of 3D-printed parts. These studies have explored various materials, test types, and methods to determine how different infill patterns, such as honeycomb and gyroid, influence the bending strength, deformation, and resilience of 3D-printed components

| Source | Material | test | Method | Remarks |
|---|---|---|---|---|
| (Birosz, Ledenyák, & Andó, 2022) [BIR 22] | PLA | Bending, deformation, force resistance, and resilience | Experimental | Honeycomb and Gyroid patterns offer better mechanical resistance. More material in sample correlates with increased resistance to load. |
| (Pop et al., 2022) [POP 22] | PLA renforcé | bending and tensile | Experimental | Infill patterns like grid, triangular, and lines affect mechanical properties in FDM 3D printing of carbon fiber-reinforced parts, with grid infill showing lower but still improved mechanical values. |
| (Chadha et al., 2019) [CHA 19] | PLA | bending and tensile | Experimental | With increase in bed temperature tensile strength and flexural strength first increases then decreases. With the increase in primary layer thickness, tensile strength and flexural strength increase. With regard to infill patterns, triangular and honeycomb exhibit better tensile strength and better flexural strength. |

**Table 3.** *Impact of infill patterns on bending of 3D-printed parts.*

Table 4 presents a compilation of studies examining the influence of infill patterns on compressive strength of 3D-printed parts.

| Source | Material | Test | Method | Remarks |
|---|---|---|---|---|
| (Aloyaydi, Sivasankaran, & Mustafa, 2020) [ALO 20] | PLA | Compressive strength | Experimental | the triangular pattern has produced the highest absorbed energy in LVI test; while the grid pattern exhibited the highest compressive strength (72 MPa) |
| (Besnea et al., 2022) [BES 22] | PLA | Compression acting force | Experimental | Diamond and honeycomb fill structures are more resistant than linear and wiggle. Filling factor influences penetration resistance, higher filling factor leads to higher resistance. |
| (Yadav, Sahai, & Sharma, 2021) [YAD 21] | PLA | Compressive strength | Experimental | The Hilbert curve showed the maximum compressive strength (121.35 MPa) at 80% infill density. It showed that the compressive properties of PLA printed specimens increase with a higher infill percentage. The roughness of the surface decreases for rectilinear patterns. |

**Table 4.** *Impact of infill patterns on Compressive strength of 3D-printed parts.*

## 4. Conclusions

This work determined the effect of infill patterns and infill densities on the mechanical performance of FDM printed parts. based on existing studies, several key conclusions are found:

– The Hilbert curve showed the maximum compressive strength (121.35 MPa) at 80% infill density. It showed that the compressive properties of PLA printed specimens increase with a higher infill percentage. The roughness of the surface decreases for rectilinear patterns.

– The Honeycomb and the Gyroid pattern provide better mechanical resistance, compared to the simple Grid pattern.

– the infill percentage is the manufacturing parameter of greatest influence on the results, although the effect is more noticeable in PLA than in ABS. The test specimens manufactured using PLA perform more rigidly and they are found to have greater tensile strength than ABS.

– The layer thickness is an essential factor to reach the maximum tensile strength in FDM printing.

– that Layer height has a significant impact on tensile strength in FDM printing materials like PLA, PETG, and PETGCF.

– The error percentage for ANN, RSM, and ANOVA were computed individually in order to Predict tensile strength of 3D parts, and ANN was chosen as it showed the least error (1-2%).

According to the existing literature, the subsequent research gaps have been discerned: The majority of the studies focused on the tensile characteristics of the produced part, while a minority also delved into the flexural resilience of the part. In-depth research on flexural strength properties is required to be investigated further in terms of layer thickness, printing speed, extrusion temperature and number of contours. Other than tensile and flexural properties, other properties such as shear stress, impact test to measure the service life of parts also need to be investigated.

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