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Makki Ajmi, Simon Bernard, Slim Souissi, Ahmed Elloumi, Pierre Maréchal. Influence of the number of contours of a specimen manufactured by FFF on the propagation of acoustic waves. The International Conference on Advances in Mechanical Engineering and Mechanics (ICAMEM 2024), Jun 2024, Sousse, Tunisia. pp.317-326, <10.1007/978-3-031-89733-7_33>. <hal-04644523>

HAL Id: hal-04644523

<https://normandie-univ.hal.science/hal-04644523v1>

Submitted on 7 Jan 2026

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Influence of the number of contours of a specimen manufactured by FFF on the propagation of acoustic waves

Makki Ajmi^{1,2}, Simon Bernard², Slim Souissi¹, Ahmed Elloumi¹, Pierre Maréchal²

¹ Laboratoire des Systèmes Électromécaniques (LASEM), National Engineering School of Sfax, University of Sfax, 3038 Sfax, Tunisia

² Laboratoire Ondes et Milieux Complexes (LOMC), UMR 6294 CNRS, Université Le Havre Normandie, 76600 Le Havre, France

makki.ajmi@enis.tn ; simon.bernard@univ-lehavre.fr ; slim.souissi@ymail.com ; loumiaahmed@gmail.com ; pierre.marechal@univ-lehavre.fr.

Abstract. This study explores the impact of walls number on the acoustic properties of 3D printed PLA samples using fused filament fabrication (FFF). The samples, with dimensions of 12,7×12,7×25,4 mm, are subjected to three infill patterns {line, combined, concentric} and four infill densities {100%, 90%, 80%, 70%}, with two levels of contours {0, 3} (without contours and with three contours). Variation of these parameters allows for modulation of the volumetric fraction of porosity, thus influencing the acoustic properties of the materials. The results reveal that the addition of contours does lead to a decrease in the velocity of acoustic waves, but rather favors the propagation of waves within the edges of the structure. This phenomenon is identified as guided waves, where contours introduce discontinuities that interfere with wave propagation through the 3D printed material. Additionally, the study highlights the influence of modulation of volumetric porosity fraction on wave propagation through the material, thus emphasizing the capability of additive manufacturing to adjust the acoustic characteristics of 3D printed materials. The practical implications of these findings are significant for real-world applications of 3D printing, such as optimizing acoustic performance in engineered materials and structures. This research enhances our understanding of the interactions between additive manufacturing and the acoustic properties of materials, revealing the critical role of contours in structural guided wave phenomena. Furthermore, this study contributes to the broader context of additive manufacturing and materials science by demonstrating how structural modifications at the micro-scale can influence acoustic properties.

Keywords: fused filament fabrication (FFF); infill pattern; infill density; polylactic acid (PLA); acoustic wave; number of contours.

1 Introduction

Additive manufacturing (AM), also known as 3D printing, has revolutionized the manufacturing landscape by enabling the creation of complex parts with a variety of materials [1, 2]. Different types of additive manufacturing technologies are evolving at a rapid pace [3]. FFF (Fused Filament Fabrication), often referred to as FDM (Fused Deposition Modeling), is currently the most widely used 3D printing process. It has experienced rapid development due to its low cost, effective working method, and flexibility. Among the materials widely used in AM, Polylactic Acid (PLA) is of particular interest due to its versatility and biocompatibility [4]. However, despite the progress made in the field of FFF, understanding the impact of manufacturing parameters on mechanical properties and the integration of non-destructive evaluation methods such as ultrasound and X-ray remain a crucial challenge due to the complexity of the internal geometry and surface condition of parts produced in AM [5, 6].

FFF allows for the control of several manufacturing parameters, including infill pattern, infill density, number of contours, layer thickness, extrusion temperature, printing speed, etc. [7]. Previous studies [8-11], have shown that the number of contours can have a significant influence on the mechanical properties of manufactured parts, particularly in terms of bending. However, these observations have primarily been confirmed through destructive mechanical testing, raising the question of whether non-destructive techniques can also detect these property variations. Among the motivations for studying the effect of contours is that the addition of contours creates structural heterogeneity, which influences the acoustic properties. This raises the question of whether this parameter will reveal a physical phenomenon. The modulus of elasticity and Poisson's ratio of additively manufactured components can be determined by measuring the velocity of ultrasonic waves in the longitudinal and shear directions. These properties are necessary to obtain information about the material's anisotropy.

In 2018, Witkin et al. [8] investigated the non-destructive experimental characterization of a powder bed additive manufactured aluminum alloy. Their work revealed that non-destructive methods offer increased precision compared to the conventional tensile testing method. Indeed, non-destructive techniques allow for the analysis of the alloy's mechanical properties without altering its structure, thereby providing a more accurate assessment of its performance. This methodology yields more precise results than the tensile testing method.

In 2021, Kuszko et al. [9] studied the influence of several parameters on the mechanical properties of parts manufactured by FFF. The studied parameters included layer thickness (0.1 mm and 0.3 mm), build angle (0° and 90°), and the

number of contours (1 and 3). The tensile tests were conducted to assess the impact of these variables on the elastic modulus of the samples. The results revealed that the build angle and the number of perimeters exert a significant influence on the mechanical properties of parts manufactured by FFF. Specifically, it was observed that increasing the number of perimeters leads to an increase in the elastic modulus. This finding suggests that perimeter density substantially affects the mechanical characteristics of parts produced by this 3D printing method.

In 2020, Charlon and Soulestin [10] conducted a comprehensive study to examine the impact of several printing parameters, such as density (from 80% to 120% with a 10% interval), extrusion temperature (from 190°C to 270°C in 20°C increments), and the number of contours (0, 1, 3, and 5) on the mechanical properties of samples produced by FFF. Their work revealed that the number of contours has a significant influence on these mechanical properties. Furthermore, through a detailed tomographic study, they demonstrated that the number of contours affects the mass and volume of the samples, which in turn influences porosity. This observation underscores the crucial importance of controlling the number of contours during FFF additive manufacturing to ensure optimal mechanical properties of the produced parts.

The use of non-destructive testing (NDT), including acoustic emission, to assess the mechanical properties of parts manufactured by AM is an emerging field. However, it remains to be determined whether these techniques are sensitive to variations induced by the number of contours in the structure of the parts. The ability of non-destructive tests to detect these variations could open new perspectives in quality control and validation of parts manufactured by AM. Although NDT has been widely used in other industrial fields to assess mechanical properties, its integration into the AM domain is relatively new. Previous research has mainly focused on using these techniques to detect manufacturing defects, but few studies have explored their ability to characterize variations in properties induced by manufacturing parameters such as the number of contours, infill pattern, infill density, etc.

This article aims to determine whether NDT, particularly acoustic wave velocity measurements, are capable of detecting variations in mechanical properties induced by the number of contours in parts manufactured by FFF. By conducting both destructive tests (DT) and NDT on samples printed with different numbers of contour, this research aims to evaluate the sensitivity of NDT to these variations. This study will contribute to expanding our understanding of the application of non-destructive tests in the AM field and exploring new opportunities for quality control of manufactured parts.

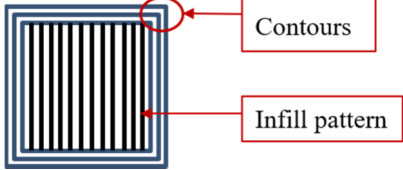

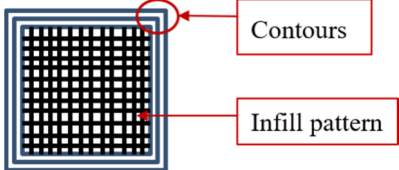
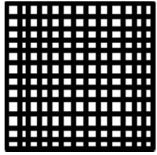
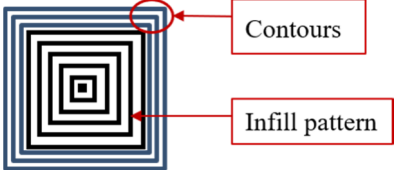
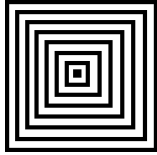
2 Methodology

2.1 Sample Preparation

In our study, we used Prusa slicer software to prepare the print files for our samples. The use of Prusa Slicer provides us with increased dimensional accuracy and better surface quality compared to Ultimaker Cura software [11]. The print settings used were as follows: nozzle diameter of 0.4 mm, platform temperature set to 60°C, a single layer thickness of 0.2 mm, and a print speed of 60 mm/s. The extruder temperature was set to 215°C [12]. The studied printing parameters were infill pattern, infill density and number of contours since these considerations affect the mechanical properties of 3D printed parts.

For each type of infill pattern {Line; Combined; Concentric} (see table 1), samples were made in four different infill densities as defined in the Prusa Slicer software {100%; 90%; 80%; 70%}, two levels of a number of contours {0; 3} making a total of 24 pieces.

Table 1. Different infill patterns with and without contours

Infill pattern	With contours	Without contours
Line		
Combined		
Concentric		

The specimens used in our study are rectangular parallelepipeds shape, with a length $L = 12.7$ mm, a width $W = 12.7$ mm and a height $H = 25.4$ mm, in view to compare the mechanical results with ultrasound measurements. The choice of this geometry offers several advantages in the context of acoustic wave propagation. The rectangular parallelepipeds shape ensures proper contact between the transducers and the sample surface, facilitating accurate ultrasonic measurements.

In this study, the FFF was processed using a Prusa i3 MK3S+ 3D printing machine using transparent PLA purchased from Prusa (Prusa Research, Prague, Czech Republic). Throughout the software processing Prusa Slicer, the printing parameters have been set as previously described in order to analyze the impact of different manufacturing parameters.

2.2 Porosity evaluation

The total volumetric fraction of porosity V_f of a porous material is one of the essential characteristics of a structure. As a definition, it is expressed by the following equation [13]:

$$V_f(\%) = 100 \times \frac{\rho_{eff}}{\rho_{PLA}} \quad (1)$$

where $\rho_{eff} = m_{eff}/V_{eff}$ is the effective mass density deduced from the measurements of m_{eff} the effective mass and V_{eff} the effective volume of the rectangular parallelepipeds shape, and ρ_{PLA} is the density of PLA material, which is supplied by the manufacturer: $1240 \text{ kg}\cdot\text{m}^{-3}$. As a result, the porosity ratio $V_f(\%)$ is determined for each combination of printing pattern and filling density.

2.3 Ultrasonic characterization

Measurement positions

Ultrasound measurements were conducted by positioning a pair of transducers in contact with both sides of the perimeter specimens. This setup facilitated the determination of longitudinal and transverse wave velocities. Time-of-flight measurements were taken in three measurement directions for each of the three studied filling patterns: Directions {1; 2; 3} along axes {X; Y; Z}, respectively (Table 1).

In this study, two types of contact transducers were used, the first type capable of producing longitudinal waves, and the second type for producing transverse waves. These transducers generate waves at a frequency of 2.25 MHz, with a diameter of

15 mm. The experimental setup for ultrasonic measurements is depicted in Figure 1, each pair of transducers (SF024, ndtXducers, Englewood, FL, USA) are placed on each side of the sample, in direct contact with it. These transducers are connected to a broadband pulse generator and receiver. Ultrasound signals reflected by or transmitted through the sample are captured using a LeCroy HDO6034 digital oscilloscope. Subsequently, these acquired signals are meticulously processed to evaluate the acoustic properties of the sample under investigation.

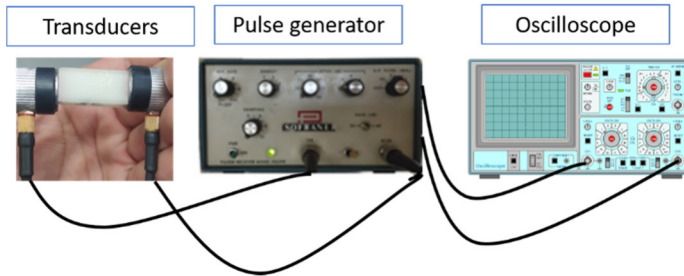


Fig. 1. Experimental setup

Evaluation of the longitudinal and transverse wave velocities

A parametric study is carried out on the FFF samples, to evaluate the influence of the number of contours versus the ultrasonic Young's modulus. In this aim, the acquired signals displaying the transmitted echoes are then analyzed to extract the longitudinal wave velocities c_L and transverse wave velocities c_T (Fig. 2).

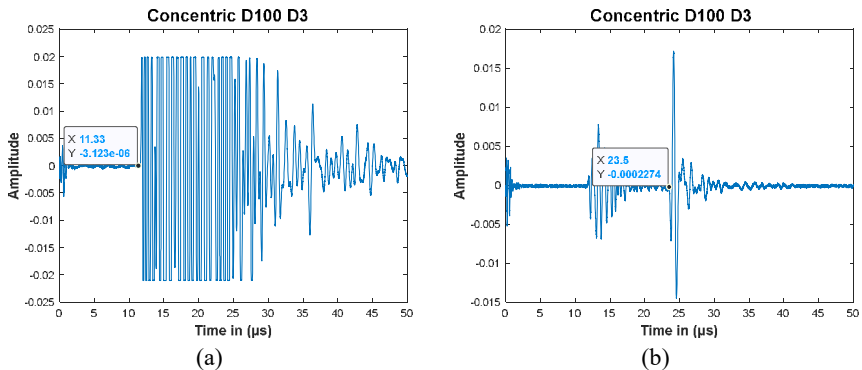


Fig. 2. Signals obtained and time indicators for identifying the time-of-flight of the longitudinal τ_L (a) and transverse τ_T (b).

The wave velocities are deduced from time-of-flight measurements where τ_L is the arrival time of the longitudinal wave, τ_T is the arrival time of the transverse wave, and D is the distance traveled by the wave:

$$\begin{cases} c_L = \frac{D}{\tau_L} \\ c_T = \frac{D}{\tau_T} \end{cases} \quad (2)$$

Next, it is necessary to convert the wave velocities into elastic properties such as Young's modulus (E). The transverse velocity (c_T) allows obtaining the shear modulus (G), while the longitudinal velocity (c_L) allows obtaining the P wave modulus (M).

$$\begin{cases} G = \rho c_T^2 \\ M = \rho c_L^2 \end{cases} \quad \text{and} \quad E = \frac{G(3M-4G)}{M-G} \quad (3)$$

3 Results

As a parametric study, the effect of the printing parameter reversed as density is varied from 70 to 100% among the defined values {100%; 90%; 80%; 70%}, while considering two values for the number of contours {0; 3}. Thus, the effect of the density parameter is studied in terms of impact on the evaluated ultrasonic Young's modulus E .

3.1 Density effect on Young's modulus E for Line infill pattern

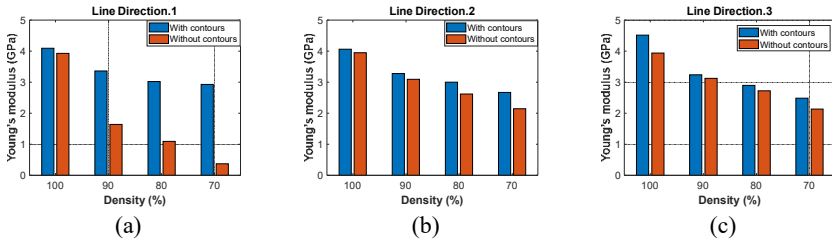


Fig. 3. Young's modulus E as function infill density for Line infill pattern: (a) Direction 1, (b) Direction 2, (c) Direction 3

Figure 3 illustrates the impact of density on the Young's modulus E in different directions of ultrasonic measurement. Overall, Young's modulus decreases with decreasing density, regardless of the measurement direction.

Along Direction 1, the number of contours significantly influences Young's modulus E . At a density of 100%, the effect of the number of contours is negligible. However, at a density of around 70%, a significant decrease in Young's modulus is observed for samples without contours. This can be explained by the fact that ultrasonic measurements are taken in the across direction of the filaments, resulting in energy loss of the waves due to barriers created in this case. Conversely, when samples are provided with contours, ultrasonic waves directly penetrate the contours (Fig. 4).

Along Direction 2, the number of contours has a slight impact on Young's modulus E because ultrasonic measurements are taken in the same direction as the filaments (along the Y-axis), thus avoiding a significant influence of sample porosity on wave propagation.

Along Direction 1 and 2, the contours introduce discontinuities within the material that interact with the ultrasonic waves. These discontinuities disrupt the wave paths, causing scattering and reflection of the waves, which in turn decreases the wave velocity. When contours are present, they provide additional paths for the waves to propagate along, leading to the phenomenon of guided waves. This guided wave propagation is influenced by the material's microstructure, as the contours create regions of varying density and elasticity, affecting how the waves travel through the material.

Along Direction 3, Young's modulus E is higher than in the other two directions. Ultrasonic measurements are taken along the height of the sample (along the Z-axis); and therefore, the removal of contours does not result in a significant difference because, in this case, the successive layers present a homogeneous medium. Moreover, in this direction, the wave propagation speed is influenced by the porosity generated between the filaments (infill density) rather than that between the layers.

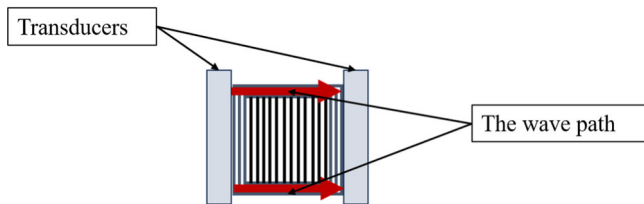


Fig. 4. The wave path in the case with contours

In 2022, Siddique et al. [14] mentioned that open-cell structures exhibit strength concentrated only along the cell edges, while closed-cell structures have strong membranes covering the cell faces. In 1982, Gibson and Ashby [15] noted that

despite this difference, the two types of structures provide comparable rigidity, thanks to the main support coming from the cell edges. For this we can understand the appearance of the guided wave phenomenon in porous samples only in the first measurement direction because the contours present a solidity which allows the passage of the wave.

For this infill pattern, the experimental values for directions 2 and 3 are close. However, the experimental values for direction 1 are significantly different compared to the other two directions. This indicates that this infill pattern imparts an anisotropic structure to the material.

3.2 Density effect on Young's modulus E for Combined infill pattern

Figure 5 depicts how density influences Young's modulus E across various ultrasonic measurement directions. Overall, Young's modulus decreases with decreasing density, regardless of the measurement direction.

For the first two directions (1 and 2) along the X and Y axes, respectively, the presence of contours has a slight influence when the density is within the range of [100, 90] %. However, beyond 90% density, a significant influence is observed. This observation can be attributed to the phenomenon where in denser samples, ultrasonic waves propagate more uniformly and consistently. In these directions, some isotropy is observed, resulting in similar outcomes for directions 1 and 2.

Regarding Direction 3 along the Z axis, although contours are not directly aligned in this direction, their presence still influences Young's modulus. The measurement technique used to calculate the propagation velocities of longitudinal and transverse $\{c_L, c_T\}$ waves is based on the principle of the first arrival of the wave. When the sample becomes more porous, the sound wave is propagating through the contours of the sample.

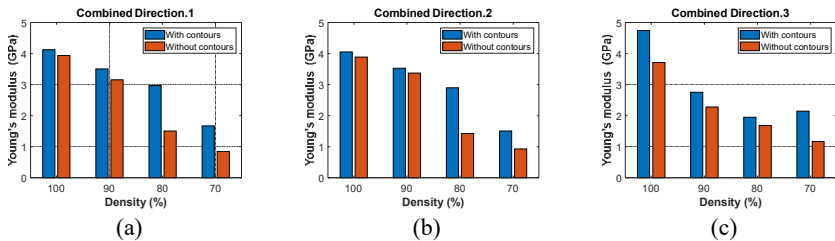


Fig. 5. Young's modulus E as function infill density for Combined infill pattern: (a) Direction 1, (b) Direction 2, (c) Direction 3

For the combined infill pattern, the experimental values for directions 1 and 2 are similar. However, the experimental values for direction 3 are significantly different from those in the other two directions. This indicates that this infill pattern imparts a uniaxial anisotropic structure to the material.

3.3 Density effect on Young's modulus E for Concentric infill pattern

Figure 6 demonstrates a notable reduction in Young's modulus E with decreasing density, irrespective of the number of contours present.

For directions 1 and 2, the number of contours did not influence the mechanical properties of the sample because the filling pattern already included contours. Therefore, adding additional contours had no impact on Young's modulus. Any minor differences observed can be attributed to measurement errors. The similar results observed in Fig.6a, 6b indicate isotropy in these two directions.

Regarding Figure 6c, the number of contours also has no influence on the mechanical properties of the sample. In this case, the phenomenon remains the same: the waves always propagate along the Z-axis, crossing the successive layers that make up the sample. These successive layers create a homogeneous environment since the studied parameters do not lead to variations along this axis.

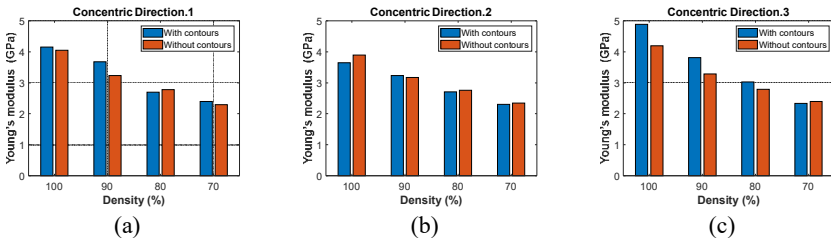


Fig. 6. Young's modulus E as function infill density for Concentric infill pattern: (a) Direction 1, (b) Direction 2, (c) Direction 3

For the concentric infill pattern, the experimental values in directions 1 and 2 are similar. However, the values in direction 3 are markedly different from those in the other two directions. This suggests that this infill pattern imparts a uniaxial anisotropic structure to the material.

4 Conclusion

This study highlights the efficiency of a non-destructive characterization technique in emphasizing the crucial importance of the number of contours as a key parameter in the filament fusion fabrication (FFF) process. The results obtained from various infill patterns, notably the line and combined infill patterns, underscore the significant impact of the number of contours on the mechanical properties of the samples. The number of contours leads to structural heterogeneity whatever the filling pattern used. In the ultrasonic measurement directions 1 and 2, the number of contours has a major influence on the Young's modulus when the samples are dense (with a density rate exceeding 90%). However, a density lower than 80% reveals a significant influence of the number of contours on the mechanical properties. These observations emphasize the crucial importance of considering the number of contours in FFF sample fabrication, particularly under lower density conditions, to ensure optimal mechanical performance.

For concentric infill pattern, it is worth noting that it did not have a significant impact on the studied mechanical properties, as it is primarily characterized by contours. Therefore, it is not appropriate to compare its effects with those of other infill patterns. However, concerning both the concentric and combined infill patterns, it is interesting to highlight the observation of isotropy in the first two measurement directions, namely along the X and Y axes. This isotropy suggests uniformity in the mechanical properties of the samples in these directions, which may be an important aspect to consider when analyzing the performance of parts manufactured by FFF.

The effectiveness of this non-destructive technique (NDT) provides motivation to study other printing parameters such as layer thickness, in order to generate porosity between layers that will influence the third direction, and to make a comparison between this measurement technique and a destructive technique (DT) such as compression test.

References

1. R. Pugliese et al, "Artificial intelligence-empowered 3D and 4D printing technologies toward smarter biomedical materials and approaches," *Polymers*, vol. 14, no. 14, p. 2794, Jul. 2022, doi: 10.3390/polym14142794.
2. G. Prashar et al, "Additive manufacturing: expanding 3D printing horizon in industry 4.0," *Int J Interact Des Manuf*, vol. 17, no. 5, pp. 2221–2235, Oct. 2023, doi: 10.1007/s12008-022-00956-4.

3. M. Revilla-León et al, “Additive manufacturing technologies used for processing polymers: current status and potential application in prosthetic dentistry,” *Journal of Prosthodontics*, vol. 28, no. 2, pp. 146–158, Feb. 2019, doi: 10.1111/jopr.12801.
4. S. T. Sikkhosana et al, “Poly(lactic acid) and its composites as functional materials for 3-D scaffolds in biomedical applications: A mini review of recent trends,” *Express Polym. Lett.*, vol. 15, no. 6, pp. 568–580, 2021, doi: 10.3144/expresspolymlett.2021.48.
5. P. R. Sreeraj et al, “A review on non-destructive evaluation and characterization of additively manufactured components,” *Prog Addit Manuf*, vol. 7, no. 2, pp. 225–248, Apr. 2022, doi: 10.1007/s40964-021-00227-w.
6. J. D. Kechagias et al, “A multi-parametric process evaluation of the mechanical response of PLA in FFF 3D printing,” *Materials and Manufacturing Processes*, vol. 38, no. 8, pp. 941–953, Jun. 2023, doi: 10.1080/10426914.2022.2089895.
7. I. J. Solomon et al, “A review on the various processing parameters in FDM,” *Materials Today: Proceedings*, vol. 37, pp. 509–514, 2021, doi: 10.1016/j.matpr.2020.05.484.
8. Witkin et al, “Experimental nondestructive characterization of an aluminum alloy prepared by powder-bed additive manufacturing,” 2018.
9. W. Kuczko et al, “Mechanical properties and geometric accuracy of angle-shaped parts manufactured using the FFF method,” *Bulletin of the Polish Academy of Sciences Technical Sciences*, pp. 137387–137387, May 2021, doi: 10.24425/bpasts.2021.137387.
10. S. Charlon et al, “Thermal and geometry impacts on the structure and mechanical properties of part produced by polymer additive manufacturing,” *J of Applied Polymer Sci*, vol. 137, no. 35, p. 49038, Sep. 2020, doi: 10.1002/app.49038.
11. N. Che Maideen et al, “the effect of different slicing software on the manufacturing performance of 3d printed parts,” *JM*, pp. 72–80, Nov. 2023, doi: 10.11113/jm.v46.490.
12. T. M. Medibew et al, “Analysis and optimization of FFF process parameters to enhance the mechanical properties of 3D printed PLA products,” *International Polymer Processing*, vol. 38, no. 1, pp. 61–76, Mar. 2023, doi: 10.1515/ipp-2022-4237.
13. H. S. Seddeq et al, “Investigation on sound absorption properties for recycled fibrous materials,” *Journal of Industrial Textiles*, vol. 43, no. 1, pp. 56–73, Jul. 2013, doi: 10.1177/15280837124446956.
14. S. H. Siddique et al, “Lessons from nature: 3D printed bio-inspired porous structures for impact energy absorption – A review,” *Additive Manufacturing*, vol. 58, p. 103051, Oct. 2022, doi: 10.1016/j.addma.2022.103051.
15. L. J. Gibson et al « The mechanics of three-dimensional cellular materials », *Proc. R. Soc. Lond. A*, vol. 382, n° 1782, p. 43-59, 1982, doi: 10.1098/rspa.1982.0088.