

Influence of Nozzle Temperature, Nozzle Diameter, and Layer Height on Tensile and Hardness Characteristics of 3D Printed CF-PLA

Karthikeyan R^{1,*}, Pradeep V P², Rajkumar S³, Karthikeyan A G⁴, Gobinath K⁵

Abstract

This research investigates the mechanical characterization of CF-PLA (Carbon Fiber-reinforced Polylactic Acid) composite material produced using Fused Deposition Modeling (FDM) technology. The study investigates the impact of different machine parameters, like nozzle temperature, nozzle diameter, and layer height, on the tensile property and hardness of CF-PLA specimens. A total of 27 samples were produced, each with different combinations of nozzle temperature (190°C, 200°C, and 210°C), nozzle diameter (0.4mm, 0.5mm, and 0.6mm), and layer height (0.1mm, 0.2mm, and 0.3mm). The specimens mechanical properties were assessed through tensile testing and hardness evaluations. The results indicate that variations in nozzle temperature, nozzle diameter, and layer height significantly influence the mechanical performance of the CF-PLA material. Tensile testing reveals a clear trend of increasing peak load and ultimate tensile strength with higher nozzle temperatures and decreased layer heights, emphasizing the crucial role of printing parameters in mechanical strength. Shore D hardness test results demonstrate consistent hardness values across samples, with average hardness ranging from 79.67 to 82.167. The quantitative analysis underscores the multifaceted nature of CF-PLA materials, where tensile strength is influenced by printing parameters, hardness remains relatively stable. These findings are pivotal for optimizing material compositions and fabrication parameters to tailor mechanical properties for specific applications, ensuring enhanced performance and durability in diverse engineering contexts.

Keywords: Fused deposition modeling, CF-PLA, nozzle diameter, tensile strength, hardness test

INTRODUCTION

3D printing often refer as additive manufacturing and rapid prototyping, involves creating three-dimensional objects or components by sequentially adding material layers based on digital model data.

*Author for Correspondence

Karthikeyan R

^{1,2,3}Assistant Professor, Department of Mechanical Engineering, Dr. N.G.P. Institute of Technology, Coimbatore, India

⁴ Assistant Professor, School of Mechanical Engineering, Reva University, Bengaluru, Karnataka, India

⁵ Assistant Professor, Department of Automobile Engineering, K.S.R College of Engineering, Tiruchengode, India

Received Date: August 22, 2024

Accepted Date: October 05, 2024

Published Date: November 14, 2024

Citation: Karthikeyan R, Pradeep V P, Rajkumar S, Karthikeyan A G, Gobinath K. Influence of Nozzle Temperature, Nozzle Diameter, and Layer Height on Tensile and Hardness Characteristics of 3D Printed CF-PLA. Journal of Polymer & Composites. 2025; 13(Special Issue 1): S674–S681p.

Unlike subtractive or formative manufacturing methods, AM builds parts layer by layer, enhancing the speed and flexibility of both the design and production processes. This technology not only complements traditional manufacturing but also allows for the efficient production of complex and customized designs, significantly reducing time and costs[1]. Today, additive manufacturing is increasingly valued for its ability to quickly produce end-use parts. 3D printing minimizes material waste, streamlines operations, lowers production costs, and reduces logistical challenges. It is now widely employed across a range of industries, including automotive, aerospace, medical, food, textiles and electronics, education, and even household uses [2]. Additive Manufacturing (AM)

technologies include Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM). Other methods like direct jetting, photopolymer jetting, and hybrid processes also play significant roles. Each technology offers unique advantages depending on material and application requirements[3]. Amongst these, FDM technology is the most popular due to its ease of use, economic accessibility, and the wide commercial availability of its raw materials. The primary source materials for additive manufacturing are thermoplastics and metals. On the other hand, FDM is still an emerging technology, and the parts it produces do not yet match the quality of injection-molded parts. The layered nature of the FDM process often leads to anisotropic mechanical properties and reduced dimensional accuracy in 3D printed parts. Additionally, these parts are prone to the staircase effect and typically have a coarse surface finish, necessitating post-processing or machining to achieve smooth surfaces[4]. In FDM, a rough surface can delay parts assembly and limit joint movement.

In FDM 3D printing, filaments are used as feedstock materials to produce parts. Among all the available filaments, polylactic acid (PLA) is the most widely used due to its lower cost and compatibility with most 3D printers. However, the mechanical properties of PLA are relatively low compared to other engineering materials, and the printed parts are not suitable for applications requiring high mechanical performance[5]. To overcome this limitation, carbon fiber (CF) reinforced PLA (CF-PLA) has been developed. CF-PLA combines the advantages of PLA, such as low cost and easy availability, with the improved mechanical properties of CF. The addition of CF to PLA increases the strength and stiffness of the printed parts, making them more suitable for applications requiring higher mechanical performance. Despite the advantages of CF-PLA, several 3D printing parameters influence the mechanical properties of the printed parts. These include nozzle diameter, printing temperature, and layer height. Nozzle diameter is the size of the hole through which the filament is extruded during the printing process. Printing temperature is the temperature of the hot end of the 3D printer. Layer height is the thickness of the layers of material added during the 3D printing process[6]. During the FDM process, a thermoplastic polymer filament is melted and extruded, depositing the material strand onto a build plate, Figure 1. The movement of the nozzle determines the deposition of the strand in the x and y directions of a plane. The three-dimensional workpiece is then constructed layer by layer in the z direction[7]. It is important to understand how these parameters affect the mechanical properties of the printed parts so that they can be optimized for the desired application. The purpose of this study was to investigate the influence of nozzle diameter, printing temperature, and layer height on the mechanical properties of ASTM specimen's 3D printed using CF-PLA filament[8]. The ASTM specimens were subjected to tensile and flexural tests as per ASTM standards to evaluate the mechanical properties. This approach aligns with the broader scope of additive manufacturing (AM), where specimens are created by adding material layers based on digital CAD models. AM technologies, such as FDM, enable the efficient production of complex and customized designs while reducing both time and costs. In alignment with the broader research fields of polymer processing and composite materials, this work contributes to the ongoing efforts to advance the manufacturing of high-performance, customized components. The findings have significant implications for various industries, including automotive, aerospace, and medical applications, where optimized polymer composites are essential for achieving superior mechanical performance and surface quality. The investigation of CF-PLA materials and the optimization of printing parameters to improve mechanical properties directly support ongoing research in polymer processing and fused filament materials.

In recent years, a substantial amount of research has been devoted to improving the quality of FDM parts. However, the complexity arises from the multitude of processing parameters that influence both the mechanical properties and dimensional accuracy of these parts. Understanding the intricate effects and interactions among these parameters on the final quality of FDM parts necessitates extensive testing runs and a thorough analysis process[9]. To streamline this exploration and minimize complexity, researchers and industry professionals frequently employ Design of Experiments (DOE) techniques. These methods are invaluable for optimizing processes, reducing the number of required runs, and simplifying the analysis procedures involved in FDM manufacturing[10].

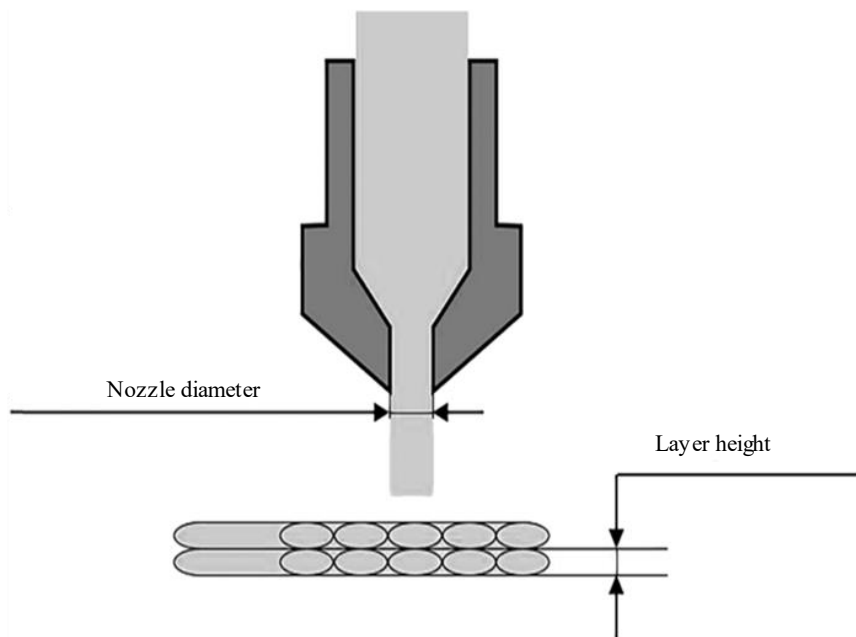


Figure 1. FDM machine parameters of nozzle diameter (D) and layer height (H).

EXPERIMENTS AND METHODS

Equipment

The test samples were fabricated using the Creality Ender-3 Pro FDM 3D printer, Figure 2. This versatile and reliable machine is well-suited for detailed research on CF-PLA printed parts. The Creality Ender-3 Pro offers an excellent platform due to its precision, dependability, and flexibility in handling various materials. Its capability to control parameters such as nozzle temperature, layer height, and printing speed is essential for conducting experiments and optimizing the printing process.

Specimen Preparation

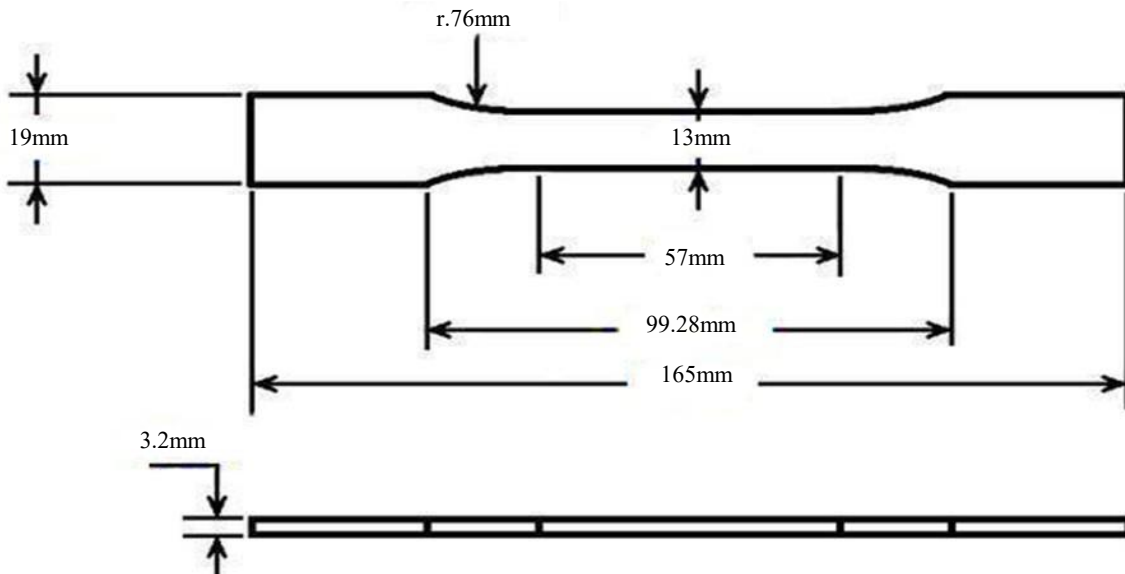
In this study, the effects of nozzle temperature, layer height, and nozzle diameter on the mechanical properties of the fabricated samples were investigated to understand the influence of these manufacturing process parameters, Table1. All the specimens were printed using the CF-PLA filament by same FDM machine. The samples shapes and dimensions were adapted to ASTM D638 for tensile test, Fig.3 and ASTM D2240 for the hardness test[11]. Multiple specimens are printed to ensure repeatability and accuracy. After printing, the specimens were rinsed with acetone to remove any residual support material[12].



Figure 2. Creality ender-3 Pro FDM 3D printer.

Table 1. Parameters of FDM of CF-PLA.

Parameters	Value range
Build Volume (mm)	220 x 220 x 250
Nozzle Diameter (mm)	0.4, 0.5, 0.6
Nozzle temperature (°C)	190, 200, 210
Bed temperature	60°C
Raster angle	0°
Printing speed (mm/s)	40-80 (recommended)
Filament diameter (mm)	1.75
Layer thickness (mm)	0.2
Volume bulk density	100%
Line height (mm)	0.1, 0.2, 0.3
Infill pattern	Line
Slicing software	Cura

**Figure 3.** ASTM D638 – tensile specimen.

Methodology

To investigate the influence of extrusion temperature, nozzle diameter, and layer height, we employed Taguchi's L9 Design of Experiments (DOE). Taguchi's DOE was chosen for its use of orthogonal arrays, ensuring that each parameter has equal weights and enabling the achievement of an finest design with the lowest number of runs and least cost. For three parameters at three levels each, only the main effects can be observed without interactions, Table 2. Each run was replicated 3 times, resulting in a total of 27 specimens fabricated to ensure repeatability in the resulting properties[13]. The S/N ratio aids in determining the optimal settings for process parameters. It highlights which settings provide the best performance by considering both the mean and variability of the response.

Mechanical Testing

To evaluate the tensile, hardness, and crystalline properties of the FDM parts, we first measured the mass of the specimens. The specimens were then tested according to ASTM D638 and ASTM D2240 standards[14]. Additionally, X-ray diffraction (XRD) tests were conducted to analyze the crystalline structure of the materials. Each test was repeated three times to ensure repeatability[15].

Table 2. Experimental plan based on Taguchi L9.

Run	Nozzle Temperature (°C)	Nozzle Diameter (mm)	Layer Height (mm)	Number of specimens
1	190	0.4	0.1	3
2	190	0.5	0.2	3
3	190	0.6	0.3	3
4	200	0.4	0.2	3
5	200	0.5	0.3	3
6	200	0.6	0.1	3
7	210	0.4	0.3	3
8	210	0.5	0.1	3
9	210	0.6	0.2	3

RESULTS AND DISCUSSION

The Taguchi method provides a systematic approach for optimizing parameters and improving product quality by utilizing orthogonal arrays (OAs) to study a large number of variables with a small number of experiments. For this study, we employed a Taguchi L9 design to investigate the influence of nozzle temperature, nozzle diameter, and layer height on the ultimate tensile strength (UTS) of FDM parts. The L9 orthogonal array is used to systematically vary the three parameters at three levels across nine experiments, Table.3. and signal-to-noise ratio (S/N) graphs were created for "larger-the-better" characteristic. The Signal-to-Noise (S/N) ratio is a crucial metric in research, especially in the context of the Taguchi method for design of experiments (DOE).

$$S/N \text{ ratio} = -10 \log \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right)$$

Tensile Test

The stress-strain curves for the specimens show a linear relationship, indicating elastic behavior within the tested strain range. The ultimate tensile strength (UTS) varies significantly among different runs, underscoring the influence of FDM parameters on tensile properties. For example, runs at 190°C (Runs 1, 2, and 3) exhibit higher tensile strengths, with Run 3 (190°C, 0.6 mm nozzle, 0.3 mm layer height) achieving the highest UTS of 65.34 MPa. Conversely, runs at 210°C show much lower tensile strengths, with Run 8 (210°C, 0.5 mm nozzle, 0.1 mm layer height) having the lowest UTS of 34.41 MPa. Increasing the nozzle diameter from 0.4 mm to 0.6 mm generally results in higher UTS within the same temperature category, suggesting that larger nozzles may improve tensile strength by enhancing layer adhesion and reducing voids. Although the layer height also affects tensile strength, the pattern is not consistent across all temperatures, indicating the need for further investigation. Runs 5 and 6, conducted at 200°C with varying nozzle diameters and layer heights, show high tensile strengths of 68.42 MPa and 68.61 MPa, respectively, highlighting the effectiveness of this temperature setting. The consistent linearity of the stress-strain curves across different runs demonstrates good repeatability of the testing conditions and material behavior. These findings highlight the potential for optimizing FDM parameters to achieve desired mechanical properties. Notably, a nozzle temperature of 190°C combined with a 0.6 mm nozzle diameter and a 0.3 mm layer height (Run 3) results in the highest tensile strength among the tested conditions.

The Signal-to-Noise (S/N) ratio analysis highlights key trends in optimizing Fused Deposition Modeling (FDM) parameters for achieving high ultimate tensile strength (UTS). Higher S/N ratios, indicating better tensile performance, are generally associated with lower nozzle temperatures and larger nozzle diameters. For instance, runs conducted at 190°C exhibit higher S/N ratios compared to those at 210°C, with Run 3 (190°C, 0.6 mm nozzle, 0.3 mm layer height) achieving the highest S/N ratio of 36.31 dB. This trend suggests that higher nozzle temperatures negatively impact tensile strength. Additionally, increasing the nozzle diameter from 0.4 mm to 0.6 mm results in higher S/N ratios within

the same temperature category, as seen in Run 6 at 200°C with an S/N ratio of 36.72 dB. The effect of layer height on S/N ratios is less consistent, indicating that other factors also influence tensile strength. Overall, the analysis underscores the importance of optimizing FDM parameters, particularly nozzle temperature and diameter, to enhance tensile strength.

Hardness Test

The hardness test results across the nine runs reveal some interesting trends related to FDM parameters, such as nozzle temperature, nozzle diameter, and layer height. The hardness values for runs conducted at 190°C and 200°C are relatively consistent, ranging from approximately 79 to 82, indicating that within this temperature range, nozzle temperature does not significantly affect hardness. At 210°C, the hardness values remain within a similar range (around 81-82), suggesting that further increasing the temperature does not significantly impact hardness. Nozzle diameter does not show a clear and consistent impact on hardness values; for instance, at 190°C, hardness values are 79.67, 80.33, and 82 for different nozzle diameters. Similarly, at 200°C and 210°C, hardness values remain in the narrow range of 79 to 82 regardless of nozzle diameter. This indicates that nozzle diameter does not significantly affect the hardness of the specimens. Additionally, layer height does not show a consistent trend affecting hardness. Runs with different layer heights at the same nozzle temperature and diameter still fall within the 79 to 82 range, suggesting that layer height, within the tested parameters, does not significantly influence the material's hardness. This suggests that the hardness of the material is relatively insensitive to the specific FDM parameters used in this study, indicating good repeatability and stability of the hardness property within the tested conditions.

Table 3. The measurements were averaged across three specimens.

Run	Nozzle temperature (°C)	Nozzle diameter (mm)	Layer height (mm)	Area (mm ²)	Peak load (kN)	UTS (MPa)	S/N ratio (dB)	Hardness test
1	190	0.4	0.1	41.622	2.09	50.20	33.71	79.66
2	190	0.5	0.2	41.622	2.53	60.77	35.68	80.33
3	190	0.6	0.3	41.622	2.72	65.34	36.31	82
4	200	0.4	0.2	41.622	2.78	66.79	36.49	82.16
5	200	0.5	0.3	41.622	2.849	68.42	36.70	79.16
6	200	0.6	0.1	41.622	2.857	68.61	36.72	82.16
7	210	0.4	0.3	41.622	1.411	33.89	30.60	81
8	210	0.5	0.1	41.622	1.432	34.41	30.73	82.33
9	210	0.6	0.2	41.622	1.523	36.59	31.27	82.5

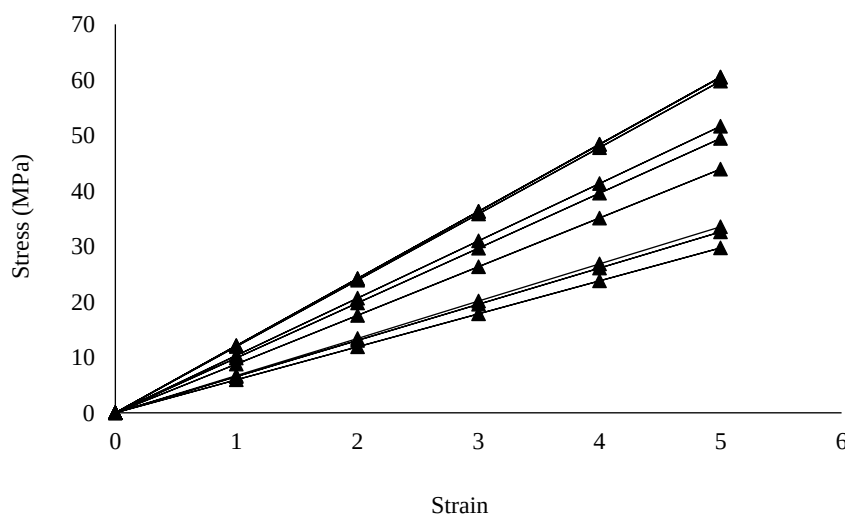


Figure 4. Stress strain plot.

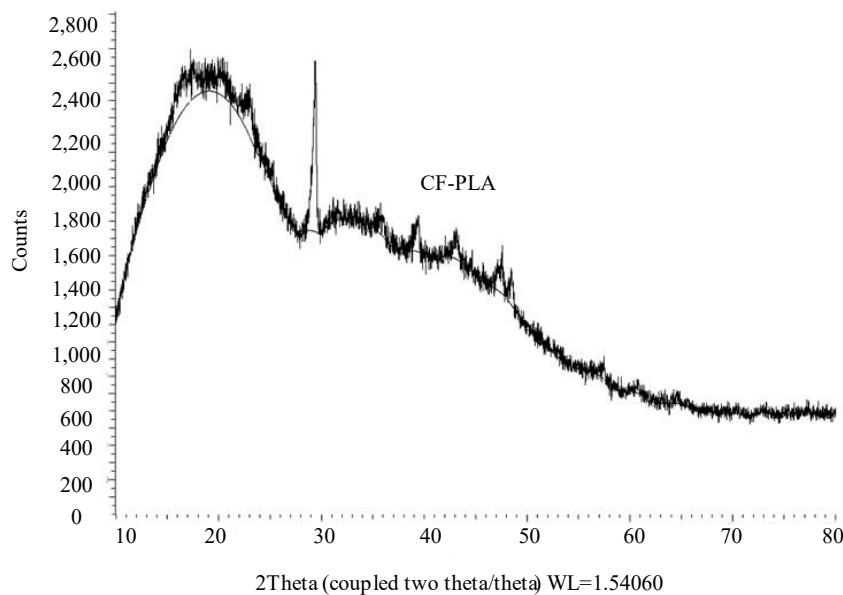


Figure 5. XRD characterization.

XRD Characterization

The X-ray diffraction (XRD) pattern provided reveals key structural characteristics of the composite material, distinguishing between Carbon Fiber (CF) and Polylactic Acid (PLA). The broad peak around 20° 2θ indicates the presence of well-dispersed carbon fiber with some degree of crystallinity, while the sharp peak around 30° 2θ corresponds to the crystalline structure of PLA. The high intensity of these peaks, reaching up to 2600 counts, signifies the significant presence and crystallinity of these materials. Additionally, the gradual decline in intensity from 30° to 80° 2θ reflects the presence of an amorphous phase or less ordered structures within the composite. Overall, the XRD pattern demonstrates that the composite contains both crystalline and amorphous phases, with distinct peaks highlighting the structural characteristics and distribution of CF and PLA within the material, Figure 4-5.

CONCLUSION

This study investigated the effects of nozzle temperature, nozzle diameter, and layer height on the mechanical properties of CF-PLA specimens fabricated using FDM technology. Using a Taguchi L9 orthogonal array, we varied these parameters across nine experimental runs. Results indicated that a nozzle temperature of 190°C , combined with a 0.6 mm nozzle diameter and 0.3 mm layer height, produced the highest ultimate tensile strength (UTS) of 60.508 MPa. Conversely, a higher temperature of 210°C generally resulted in lower UTS. The hardness values were consistent across all temperatures, ranging from 79.67 to 82.67, indicating minimal impact from temperature variations. The findings highlight the importance of optimizing FDM parameters to enhance the mechanical performance of CF-PLA composites, particularly for achieving high tensile strength. Future research should explore additional properties and parameter interactions to further improve the material's performance in engineering applications. These results underscore the importance of optimizing FDM parameters to enhance the mechanical performance of CF-PLA composites. Future research should explore additional properties and investigate the interactions between different parameters to further improve material performance in engineering applications. This could include testing different filament materials, advanced post-processing techniques, and assessing long-term durability under various operational conditions.

Declaration of Interest

The authors declare no conflicts of interest regarding the research presented in this article. This work was conducted impartially, and there are no financial, personal, or professional affiliations that could be perceived as influencing the research outcome. The authors affirm their commitment to maintaining the highest standards of integrity and transparency in reporting their findings.

REFERENCES

1. M. Askari et al., "Additive manufacturing of metamaterials: A review," *Addit Manuf*, vol. 36, Dec. 2020, doi: 10.1016/j.addma.2020.101562.
2. D. Zindani and K. Kumar, "An insight into additive manufacturing of fiber reinforced polymer composite," Dec. 01, 2019, KeAi Publishing Communications Ltd. doi: 10.1016/j.ijlmm.2019.08.004.
3. K. Rajaguru, T. Karthikeyan, and V. Vijayan, "Additive manufacturing-State of art," in *Materials Today: Proceedings*, Elsevier Ltd, 2020, pp. 628–633. doi: 10.1016/j.matpr.2019.06.728.
4. M. N. Ahmad and A. Yahya, "Effects of 3D Printing Parameters on Mechanical Properties of ABS Samples," *Designs (Basel)*, vol. 7, no. 6, Dec. 2023, doi: 10.3390/designs7060136.
5. W. J. Chong et al., "Biodegradable PLA-ZnO nanocomposite biomaterials with antibacterial properties, tissue engineering viability, and enhanced biocompatibility," *Smart Materials in Manufacturing*, vol. 1, p. 100004, 2023, doi: 10.1016/j.smmf.2022.100004.
6. M. N. Ahmad and A. Yahya, "Effects of 3D Printing Parameters on Mechanical Properties of ABS Samples," *Designs (Basel)*, vol. 7, no. 6, Dec. 2023, doi: 10.3390/designs7060136.
7. M. Caputo, O. Rashwan, D. Waryoba, and K. McDade, "Surface texture and thermo-mechanical properties of material extruded and ironed polylactic acid," *Addit Manuf*, vol. 59, Nov. 2022, doi: 10.1016/j.addma.2022.103084.
8. R. Karthikeyan, V. P. Pradeep, S. Rajkumar, and K. Gobinath, "Effect of Combined Internal Structure on Mechanical Properties of FDM 3D Printed Parts," *Materials Science Forum*, vol. 1120, pp. 61–67, Apr. 2024, doi: 10.4028/p-wgqyy2.
9. A. Rodríguez-Panes, J. Claver, and A. M. Camacho, "The influence of manufacturing parameters on the mechanical behaviour of PLA and ABS pieces manufactured by FDM: A comparative analysis," *Materials*, vol. 11, no. 8, Aug. 2018, doi: 10.3390/ma11081333.
10. A. Alafaghani and A. Qattawi, "Investigating the effect of fused deposition modeling processing parameters using Taguchi design of experiment method," *J Manuf Process*, vol. 36, pp. 164–174, Dec. 2018, doi: 10.1016/j.jmapro.2018.09.025.
11. R. Sala, S. Regondi, S. Graziosi, and R. Pugliese, "Insights into the printing parameters and characterization of thermoplastic polyurethane soft triply periodic minimal surface and honeycomb lattices for broadening material extrusion applicability," *Addit Manuf*, vol. 58, Oct. 2022, doi: 10.1016/j.addma.2022.102976.
12. S. Hasanov, A. Gupta, A. Nasirov, and I. Fidan, "Mechanical characterization of functionally graded materials produced by the fused filament fabrication process," *J Manuf Process*, vol. 58, pp. 923–935, Oct. 2020, doi: 10.1016/j.jmapro.2020.09.011.
13. J. R. C. Dizon, A. H. Espera, Q. Chen, and R. C. Advincula, "Mechanical characterization of 3D-printed polymers," Mar. 01, 2018, Elsevier B.V. doi: 10.1016/j.addma.2017.12.002.
14. J. R. C. Dizon, A. H. Espera, Q. Chen, and R. C. Advincula, "Mechanical characterization of 3D-printed polymers," Mar. 01, 2018, Elsevier B.V. doi: 10.1016/j.addma.2017.12.002.
15. A. Nasirov and I. Fidan, "Prediction of mechanical properties of fused filament fabricated structures via asymptotic homogenization," *Mechanics of Materials*, vol. 145, Jun. 2020, doi: 10.1016/j.mechmat.2020.103372.