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A Review of Factors Affecting the Mechanical Performance of PLA in FDM 3D Printing

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Abstract. 3D printing has rapidly evolved due to its significant advantages in rapid prototyping. 3D-printed products for industrial applications require stable mechanical properties, which are influenced by various factors. The lack of a comprehensive discussion addressing the factors affecting mechanical properties is the main reason for this review. This article aims to provide an overview of Fused Deposition Modeling (FDM) 3D printing concerning the factors that influence the mechanical performance of FDM 3D products using polylactic acid (PLA) material. The article covers the impact of material factors, process parameters (such as layer thickness, infill patterns, print orientation, infill patterns, infill density, infill width, temperature, and printing speed), as well as post-processing treatments as key considerations. The contribution of this article is to explain to researchers and industry practitioners the factors that affect the mechanical performance of FDM 3D printed products.

Keywords: 3D Printing, Fused Deposition Modeling (FDM), Mechanical Properties, Polylactic Acid (PLA), Process Parameters

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1. Introduction

3D printers are manufacturing devices designed to produce prototypes swiftly, cost-effectively, and with minimal waste [1,2]. These machines are increasingly utilized for manufacturing products that require mechanical resistance in engineering applications. In operation, this machine creates products layer by layer, with the most widely used technology being FDM. The operating principle of FDM is to extrude melted material filament through a heated nozzle controlled by regulated movement. The hot extruded filament then solidifies to form deposits that conform to the 3D model [1]. When used for prototyping or engineering applications, the mechanical behavior of products produced by 3D printing become a crucial consideration [2‑4]. Therefore, various printing process parameters that can influence these mechanical performance must be carefully considered.

The conversion of 3D designs for the printing process is performed using slicing software, which transforms STL files into G-code. This software allows users to set process parameter values such as infill, build angle and orientation, layer thickness, printing temperature, layer thickness, and printing speed. Infill parameters include infill pattern and infill density, while printing temperature encompasses nozzle temperature and build plate temperature [7]. By considering these process parameters, the quality and mechanical behavior of the resulting 3D printed products can be better controlled [8–10]. The mechanical characteristics of FDM 3D printing products are influenced not only by the type of filament material but also by the type of 3D printer, design, slicing software, process parameters, and post-processing treatments (see Figure 1).

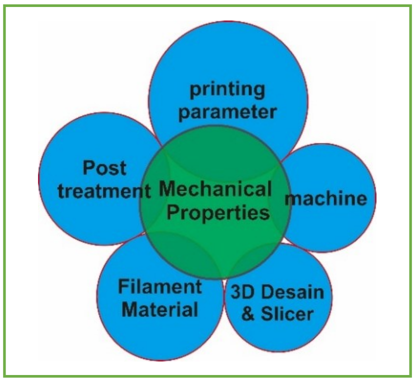

Figure 1. Factors influencing the mechanical properties of 3D printed products [5]

Polylactic Acid (PLA) is widely used in 3D printing due to its high tensile strength, low density, and higher strength-to-weight ratio compared to metallic materials. PLA is easy to print because it has a low melting point and requires minimal energy [6]. Additionally, PLA is a biodegradable polymer that does not emit harmful odors or vapors. Therefore, PLA was chosen in this study due to its low production cost and beneficial properties, including its advantages in medical applications because it is non-toxic metabolically [7‑9].

The mechanical characteristics of PLA-based products from FDM 3D printing are influenced by process parameters, which have been the focus of intensive research in recent years [10]. In the studies conducted so far, analysis of variance has been used to determine the effect of printing parameters on mechanical behavior. ANOVA has been employed to optimize process parameters with the fastest printing time while minimizing loss of final strength [11,12]. Additionally, mechanical properties are optimized to identify suitable printing process parameters through regression equations and mathematical modeling using the Taguchi method [13‑15]. Despite numerous studies, a comprehensive discussion regarding all factors influencing the mechanical properties of FDM 3D printed products is still lacking.

In the development of filament materials for 3D printing, PLA has significant potential, necessitating adequate literature to maximize its mechanical properties in printed products. This review aims to provide a comprehensive overview of the critical factors influencing the mechanical properties of products based on tensile, flexural, compressive, and other mechanical tests from various previous studies. The focus of the printing technology discussed is FDM, along with various printing parameters such as printing speed, layer thickness, printing temperature, orientation, and raster angle. Additionally, other aspects such as the type of filament material, object design, and printer brand are also discussed. The data obtained is expected to serve as a reference for researchers and the FDM 3D printing industry in designing and producing objects for applications in engineering and biomedical fields using PLA.

2. Filament

2.1 Filament Color

Filament materials are the raw materials used in 3D printing and are available in several color options. Each filament color has distinct characteristics. As shown in Figure 2, the differences in PLA filament colors under the same processing conditions result in different glass transition temperatures (Tg). Based on Dynamic Mechanical Analysis (DMA) testing, the glass transition temperature of black filament is higher compared to natural and green filaments. Thermogravimetric analysis (TGA) of the three colors shows varying degradation temperatures for each case. The green PLA has a lower initial degradation temperature compared to the others, while natural PLA exhibits a higher initial degradation temperature. The thermal degradation curves indicate that green PLA experiences a faster weight loss, followed by black PLA, and lastly the natural filament [16].

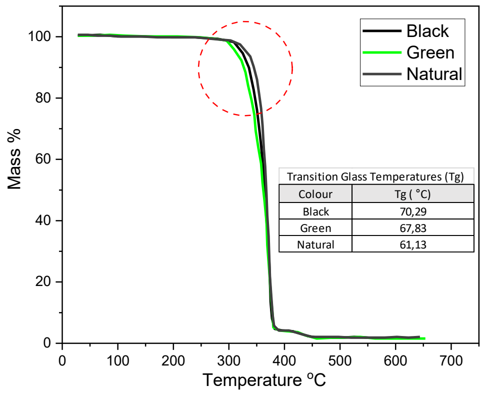

Figure 2. TGA analysis and Tg temperature of PLA colors [16]

Furthermore, the impact of different filament colors affects various aspects of FDM print results, including mechanical strength, dimensional accuracy [17,18], specimen weight [19], and tribological quality [20]. Figure 3 shows that the tensile strength of the natural color is higher compared to other colors, even at different infill densities, where the natural color remains superior [21]. Tribological tests reveal that print orientation and filament color significantly influence the tribological quality of the printed objects. In certain cases, changes in filament strength can be affected by storage conditions that alter the pigment of the filament. The filament color can fade due to moisture in the air, which affects its structural composition. A drier storage environment can enhance the strength of PLA filament but may also make it more brittle [22].

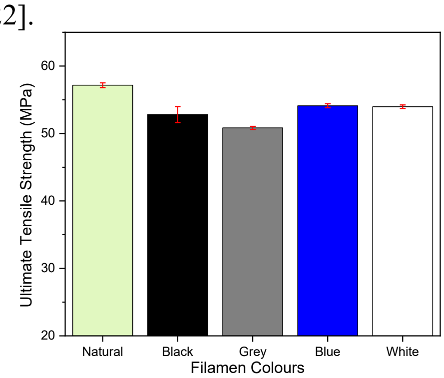

Figure 3. Differences in tensile strength values of PLA filament colors [23]

2.2 Recycled Filament

The large amount of PLA waste from industries, households, and leftover materials from 3D printing provides the foundation for using recycled PLA as filament material. Although virgin PLA has higher tensile strength compared to recycled PLA (Re-PLA) across all layer thicknesses and infill levels, research indicates that 3D printing with both PLA and Re-PLA has good potential for real-world applications, especially from the perspective of mechanical strength and environmental awareness [24]. Re-PLA remains a viable option despite the reduction in strength [25]. The feasibility of Re-PLA holds up through the second recycling process. However, in the third tensile test of Re-PLA, mechanical properties decrease by approximately 20–50%, as shown in Figure 4. A significant drop occurs during the third recycling cycle, whereas during the first and second cycles, the tensile strength only declines by about 5–18%. To mitigate excessive declines in mechanical properties, researchers mix virgin PLA with Re-PLA.

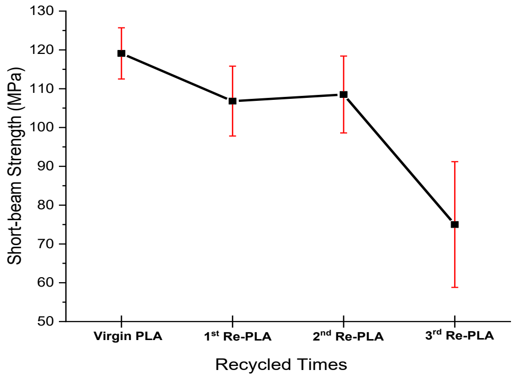

Figure 4. Decrease in mechanical strength from the Re-PLA process [25]

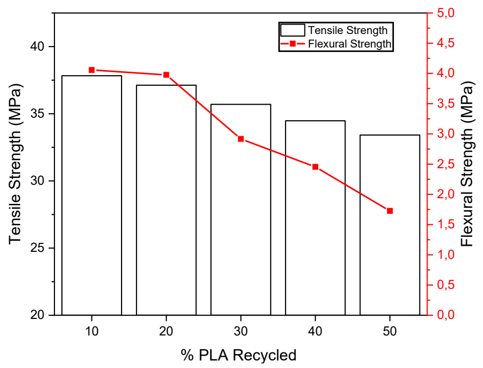

Figure 5. Effect of Re-PLA blend percentage [26]

Figure 5 shows the evaluation results of the percentage of virgin PLA and Re-PLA mixtures through tensile and bending tests. The test results indicate a drastic decrease in bending strength with a mixture containing 30% Re-PLA, while the reduction in strength with 10–20% Re-PLA mixtures is not as significant. A similar pattern is also observed in the tensile test results.

3. 3D modelling to STL file and printing machine

3D printing begins with the creation of a 3D design that is converted into a stereolithography (STL) file. The STL file is then processed using slicing software to precisely determine the nozzle movement path and the filament extrusion flow rate during the printing of the 3D structure. Predictions and experiments are conducted for various printer operating conditions, including variations in nozzle speed from slow to medium, as well as surface resolution from rough to smooth [27]. The use of different slicing software affects the dimensional accuracy and surface roughness of the 3D product due to differences in algorithms that lead to variations in the printing execution on 3D printing machines [28].

The numerous manufacturers of printers and control software result in unstandardized printing methods, so different machines can produce different mechanical properties even when using the same filament and similar parameter settings [29]. Among various open-source slicing software, Cura Ultimaker is the most widely used due to its ability to produce the best product quality [30,31]. Meanwhile, performance differences have been observed between industrial commercial 3D machines and low-cost 3D machines. Based on tensile and compressive tests, low-cost 3D machines can achieve only a maximum of 54.69% of ultimate tensile strength and 75.55% of ultimate compressive strength compared to specimens printed using commercial 3D machines [31].

4. Printing parameters

The printing parameters frequently discussed in previous research include:

4.1 Printing Orientation and Printing Angle

A crucial factor affecting the quality, strength, and production efficiency of 3D-printed parts is the printing orientation and angle. Orientation refers to how the object is positioned on the printer bed during the printing process, impacting how material layers are stacked. Additionally, orientation and printing angle influence the movement of the nozzle along the X, Y, and Z axes during product fabrication. Analysis shows that parts printed along the X-axis have higher tensile and impact strength compared to those printed along the Y and Z axes. Specifically, prints oriented along the X-axis demonstrate an increase in tensile strength of approximately 60–64% [32]. As illustrated in Figure 6, the X-axis orientation yields the highest tensile and impact strength, whereas the Z-axis orientation exhibits the lowest tensile and impact strength.

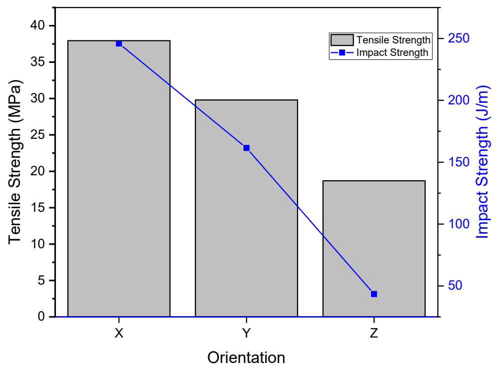

Figure 6. The Effect of Printing Orientation on Tensile and Impact Strength [33]

Printing angle refers to the inclination of an object during 3D printing. In FDM-based printing, objects with steep angles (greater than 45° from the surface) require supports to stabilize the material. Without support, steep angles can cause warping or instability since the deposited material lacks sufficient backing. At a vertical angle (90°), the tensile strength decreases by approximately 36% compared to flat angles (0°) due to differences in the fracture mode and the load direction. Lower printing angles tend to enhance strength since the tensile load aligns with the print direction [34,35]. Additionally, build time increases as the angle shifts from flat to upright [36]. Printing angle also impacts the amount of filament consumed. As illustrated in Figure 7, the flat position proves to be the most efficient compared to upright and on edge positions. This efficiency is demonstrated by the balance between tensile strength, filament usage, and printing time. In the flat position, less filament is consumed, and printing takes less time while still yielding high tensile strength compared to other orientations.

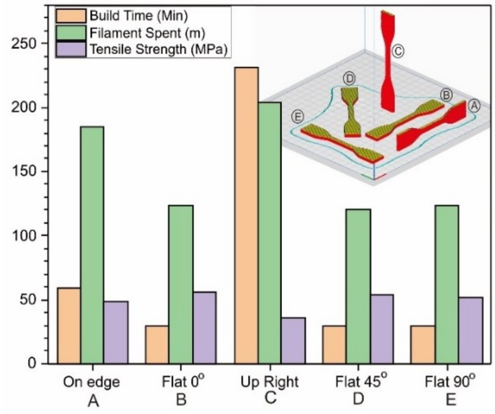

Figure 7. The impact of printing angles on tensile strength, filament, and print time [36]

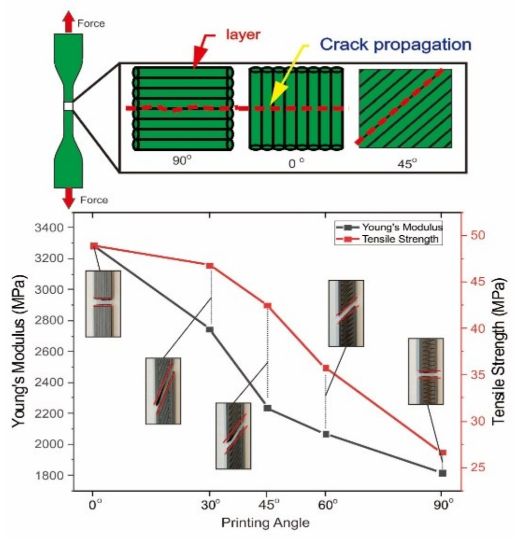

Figure 8. The influence of angle on fracture patterns and tensile test results [37]

Figure 8 illustrates the differences in fracture patterns observed in samples printed at various angles. As the product deforms, fracture mechanisms and crack propagation occur gradually, influenced by the printing angle and orientation [38]. The elastic modulus decreases with increasing print angle. The highest and lowest tensile strengths are achieved at 0° and 90°, respectively. At a 0° raster angle, the tensile load aligns with the raster direction, resulting in the highest strength. In contrast, printing at 90° leads to failure due to weaker inter-layer adhesion. Additionally, spatial orientation has a smaller impact on Young's modulus than it does on tensile strength, indicating that inter-layer bonding plays a more crucial role in tensile performance than in elasticity [39].

4.2 Infill Pattern

Infill patterns are internal structures that fill a 3D-printed object, influencing its strength, weight, material consumption, and printing time [40–42]. Popular infill patterns available in slicer software are shown in Figure 9. Among these, the grid pattern is most suitable for tensile-load-bearing specimens as it offers maximum resistance to applied tensile forces [43,44]. This finding has been validated through Finite Element Analysis (FEA), producing consistent results [45]. However, research by Rismalia M. et al. found that the concentric pattern demonstrated superior tensile strength compared to both the grid and tri-hexagon patterns [46]. The influence of infill patterns on mechanical strength, printing time, and filament consumption is summarized in Table 1. Each pattern presents trade-offs between strength, efficiency, and material usage, making it crucial to select the right one based on the specific application.

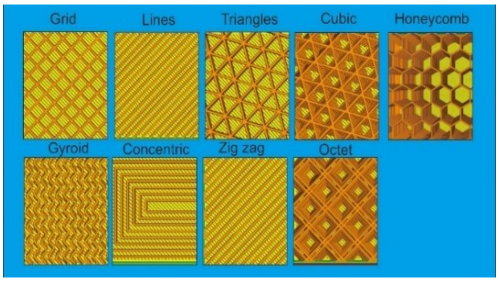

Figure 9. Variations in Infill Patterns

4.3 Infill Density

Infill density is the amount of material used to fill the interior of a 3D-printed object., expressed as a percentage. A 0% infill means the object is entirely hollow, while 100% infill indicates the object is completely solid. Infill density helps optimize printing time and material usage while still maintaining the required mechanical properties [47]. The higher the infill percentage, the better the mechanical properties, including strength, stiffness, and impact resistance [48–53]. As shown in Figure 10, PLA specimens printed with 100% infill density demonstrate the highest values for hardness, tensile strength, impact resistance, and flexural strength, with values of 97 HRC, 53 MPa, 70 J/m², and 53 MPa, respectively.

Table 1. The Influence of Infill Patterns [44,54]

Infill pattern	Strength	Time	Material need
Grid	H	M	M
Lines	L	F	L
Triangle	H	L	H
Cubic	H	M	H
Gyroid	H	F	H
Concentric	H	M	L
Zigzag	M	F	L
Octet	H	L	H
Honeycomb	H	L	H

Notes : M= Moderate ; H= High ; L= Low
F= Fast

The variation in infill density exhibits better tensile strength compared to specimens with uniform infill density. Specimens with varying infill densities are also lighter in weight, optimizing material usage. Experimental impact tests reveal that impact strength is directly proportional to infill density. Thus, varying the infill density can lead to changes in impact strength across specimens [55]. Static compression tests indicate that strength increases with higher infill density [56]. The results suggest that compressive strength is heavily influenced by infill density, with higher values observed at lower porosity levels and denser infill structures [57]. Figure 11 displays the differences in infill density observed through Scanning Electron Microscopy (SEM) analysis. It clearly shows that as infill density increases, the spacing between filaments becomes tighter, resulting in smaller pores. The closer filament proximity leads to a greater number of bonds, directly influencing mechanical properties [58,59].

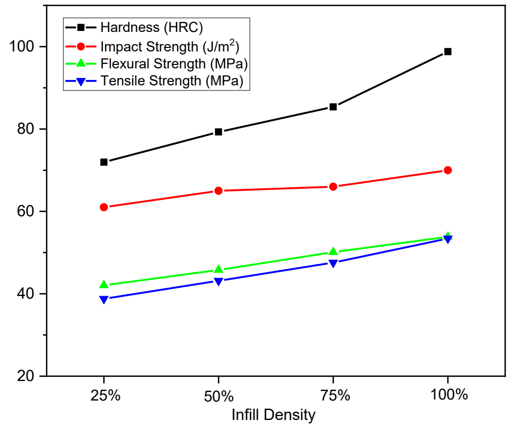

Figure 10. The Effect of Infill Density on Mechanical Properties [60]

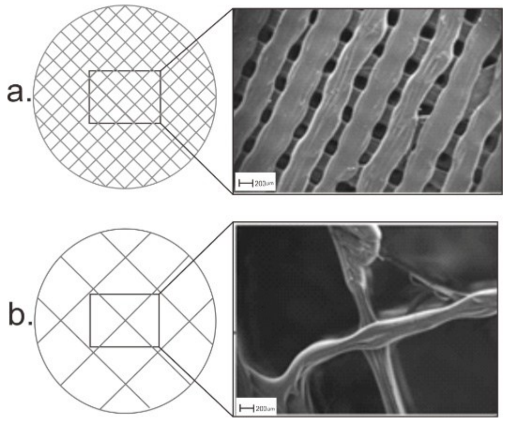

Figure 11 . Infill distance a. 0,5 mm b. 2,5 mm [21]

4.4 Layer Thickness

Layer thickness refers to the height of each material layer deposited during the printing process, typically measured in millimeters. This parameter plays a crucial role in both print quality and speed. Layer thickness is an easily adjustable factor to modify the mechanical properties of custom 3D prints [61,62]. Lower layer thickness values have been shown to enhance tensile strength due to the increased bonding area between layers [39,63]. As illustrated in Figure 12, a layer thickness of 0.1 mm results in a denser structure compared to 0.3 mm and 0.6 mm layers. The 0.1 mm layer produces fewer voids than the thicker layers, indicating better interlayer diffusion. This directly improves layer adhesion and, consequently, the tensile strength of the print [64].

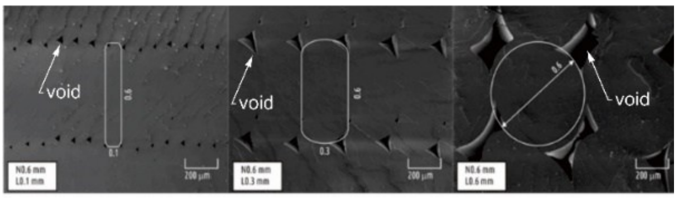

Figure 12. SEM images of different layer thicknesses [65]

Additionally, layer thickness affects both the flexural strength and tensile strength of the test specimens [66,67]. Flexibility tends to decrease as layer thickness increases. Thicker layers provide stronger bonding to withstand bending loads. However, thicker layers are more prone to delamination cracks at a 90° angle, while thinner layers show delamination at a 45° angle [68]. Studies reveal that layer thickness has a greater impact than build orientation or raster angle on mechanical properties [12]. Furthermore, increased layer thickness reduces friction forces, with a 45° angle offering the best wear resistance [69]. On the downside, thicker layers also lead to higher filament consumption and longer printing times [70].

4.5 Printing Speed

Printing speed refers to the rate at which the nozzle moves during the printing process, typically measured in millimeters per second (mm/s). This parameter significantly influences the print quality, production time, and mechanical strength of the printed object. As the printing speed increases, the mechanical strength tends to decrease. Specifically, higher speeds can reduce the volume of extruded material, which compromises print stability and layer adhesion [71].

Figure 13 illustrates the effect of varying printing speeds from 20 mm/s to 100 mm/s. The sample strength diminishes with increasing speed. Within the 50-80 mm/s range, the mechanical properties remain relatively consistent. However, beyond 80 mm/s, a notable drop in strength occurs. At a lower speed of 20 mm/s, the sample demonstrates superior strength, but the trade-off is longer printing time. Thus, as printing speed increases, the mechanical strength progressively declines [72].

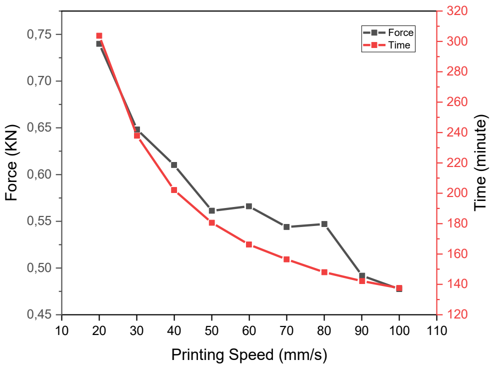

Figure 13. The effect of printing speed on strength and time [73]

Printing speed can be measured through out-of-process methods using timers and in-process methods using encoder measurements in slicer software. While slicer software can estimate printing time, the actual total time is often longer because it does not account for machine preparation, nozzle heating, and bed warming [74] . Dimensional quality of prints is significantly influenced by print speed, showing lower dimensional deviation at lower speeds and no significant dependence on extrusion temperature [75] . An optimal print speed results in better bonding between raster and layers and increases crystallinity for improved wear resistance [76] . However, increasing print speed may reduce mass, surface hardness, and lead to increased porosity and surface roughness [77].

4.6. Printing Temperature

Printing temperature refers to the temperature used to melt the filament. Proper temperature settings are crucial for ensuring successful prints, achieving good quality, and preventing issues during the printing process. The printing temperature is influenced by the type of filament material used. For PLA, it is essential to know the melting temperature or glass transition temperature accurately to ensure the filament melts completely in the heating chamber.

As shown in Figure 14, the normal extrusion temperature for PLA ranges from 200°C to 230°C, which can produce printed products of the highest quality. Higher nozzle temperatures lead to fewer shape deformities (with low uncertainty) in the specimens. Additionally, printing temperature can affect the accuracy of printed results. Most measured dimensions tend to be larger than the original CAD file dimensions in height but smaller in width and length .

Increasing the printing temperature can effectively enhance the ultimate tensile strength and surface hardness of the material (Figure 15). However, it was previously noted that excessively high temperatures can reduce printing accuracy, even though strength may increase. A significant improvement in the tensile strength of PLA occurs between temperatures of 185°C and 195°C.

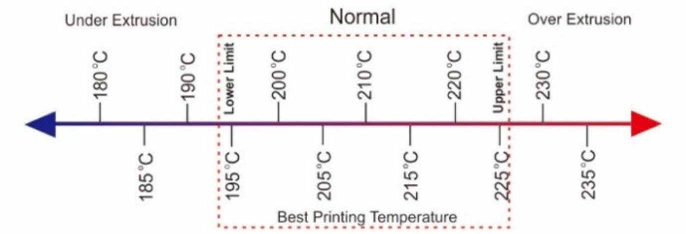

Figure 14. Melting temperature of PLA for 3D printing [78,79]

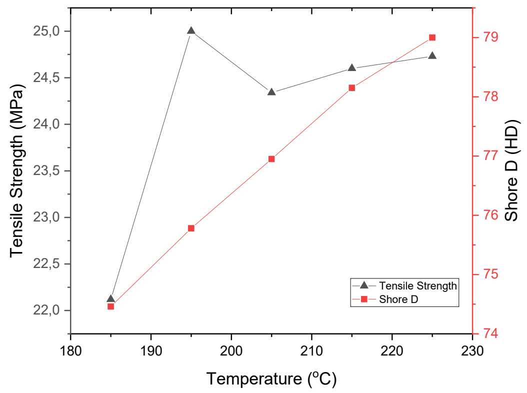

Figure 15. The effect of printing temperature on surface hardness and tensile strength [79]

Although the strain value at the fracture point increases with the rising nozzle temperature, the strain at the fracture point does not appear to be affected by the nozzle temperature. Despite the general strengthening effects of the annealing process, negative effects on the mechanical properties of PLA-based samples have been observed due to the potential for stress accumulation. Based on these findings, thermal annealing of 3D printed PLA parts is not recommended [80]. Selecting the appropriate temperature can enhance tensile strength and surface roughness [81]. The average strip width tends to increase with the rising temperature for PLA samples [82].

4.8 Nozel diameter

The nozzle diameter affects the performance of FDM printing, including accuracy, printing time, as well as compressive and flexural strength [83]. The nozzle geometry influences the material flow pattern [84], where larger nozzles can accelerate manufacturing time by up to 50% [85] and enhance density and tensile strength, although the correlation is not linear [86]. Generally, tensile strength increases with nozzle diameter [87]; however, smaller nozzles yield smoother results and better adhesion, which consequently leads to longer printing times [88].

4.9 Shell Thickness

Shell thickness refers to the thickness of the outer layer of a printed object. The shell is the first part to be printed before the infill, determining the strength, surface quality, and durability of the object. Thinner shells can enhance tensile strength and surface quality [89]. However, increasing the number of shells risks creating structural defects [90]. Additionally, layer alignment can improve surface smoothness, although it may reduce tensile strength and elongation at break [91]. Therefore, it is essential to balance shell thickness with other parameters to achieve optimal mechanical performance while considering time efficiency and material usage [92].

5. Post Treatment

The mechanical properties of 3D printed products are significantly influenced by the temperature during the printing process as well as post-processing. To enhance mechanical performance, post-treatment is conducted through heat treatment. Research results indicate that temperature variations significantly affect the physical and mechanical properties of 3D printed structures [93]. Heat treatment post-processing also plays a crucial role in modifying the mechanical properties of the products. Heat treatment at 75 °C results in a small increase in the maximum force during bending tests. However, the deformation and recovery of the material during heat treatment do not significantly decrease the maximum force [94]. Thermally annealed PLA above the glass transition temperature increases the degree of crystallinity to its maximum level. The increase in crystallinity of FDM-PLA enhances the bending stress of the samples by 11–17%. Therefore, thermal annealing can efficiently improve the efficiency of its mechanical properties [95].

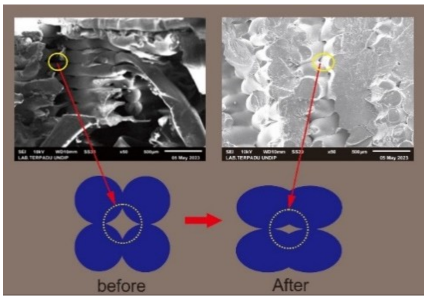

Figure 16. The effect of heat treatment on 3D FDM products [96]

Figure 16 shows the fracture pattern on PLA samples before and after heat treatment (annealing). Before the annealing process, the sample structure appears to have many voids, with an irregular fracture pattern. In contrast, after the annealing process, the voids decrease in size, resulting in a more orderly fracture pattern and increased brittleness.

6. Discussion

The mechanical properties of PLA 3D printing products are influenced by various factors, including material, design, printing machines, printing parameters, and post-processing treatments. Among the extensive literature, the factors most researched due to their significant impact on mechanical properties are material, process parameters, and post-processing treatments. Printing process parameters include printing angle and orientation, layer thickness, infill density, printing speed, and printing temperature. Although various studies have been conducted, differences in the tested parameters make it challenging to determine the best parameter combinations definitively. This opens up opportunities for various options in the optimization process. In general, the main factors affecting the mechanical properties of PLA in 3D printing can be summarized by considering the interrelationship between process parameters and the materials used.

The differences in the color of PLA filament have a significant impact on the thermal and mechanical properties of the resulting 3D prints. Black filament exhibits better thermal resistance, while natural-colored filament shows higher tensile strength. Additionally, environmental factors such as humidity can also affect filament performance. Therefore, it is essential to consider the desired properties and storage conditions when selecting filament color to maintain print quality. Furthermore, the use of Re-PLA shows a decline in mechanical properties, especially after the third recycling. However, blending virgin PLA with Re-PLA is an effective option to reduce the decline in mechanical properties.

The orientation and printing angle in 3D printing significantly affect the quality, strength of the printed products, as well as time efficiency and material consumption. Printing along the X-axis yields the highest tensile and impact strength, while the Z-axis has the lowest strength. The printing angle also plays a crucial role; steeper angles require support to prevent warping, while a flat orientation (0°) is more efficient in terms of tensile strength, printing time, and filament consumption compared to vertical (90°) or edge orientations. Ultimate tensile strength decreases with increasing printing angle, and the modulus of elasticity diminishes at higher printing angles

Infill patterns in 3D printing play a crucial role in determining the strength, weight, material consumption, and printing time of objects. Several popular patterns in slicer software have different advantages. The grid pattern, for instance, provides maximum resistance to tensile loads and is suitable for specimens subjected to heavy loads. The gyroid pattern speeds up printing time, while the concentric pattern offers competitive tensile strength compared to the tri-hexagon pattern. Each infill pattern presents different combinations in terms of strength, printing time, and material requirements, with patterns like grid and cubic showing high strength but requiring longer printing times and more material.

Layer thickness is an important parameter in 3D printing that affects the quality, speed, and mechanical properties of the printed objects. This thickness correlates with tensile strength, flexural strength, and wear resistance, where thinner layers tend to produce higher tensile strength due to the larger bonding area between layers. However, thicker layers perform better under bending loads, although they are more susceptible to delamination cracks at certain angles. Additionally, increasing layer thickness generally decreases Young's modulus and tensile strength while increasing filament consumption and printing time.

Printing speed in 3D printing significantly affects the quality, time, and strength of the printed objects. Increasing the printing speed tends to reduce mechanical strength, especially above 80 mm/s, where there is a significant decrease in strength. Higher speeds can reduce extrusion volume, decrease printing stability, and increase porosity and surface roughness. Additionally, dimensional deviations are lower at lower printing speeds with higher extrusion temperatures. While the right printing speed can improve interlayer bonding and enhance wear resistance, high speeds generally reduce the mass, hardness, and tensile strength of the product.

Printing temperature is a crucial factor in the 3D printing process, particularly in melting the filament to produce high-quality prints. For PLA material, the optimal temperature ranges from 200°C to 230°C. Higher nozzle temperatures can reduce deformation and improve tensile strength as well as surface hardness, although they may decrease the dimensional accuracy of the print. At temperatures between 185°C and 195°C, the tensile strength of PLA increases significantly. However, excessively high temperatures can cause issues such as stress buildup that decreases the mechanical properties of the material. Selecting the appropriate temperature also affects surface roughness and product dimensions.

The mechanical properties of 3D printed products, particularly using PLA, are influenced by process temperature and post-printing treatments. Heat treatment, such as thermal annealing, can enhance the degree of crystallinity and mechanical strength, including an increase in flexural stress of up to 11–17%. Samples subjected to heat treatment at 75°C show a slight increase in the maximum bending force without significantly reducing deformation. The increase in crystallinity at temperatures above the glass transition also helps improve the mechanical strength of PLA, making it more suitable for applications like implants that can be sterilized through radiation.

The mechanical properties of 3D printed products strongly support the sustainable application of 3D printing technology, as they enable the production of components with optimal strength, durability, and material efficiency. This technology has rapidly advanced, and scientific and technological progress has leveraged 3D printing capabilities in various sectors, including manufacturing technology in the furniture industry [97]. In the context of the furniture industry, the application of this technology can produce more precise products with reduced material waste, as well as greater design flexibility. Additionally, the mechanical properties of 3D printed materials can also have a significant impact on sustainability and innovation in other industries, such as aerospace, automotive, medical, and printing [98]. In the aerospace and automotive industries, 3D printed materials can reduce component weight, improve fuel efficiency, and enhance engine performance. In the medical sector, 3D printing offers great potential for creating more precise medical devices, custom prosthetics, and cost-effective, environmentally friendly medical solutions. Thus, the application of this technology not only drives technological advancement but also supports sustainability principles across various industrial fields.

7. Conclusion

The mechanical properties of PLA 3D printed products are influenced by a range of factors, including material selection, printing parameters, and post-processing treatments. Variations in filament color significantly impact thermal and mechanical properties, while orientation and printing angles affect strength and material efficiency. Infill patterns contribute to the object's overall strength, weight, and printing time. Furthermore, optimizing printing speed and temperature is essential for achieving high-quality results, as inappropriate settings can compromise strength and dimensional accuracy. Post-treatment processes like thermal annealing can enhance the crystallinity and mechanical performance of PLA, making it suitable for specialized applications. Overall, a comprehensive understanding of these interrelated factors is crucial for optimizing PLA 3D printing to achieve desired mechanical properties. This research contributes to advancing sustainable science and technology by providing valuable insights into the optimization of PLA-based 3D printed products, which can have significant applications in various industries, including engineering and biomedical fields.

References

[1] Rajan K, Samykano M, Kadirgama K, Harun WSW, Rahman MM. Fused deposition modeling: process, materials, parameters, properties, and applications. Int J Adv Manuf Technol 2022;120:1531–70. https://doi.org/10.1007/s00170-022-08860-7.

[2] Lanzotti A, Grasso M, Staiano G, Martorelli M. The impact of process parameters on mechanical properties of parts fabricated in PLA with an open-source 3-D printer. Rapid Prototyp J 2015;21:604–17. https://doi.org/10.1108/RPJ-09-2014-0135.

[3] Cantrell JT, Rohde S, Damiani D, Gurnani R, DiSandro L, Anton J, et al. Experimental characterization of the mechanical properties of 3D-printed ABS and polycarbonate parts. Rapid Prototyp J 2017;23:811–24. https://doi.org/10.1108/RPJ-03-2016-0042.

[4] Amza CG, Zapciu A, Constantin G, Baciu F, Vasile MI. Enhancing mechanical properties of polymer 3D printed parts. Polymers (Basel) 2021;13:1–18. https://doi.org/10.3390/polym13040562.

[5] Pandzic A, Hodzic D, Milovanovic A. Effect of infill type and density on tensile properties of pla material for fdm process. Ann DAAAM Proc Int DAAAM Symp 2019;30:545–54. https://doi.org/10.2507/30th.daaam.proceedings.074.

[6] Joseph TM, Kallingal A, Suresh AM, Mahapatra DK, Hasanin MS, Haponiuk J, et al. 3D printing of polylactic acid: recent advances and opportunities. Int J Adv Manuf Technol 2023;125:1015–35. https://doi.org/10.1007/s00170-022-10795-y.

[7] Elmowafy EM, Tiboni M, Soliman ME. Biocompatibility, biodegradation and biomedical applications of poly(lactic acid)/poly(lactic-co-glycolic acid) micro and nanoparticles. J Pharm Investig 2019;49:347–80. https://doi.org/10.1007/s40005-019-00439-x.

[8] Oleksy M, Dynarowicz K, Aebisher D. Advances in Biodegradable Polymers and Biomaterials for Medical Applications—A Review. Molecules 2023;28. https://doi.org/10.3390/molecules28176213.

[9] Kurowiak J, Klekiel T, Będziński R. Biodegradable Polymers in Biomedical Applications: A Review—Developments, Perspectives and Future Challenges. Int J Mol Sci 2023;24. https://doi.org/10.3390/ijms242316952.

[10] Saefudin S, Cahyandari D, Afif IY, Raharjo S, Subri M, Irawan B. Analisa Parameter Pencetakan Terhadap Sifat Mekanik Polylactic Acid Menggunakan Mesin Cetak 3 Dimensi Fused Deposition Modelling. J Rekayasa Mesin 2023;18:193. https://doi.org/10.32497/jrm.v18i2.4195.

[11] Le L, Rabsatt MA, Eisazadeh H, Torabizadeh M. Reducing print time while minimizing loss in mechanical properties in consumer FDM parts. Int J Light Mater Manuf 2022;5:197–212. https://doi.org/10.1016/j.ijlmm.2022.01.003.

[12] Lokesh N, Praveena BA, Sudheer Reddy J, Vasu VK, Vijaykumar S. Evaluation on effect of printing process parameter through Taguchi approach on mechanical properties of 3D printed PLA specimens using FDM at constant printing temperature. Mater Today Proc 2022;52:1288–

93. https://doi.org/10.1016/j.matpr.2021.11.054.
[13] Aslani KE, Chaidas D, Kechagias J, Kyratsis P, Salonitis K. Quality performance evaluation of thinwalled PLA 3D printed parts using the taguchi method and grey relational analysis. J Manuf Mater Process 2020;4. https://doi.org/10.3390/jmmp4020047.
[14] Kafshgar AR, Rostami S, Aliha MRM, Berto F. Optimization of Properties for 3D Printed PLA Material Using Taguchi, ANOVA and Multi-Objective Methodologies. Procedia Struct Integr 2021;34:71–7. https://doi.org/10.1016/j.prostr.2021.12.011.
[15] Hikmat M, Rostam S, Ahmed YM. Investigation of tensile property-based Taguchi method of PLA parts fabricated by FDM 3D printing technology. Results Eng 2021;11. https://doi.org/10.1016/j.rineng.2021.100264.
[16] Soares JB, Finamor J, Silva FP, Roldo L, Cândido LH. Analysis of the influence of polylactic acid (PLA) colour on FDM 3D printing temperature and part finishing. Rapid Prototyp J 2018;24:1305–16. https://doi.org/10.1108/RPJ-09-2017-0177.
[17] Frunzaverde D, Cojocaru V, Ciubotariu CR, Miclosina CO, Ardeljan DD, Ignat EF, et al. The Influence of the Printing Temperature and the Filament Color on the Dimensional Accuracy, Tensile Strength, and Friction Performance of FFF-Printed PLA Specimens. Polymers (Basel) 2022;14. https://doi.org/10.3390/polym14101978.
[18] Frunzaverde D, Cojocaru V, Bacescu N, Ciubotariu CR, Miclosina CO, Turiac RR, et al. The Influence of the Layer Height and the Filament Color on the Dimensional Accuracy and the Tensile Strength of FDM-Printed PLA Specimens. Polymers (Basel) 2023;15. https://doi.org/10.3390/polym15102377.
[19] Hanon MM, Zsidai L, Ma Q. Accuracy investigation of 3D printed PLA with various process parameters and different colors. Mater Today Proc 2021;42:3089–96. https://doi.org/10.1016/j.matpr.2020.12.1246.
[20] Hanon MM, Zsidai L. Comprehending the role of process parameters and filament color on the structure and tribological performance of 3D printed PLA. J Mater Res Technol 2021;15:647–60. https://doi.org/10.1016/j.jmrt.2021.08.061.
[21] Spina R. Performance analysis of colored PLA products with a fused filament fabrication process. Polymers (Basel) 2019;11. https://doi.org/10.3390/polym11121984.
[22] Valerga AP, Batista M, Salguero J, Girot F. Influence of PLA filament conditions on characteristics of FDM parts. Materials (Basel) 2018;11. https://doi.org/10.3390/ma11081322.
[23] Wittbrodt B, Pearce JM. The effects of PLA color on material properties of 3-D printed components. Addit Manuf 2015;8:110–6. https://doi.org/10.1016/j.addma.2015.09.006.
[24] Atakok G, Kam M, Koc HB. Tensile, three-point bending and impact strength of 3D printed parts using PLA and recycled PLA filaments: A statistical investigation. J Mater Res Technol 2022;18:1542–54. https://doi.org/10.1016/j.jmrt.2022.03.013.
[25] Lanzotti A, Martorelli M, Maietta S, Gerbino S, Penta F, Gloria A. A comparison between mechanical properties of specimens 3D printed with virgin and recycled PLA. Procedia CIRP 2019;79:143–6. https://doi.org/10.1016/j.procir.2019.02.030.
[26] Babagowda, Kadadevara Math RS, Goutham R, Srinivas Prasad KR. Study of Effects on Mechanical Properties of PLA Filament which is blended with Recycled PLA Materials. IOP Conf Ser Mater Sci Eng 2018;310. https://doi.org/10.1088/1757-899X/310/1/012103.
[27] Nijdam JJ, Agarwal D, Schon BS. An experimental assessment of filament-extrusion models used in slicer software for 3D food-printing applications. J Food Eng 2022;317. https://doi.org/10.1016/j.jfoodeng.2021.110711.
[28] Che Maideen N, Nazri MH, Budin S, Koay Mei H, Yusoff H, Sahudin S. the Effect of Different Slicing Software on the Manufacturing Performance of 3D Printed Parts. J Mek 2023:72–80. https://doi.org/10.11113/jm.v46.490.
[29] Vettori M, Bergonzi L. A territorial round-robin experiment for the evaluation of mechanical properties of FDM PLA produced by distributed facilities. IOP Conf Ser Mater Sci Eng 2021;1038:012069. https://doi.org/10.1088/1757-899x/1038/1/012069.

[30] Cahyati S, Aziz HR. The Influence of Different Slicer Software on 3d Printing Products Accuracy and Surface Roughness. J Rekayasa Mesin 2021;12:371–80. https://doi.org/10.21776/ub.jrm.2021.012.02.14.
[31] Syamsuzzaman M, Mardi NA, Fadzil M, Farazila Y. Investigation of layer thickness effect on the performance of low-cost and commercial fused deposition modelling printers. Mater Res Innov 2014;18:S6-485-S6-489. https://doi.org/10.1179/1432891714Z.0000000001030.
[32] Afrose MF, Masood SH, Iovenitti P, Nikzad M, Sbarski I. Effects of part build orientations on fatigue behaviour of FDM-processed PLA material. Prog Addit Manuf 2016;1:21–8. https://doi.org/10.1007/s40964-015-0002-3.
[33] Patadiya NH, Dave HK, Rajpurohit SR. Effect of Build Orientation on Mechanical Strength of FDM Printed PLA. Lect Notes Multidiscip Ind Eng 2020;Part F164:301–7. https://doi.org/10.1007/978-981-32-9433-2_26.
[34] Çakan BG. Effects of raster angle on tensile and surface roughness properties of various FDM filaments. J Mech Sci Technol 2021;35:3347–53. https://doi.org/10.1007/s12206-021-0708-8.
[35] Yao T, Ye J, Deng Z, Zhang K, Ma Y, Ouyang H. Tensile failure strength and separation angle of FDM 3D printing PLA material: Experimental and theoretical analyses. Compos Part B Eng 2020;188. https://doi.org/10.1016/j.compositesb.2020.107894.
[36] ERYILDIZ M. Effect of Build Orientation on Mechanical Behaviour and Build Time of FDM 3D-Printed PLA Parts: An Experimental Investigation. Eur Mech Sci 2021;5:116–20. https://doi.org/10.26701/ems.881254.
[37] Khosravani MR, Reinicke T. Effects of raster layup and printing speed on strength of 3D-printed structural components. Procedia Struct Integr 2020;28:720–5. https://doi.org/10.1016/j.prostr.2020.10.083.
[38] Marşavina L, Vălean C, Mărghitaș M, Linul E, Razavi N, Berto F, et al. Effect of the manufacturing parameters on the tensile and fracture properties of FDM 3D-printed PLA specimens. Eng Fract Mech 2022;274. https://doi.org/10.1016/j.engfracmech.2022.108766.
[39] Vălean C, Marşavina L, Mărghitaşl M, Linul E, Razavi N, Berto F. Effect of manufacturing parameters on tensile properties of FDM printed specimens. Procedia Struct Integr 2020;26:313–20. https://doi.org/10.1016/j.prostr.2020.06.040.
[40] Ma Q, Rejab MRM, Kumar AP, Fu H, Kumar NM, Tang J. Effect of infill pattern, density and material type of 3D printed cubic structure under quasi-static loading. Proc Inst Mech Eng Part C J Mech Eng Sci 2021;235:4254–72. https://doi.org/10.1177/0954406220971667.
[41] Cabreira V, Santana RMC. Effect of infill pattern in fused filament fabrication (FFF) 3D printing on materials performance. Rev Mater 2020;25:1–9. https://doi.org/10.1590/s1517-707620200003.1126.
[42] Agus Tri Wahyudi, Dini Cahyandari, Saefudin S, Muhammad Subri. Impact of infill pattern and line width on tensile strength of PLA FDM 3d printing. TEKNOSAINS J Sains, Teknol Dan Inform 2025;12:98–103. https://doi.org/10.37373/tekno.v12i1.1221.
[43] Sriya Ambati S, Ambatipudi R. Effect of infill density and infill pattern on the mechanical properties of 3D printed PLA parts. Mater Today Proc 2022;64:804–7. https://doi.org/10.1016/j.matpr.2022.05.312.
[44] Aloyaydi B, Sivasankaran S, Mustafa A. Investigation of infill-patterns on mechanical response of 3D printed poly-lactic-acid. Polym Test 2020;87. https://doi.org/10.1016/j.polymertesting.2020.106557.
[45] Dezaki ML, Mohd Ariffin MKA. The effects of combined infill patterns on mechanical properties in fdm process. Polymers (Basel) 2020;12:1–20. https://doi.org/10.3390/polym12122792.
[46] Rismalia M, Hidajat SC, Permana IGR, Hadisujoto B, Muslimin M, Triawan F. Infill pattern and density effects on the tensile properties of 3D printed PLA material. J Phys Conf Ser 2019;1402. https://doi.org/10.1088/1742-6596/1402/4/044041.
[47] Pandzic A, Hodzic D, Milovanovic A. Effect of infill type and density on tensile properties of

pla material for fdm process. Ann DAAAM Proc Int DAAAM Symp 2019;30:545–54. https://doi.org/10.2507/30th.daaam.proceedings.074.
[48] Alhazmi MW, Backar AH. Influence of Infill density and Orientation on the Mechanical Response of PLA+ Specimens Produced using FDM 3D Printing. Int J Adv Sci Technol 2020;29:3362–71.
[49] Dobos J, Hanon MM, Oldal I. Effect of infill density and pattern on the specific load capacity of FDM 3D-printed PLA multi-layer sandwich. J Polym Eng 2022;42:118–28. https://doi.org/10.1515/polyeng-2021-0223.
[50] Pandžić A, Hodžić D, Kadrić E. Experimental Investigation on Influence of Infill Density on Tensile Mechanical Properties of Different FDM 3D Printed Materials. TEM J 2021;10:1195–201. https://doi.org/10.18421/TEM103-25.
[51] Seol K-S, Zhao P, Shin B-C, Zhang S-U. Infill Print Parameters for Mechanical Properties of 3D Printed PLA Parts. J Korean Soc Manuf Process Eng 2018;17:9–16. https://doi.org/10.14775/ksmpe.2018.17.4.009.
[52] Böğrekci İ, Demircioğlu P, Saygın Sucuoğlu H, Turhanlar O. the Effect of the Infill Type and Density on Hardness of 3D Printed Parts. Int J 3D Print Technol Digit Ind 2019;3:212–9.
[53] Derise MR, Zulkharnain A. Effect of infill pattern and density on tensile properties of 3d printed polylactic acid parts via fused deposition modeling (FDM). Int J Mech Mechatronics Eng 2020;20:54–63.
[54] Suteja J. Effect of Infill Pattern, Infill Density, and Infill Angle on the Printing Time and Filament Length of 3D Printing. J Rekayasa Mesin 2021;12:145. https://doi.org/10.21776/ub.jrm.2021.012.01.16.
[55] Tanveer MQ, Haleem A, Suhaib M. Effect of variable infill density on mechanical behaviour of 3-D printed PLA specimen: an experimental investigation. SN Appl Sci 2019;1. https://doi.org/10.1007/s42452-019-1744-1.
[56] Maszybrocka J, Dworak M, Nowakowska G, Osak P, Łosiewicz B. The Influence of the Gradient Infill of PLA Samples Produced with the FDM Technique on Their Mechanical Properties. Materials (Basel) 2022;15. https://doi.org/10.3390/ma15041304.
[57] Dave HK, Rajpurohit SR, Patadiya NH, Dave SJ, Sharma KS, Thambad SS, et al. Compressive Strength of PLA based Scaffolds: Effect of layer height, Infill Density and Print Speed. Int J Mod Manuf Technol 2019;11:21–7.
[58] Bergonzi L, Vettori M, Stefanini L, D'Alcamo L. Different infill geometry influence on mechanical properties of FDM produced PLA. IOP Conf Ser Mater Sci Eng 2021;1038:012071. https://doi.org/10.1088/1757-899x/1038/1/012071.
[59] Birosz MT, Andó M, Ledenyák D. Effect of FDM Infill Patterns on Mechanical Properties. SSRN Electron J 2021. https://doi.org/10.2139/ssrn.3950131.
[60] Gunasekaran KN, Aravinth V, Kumaran CBM, Madhankumar K, Kumar SP. Investigation of mechanical properties of PLA printed materials under varying infill density. Mater Today Proc 2021;45:1849–56. https://doi.org/10.1016/j.matpr.2020.09.041.
[61] Lužanin O, Movrin D, Plan M. Effect of Layer Thickness , Deposition Angle , and Infill on Maximum Flexural Force in Fdm-Built Specimens 2014;39.
[62] Liu Y, Bai W, Cheng X, Tian J, Wei D, Sun Y, et al. Effects of printing layer thickness on mechanical properties of 3D-printed custom trays. J Prosthet Dent 2021;126:671.e1-671.e7. https://doi.org/10.1016/j.prosdent.2020.08.025.
[63] Rajpurohit SR, Dave HK. Effect of process parameters on tensile strength of FDM printed PLA part. Rapid Prototyp J 2018;24:1317–24. https://doi.org/10.1108/RPJ-06-2017-0134.
[64] Giri J, Chiwande A, Gupta Y, Mahatme C, Giri P. Effect of process parameters on mechanical properties of 3d printed samples using FDM process. Mater Today Proc 2021;47:5856–61. https://doi.org/10.1016/j.matpr.2021.04.283.
[65] Kuznetsov VE, Solonin AN, Urzhumtsev OD, Schilling R, Tavitov AG. Strength of PLA components fabricated with fused deposition technology using a desktop 3D printer as a function

of geometrical parameters of the process. Polymers (Basel) 2018;10. https://doi.org/10.3390/polym10030313.
[66] Abdullah Z, Ting HY, Ali MAM, Fauadi MHFM, Kasim MS, Hambali A, et al. The effect of layer thickness and raster angles on tensile strength and flexural strength for fused deposition modeling (FDM) parts. J Adv Manuf Technol 2018;12:147–58.
[67] Zharylkassyn B, Perveen A, Talamona D. Effect of process parameters and materials on the dimensional accuracy of FDM parts. Mater Today Proc 2021;44:1307–11. https://doi.org/10.1016/j.matpr.2020.11.332.
[68] Nugroho A, Ardiansyah R, Rusita L, Larasati IL. Effect of layer thickness on flexural properties of PLA (PolyLactid Acid) by 3D printing. J Phys Conf Ser 2018;1130. https://doi.org/10.1088/1742-6596/1130/1/012017.
[69] Amirruddin MS, Ismail KI, Yap TC. Effect of layer thickness and raster angle on the tribological behavior of 3D printed materials. Mater Today Proc 2021;48:1821–5. https://doi.org/10.1016/j.matpr.2021.09.139.
[70] Wu J. Study on optimization of 3D printing parameters. IOP Conf Ser Mater Sci Eng 2018;392. https://doi.org/10.1088/1757-899X/392/6/062050.
[71] Khosravani MR, Berto F, Ayatollahi MR, Reinicke T. Characterization of 3D-printed PLA parts with different raster orientations and printing speeds. Sci Rep 2022;12. https://doi.org/10.1038/s41598-022-05005-4.
[72] Yu Z, Gao Y, Jiang J, Gu H, Lv S, Ni H, et al. Study on Effects of FDM 3D Printing Parameters on Mechanical Properties of Polylactic Acid. IOP Conf Ser Mater Sci Eng 2019;688. https://doi.org/10.1088/1757-899X/688/3/033026.
[73] Miazio L. Impact of Print Speed on Strength of Samples Printed in FDM Technology. Agric Eng 2019;23:33–8. https://doi.org/10.1515/agriceng-2019-0014.
[74] Dorado R, Pérez FJ, Medina G, Guerrero F. Experimental measuring of printing speed in FDM. IOP Conf Ser Mater Sci Eng 2021;1193:012037.
[75] Ansari AA, Kamil M. Effect of print speed and extrusion temperature on properties of 3D printed PLA using fused deposition modeling process. Mater Today Proc 2021;45:5462–8. https://doi.org/10.1016/j.matpr.2021.02.137.
[76] Renganathan S, D S. Effect of fill pattern and printing speed on friction characteristics of FDM printed polylactic acid polymer. Adv Mater Process Technol 2022;8:1583–92. https://doi.org/10.1080/2374068X.2021.1948707.
[77] KAMER MS, TEMİZ Ş, YAYKAŞLI H, KAYA A, AKAY O. Effect of Printing Speed on Fdm 3D-Printed Pla Samples Produced Using Different Two Printers. Int J 3D Print Technol Digit Ind 2022;6:438–48. https://doi.org/10.46519/ij3dptdi.1088805.
[78] S. Alsoufi M, W. Alhazmi M, K. Suker D, A. Alghamdi T, A. Sabbagh R, A. Felemban M, et al. Experimental Characterization of the Influence of Nozzle Temperature in FDM 3D Printed Pure PLA and Advanced PLA+. Am J Mech Eng 2019;7:45–60. https://doi.org/10.12691/ajme-7-2-1.
[79] Hsueh MH, Lai CJ, Liu KY, Chung CF, Wang SH, Pan CY, et al. Effects of printing temperature and filling percentage on the mechanical behavior of fused deposition molding technology components for 3d printing. Polymers (Basel) 2021;13. https://doi.org/10.3390/polym13172910.
[80] Behzadnasab M, Yousefi AA, Ebrahimibagha D, Nasiri F. Effects of processing conditions on mechanical properties of PLA printed parts. Rapid Prototyp J 2020;26:381–9. https://doi.org/10.1108/RPJ-02-2019-0048.
[81] Popović M, Pjević M, Milovanović A, Mladenović G, Milošević M. Printing parameter optimization of PLA material concerning geometrical accuracy and tensile properties relative to FDM process productivity. J Mech Sci Technol 2023;37:697–706. https://doi.org/10.1007/s12206-023-0113-6.
[82] Akbaş OE, Hıra O, Hervan SZ, Samankan S, Altınkaynak A. Dimensional accuracy of FDM-printed polymer parts. Rapid Prototyp J 2020;26:288–98. https://doi.org/10.1108/RPJ-04-2019-0115.

[83] Tayyab M, Tanveer MQ, Singari RM, Sathikh PM. Effect of Nozzle Diameter on the Physical Behavior of FDM-Printed Part: An Experimental Study 2024:489–500. https://doi.org/10.1007/978-981-97-4947-8_40.

[84] Schuller T, Jalaal M, Fanzio P, Galindo-Rosales FJ. Optimal shape design of printing nozzles for extrusion-based additive manufacturing. Addit Manuf 2024;84. https://doi.org/10.1016/j.addma.2024.104130.

[85] Ermolai V, Irimia AI. Influence of Nozzle Parameters in 3D Printing Under the Manufacturing Time. Bull Polytech Inst Iași Mach Constr Sect 2021;67:63–72. https://doi.org/10.2478/bipcm-2021-0017.

[86] Triyono J, Sukanto H, Saputra RM, Smaradhana DF. The effect of nozzle hole diameter of 3D printing on porosity and tensile strength parts using polylactic acid material. Open Eng 2020;10:762–8. https://doi.org/10.1515/eng-2020-0083.

[87] Kiński W, Pietkiewicz P. Influence of the Printing Nozzle Diameter on Tensile Strength of Produced 3D Models in FDM Technology. Agric Eng 2020;24:31–8. https://doi.org/10.1515/agriceng-2020-0024.

[88] KARTAL F, KAPTAN A. Investigating the Effect of Nozzle Diameter on Tensile Strength in 3D-Printed Printed Polylactic Acid Parts. Black Sea J Eng Sci 2023;6:276–87. https://doi.org/10.34248/bsengineering.1287141.

[89] Bhosale V, Gaikwad P, Dhere S, Sutar C, Raykar SJ. Analysis of process parameters of 3D printing for surface finish, printing time and tensile strength. Mater Today Proc 2022;59:841–6. https://doi.org/10.1016/j.matpr.2022.01.210.

[90] Szot W, Rudnik M. Effect of the Number of Shells on Selected Mechanical Properties of Parts Manufactured by FDM/FFF Technology. Adv Mater Sci 2024;24:86–103. https://doi.org/10.2478/adms-2024-0006.

[91] Kowalska N, Szczygieł P, Skrzyniarz M, Błasiak S. Effect of shells number and machining on selected properties of 3D-printed PLA samples. Polimery 2024;69:186–90. https://doi.org/10.14314/polimery.2024.3.6.

[92] Suteja TJ. Optimization of Infill Density, Layer Height, and Shell Thickness to Achieve Maximum Bending Strength and Minimum Printing Time of PLA 3D Printed Part. J Polimesin 2023;21:1–5. https://doi.org/10.30811/jpl.v21i5.3883.

[93] Bakar AABA, Zainuddin MZ Bin, Adam AN Bin, Noor ISBM, Tamchek N Bin, Alauddin MS Bin, et al. The study of mechanical properties of poly(lactic) acid PLA-based 3D printed filament under temperature and environmental conditions. Mater Today Proc 2022;67:652–8. https://doi.org/10.1016/j.matpr.2022.06.198.

[94] Chalgham A, Ehrmann A, Wickenkamp I. Mechanical properties of fdm printed pla parts before and after thermal treatment. Polymers (Basel) 2021;13. https://doi.org/10.3390/polym13081239.

[95] Wach RA, Wolszczak P, Adamus-Wlodarczyk A. Enhancement of Mechanical Properties of FDM-PLA Parts via Thermal Annealing. Macromol Mater Eng 2018;303. https://doi.org/10.1002/mame.201800169.

[96] Saefudin S, Cahyandari D, Afif IY, Raharjo S, Subri M, Anwar AN. Peningkatan Sifat Mekanik Produk 3D Printing dengan Proses Annealing. J Ilm Momentum 2023;19:80. https://doi.org/10.36499/jim.v19i1.8568.

[97] Tuazon BJ, Dizon JRC. Additive Manufacturing Technology in the Furniture Industry: Future Outlook for Developing Countries. Adv Sustain Sci Eng Technol 2024;6:02403024. https://doi.org/10.26877/asset.v6i3.908.

[98] Mohammed R, Shaik AS, Mohammed S, Bunga KK, Aggala C, Babu BP, et al. Advancements and Challenges in Additive Manufacturing: Future Directions and Implications for Sustainable Engineering. Adv Sustain Sci Eng Technol 2025;7:0250108. https://doi.org/10.26877/asset.v7i1.1079.