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Optimization Of Heat Treatment Process Parameters for FDM 3D Printed PLA To Improve Mechanical Performance

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Abstract**—Additive manufacturing has become an important manufacturing approach for producing complex components with reduced material waste and shorter production time. Among various additive manufacturing techniques, Fused Deposition Modeling (FDM) is widely used due to its simplicity, low operational cost, and compatibility with thermoplastic materials such as Polylactic Acid (PLA). However, the mechanical performance of FDM printed parts is often limited by weak interlayer bonding, internal voids, and anisotropic material behavior. To address these limitations, post-processing techniques such as heat treatment are commonly employed to enhance the structural integrity of printed components.**

The present study investigates the influence of heat treatment parameters on the mechanical performance of PLA components fabricated using FDM technology. Standard test specimens were produced using controlled printing parameters and subsequently subjected to thermal treatment under different temperature conditions. Mechanical characterization was carried out through tensile, compressive, and impact tests based on established ASTM standards. The experimental analysis focuses on identifying the optimal heat treatment conditions that improve the strength and durability of the printed components while maintaining dimensional stability.

The results indicate that appropriate heat treatment promotes molecular rearrangement and increased crystallinity within the PLA structure, which significantly enhances the mechanical properties of the printed parts. Improved tensile strength, compressive resistance, and impact toughness were observed for the heat-treated specimens compared with untreated samples. The study demonstrates that optimization of heat treatment parameters can effectively improve the mechanical performance of FDM printed PLA components, making them more suitable for functional engineering applications.

Index Terms**—Additive Manufacturing, Fused Deposition Modeling (FDM), Polylactic Acid (PLA), Heat Treatment, Annealing, Mechanical Properties, Process Optimization, 3D Printing.**

I. INTRODUCTION

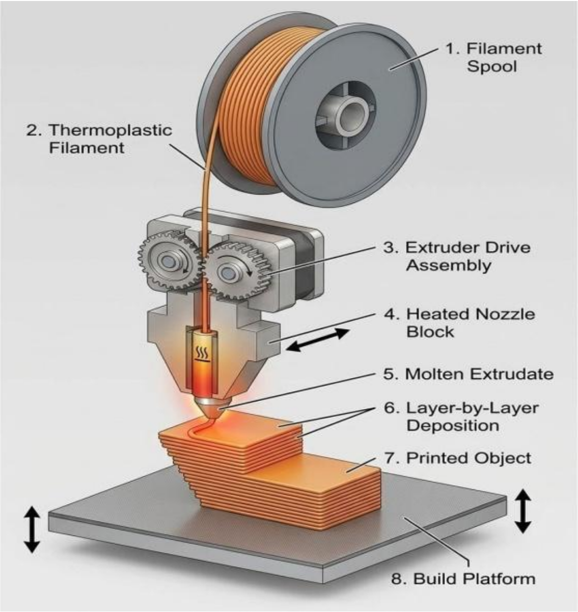


Fig. 1: Schematic representation of the FDM 3D printing process

Additive manufacturing is a revolutionary approach that allows for the direct creation of complex structures from digital models without conventional tooling. This technology has been embraced by various industries like aerospace, automotive, biomedical engineering, and product development because of its flexibility and efficiency in producing customized components [14].

Among different additive manufacturing methods, Fused Deposition Modeling (FDM) is popular for making polymer components. In this method, thermoplastic filament is heated, extruded through a nozzle, and deposited layer by layer to form a three-dimensional object [7]. The ease of access and cost-effectiveness of FDM systems has led to their broad use in industrial and research settings.

Despite its benefits, FDM-made components often show mechanical limitations when compared to traditionally manufactured parts. These limitations are mainly due to weak bonding between layers, internal voids, and uneven material behavior resulting from the manufacturing process [12]. Therefore, significant research has focused on improving the mechanical performance of FDM-fabricated parts.

1.1. Background of Additive Manufacturing

Additive manufacturing refers to a set of technologies that create components by adding material layer by layer according to a digital model. Unlike subtractive manufacturing methods, additive processes reduce material waste and enable the production of complex shapes that are difficult to achieve with traditional techniques [14].

FDM has gained popularity among various additive manufacturing methods due to its ability to process a wide range of thermoplastic materials such as PLA, ABS, PETG, and composite filaments [1][13]. The process involves melting thermoplastic filament and depositing it through a controlled extrusion system to create successive layers that make up the final part.

Research has shown that the mechanical properties of FDM-fabricated components are significantly influenced by process parameters like printing temperature, layer height, infill density, and build orientation [3][7]. Optimizing these parameters is crucial for enhancing the structural performance of printed parts.

1.2. Importance of PLA in FDM Printing

Among the various thermoplastic materials used in FDM printing, PLA stands out as one of the most widely adopted materials thanks to its favorable properties. PLA is a biodegradable polymer made from renewable resources like corn starch and sugarcane, making it an eco-friendly option [6].

PLA offers several benefits, including a low printing temperature, minimal warping during printing, and a good surface finish. These traits make it well-suited for prototyping, biomedical devices, and consumer products [6]. Additionally, PLA shows good stiffness and dimensional accuracy compared to many other thermoplastic materials used in additive manufacturing.

However, despite these advantages, PLA parts made using FDM often have lower mechanical strength compared to injection-molded parts because of interlayer defects and internal porosity [4]. These limitations have prompted researchers to explore various approaches to improve the mechanical properties of PLA-based printed components.

1.3. Need for Heat Treatment of PLA Printed Parts

Heat treatment, or annealing, is a post-processing technique used to improve the structural properties of polymer materials. During annealing, the material is heated to a temperature below its melting point and held there for a specific period, allowing molecular chains to rearrange into more stable crystalline structures.

Several studies have reported that annealing can significantly boost the mechanical properties of PLA components made using FDM. Singh et al. found that heat treatment improves the tensile strength and dimensional stability of PLA parts [5]. Similarly, Chiscop et al. showed that controlled annealing conditions can reduce internal stresses and enhance the dimensional stability of FDM-printed components [10].

Recent research has also looked into advanced annealing techniques like cyclic heat treatment, which has potential for improving the functional performance of PLA components made using additive manufacturing [19].

Thus, optimizing heat treatment parameters is vital for improving the mechanical performance and structural reliability of PLA components created with FDM technology.

II. LITERATURE REVIEW

Several researchers have investigated the mechanical performance and processing behaviour of polylactic acid (PLA) components produced through fused deposition modelling (FDM). Early work by Sang Woo Ahn et al. (2002) examined the anisotropic mechanical behaviour of FDM-fabricated parts through tensile and compression experiments. Their findings indicated that mechanical properties are strongly influenced by raster orientation, establishing one of the earliest explanations for anisotropic behaviour in additively manufactured components.

Further studies explored the influence of build orientation and process parameters on the mechanical behaviour of FDM-printed PLA. Anthony J. Torrado et al. (2015) performed tensile testing on PLA specimens fabricated with different build orientations and reported that mechanical strength varies significantly depending on the orientation of deposited layers. Their results highlighted the critical role of interlayer bonding in determining structural performance. Similarly, Francisco J. Chacón et al. (2017) investigated the influence of printing parameters such as layer height, build orientation, and infill density. Their experimental results demonstrated that internal structure and printing orientation strongly affect the tensile strength and overall mechanical performance of printed components.

Process parameter optimization has also been widely investigated in additive manufacturing. Alessandro Lanzotti et al. (2015) conducted a systematic experimental and statistical analysis to optimize FDM processing parameters. Their study demonstrated that proper adjustment of parameters such as layer thickness and printing speed can significantly improve dimensional accuracy and mechanical properties. In another study, Nima Rankouhi et al. (2016) examined the failure behaviour of FDM-printed PLA using mechanical characterization and fracture surface analysis. They concluded that weak interlayer adhesion is the primary cause of failure in printed components, emphasizing the importance of improving bonding between layers.

In addition to printing parameters, post-processing treatments such as thermal annealing have been shown to influence the mechanical behaviour of PLA materials. Several studies have reported that annealing within the temperature range of 60–120 °C can increase the crystallinity of PLA, leading to improvements in stiffness and thermal resistance. These findings are supported by polymer thermal studies which explain that increased crystallinity enhances both mechanical strength and thermal stability of the material.

Researchers have also investigated the combined effect of printing parameters and post-processing techniques. Optimization studies employing Taguchi experimental design methods demonstrated that mechanical properties can be improved when both printing conditions and annealing parameters are optimized simultaneously. Similarly, studies on reinforced PLA composites have shown that the addition of fibres or particles, combined with annealing treatment, improves stiffness and thermal stability of printed components.

The influence of annealing duration has also been explored in experimental studies. Results indicate that mechanical strength increases up to an optimal annealing time; however, excessive heating may lead to dimensional deformation of the printed parts. To overcome this issue, Alexandru Chiscop et al. (2020) proposed a constrained annealing technique in which printed components are embedded in materials such as salt or silicone during heat treatment. This method effectively reduces dimensional distortion and allows PLA components to withstand higher temperatures without significant deformation.

Additional research has examined the relationship between microstructure and mechanical performance of PLA materials. Andrea Butto et al. (2018) studied thermal treatment of PLA filaments using solid-state drawing combined with annealing. Their results indicated that molecular chain alignment increases crystallinity and significantly improves tensile strength. The structural and thermal behaviour of PLA has also been reviewed by Salah Farah et al. (2016), who emphasized that crystallinity plays a crucial role in determining the mechanical properties of the polymer.

Comprehensive reviews have further summarized the factors influencing the performance of PLA in additive manufacturing. Suresh Bhandari et al. (2019) provided an extensive overview of PLA materials used in FDM processes, highlighting that both printing parameters and post-processing treatments significantly affect mechanical performance. Similarly, Ricardo Teixeira et al. (2020) reviewed heat treatment effects in additive manufacturing materials and concluded that thermal post-processing can substantially improve microstructure and mechanical behaviour.

More recent research has focused on optimization techniques and advanced processing methods.

Muhammad Abidin et al. (2023) used the Taguchi design method to optimize FDM parameters for PLA scaffold fabrication, demonstrating that printing parameters significantly influence porosity and structural accuracy in biomedical applications. Additionally, Karthik Singamneni et al. (2019) investigated hybrid fused filament fabrication processes for metals and ceramics, expanding the application scope of FDM technology. A more recent study by Ozan Cicek and Benjamin Johnson (2025) applied a combined Taguchi and Grey Relational Analysis (GRA) approach for multi-objective optimization of FDM parameters, achieving improvements in both dimensional accuracy and mechanical performance.

Finally, Muhammad Abidin et al. (2022) introduced a cyclic annealing treatment method for 3D-printed PLA parts. Their research demonstrated that repeated heating and cooling cycles can further enhance stiffness and thermal stability, suggesting a promising post-processing strategy for improving the performance of FDM-fabricated PLA components.

2.1. FDM Printing Parameters Affecting Mechanical Properties

The mechanical performance of FDM-fabricated components is strongly affected by various printing parameters. Layer thickness, raster angle, printing temperature, and infill density are crucial factors that determine the strength and structural integrity of printed parts.

Sood et al. conducted an analysis of FDM process variables and reported that build orientation and layer thickness significantly affect tensile strength and surface quality of printed components [7]. Lanzotti et al. also studied the influence of process parameters on mechanical properties and found that changes in printing parameters can lead to notable differences in mechanical performance [3].

Chacón et al. looked into the effects of process parameters on PLA structures made through FDM and noted significant uneven behavior in mechanical properties due to the layered manufacturing process [2].

Research by Rankouhi et al. indicated that interlayer bonding is crucial for determining the failure behavior of FDM-made parts [4].

In addition to pure polymer materials, studies have examined the use of composite materials in FDM. Ning et al. looked into carbon fiber reinforced thermoplastic composites made using FDM and demonstrated improved stiffness and strength compared to standard polymer filaments [8][20].

2.2. Heat Treatment and Crystallization of PLA

Heat treatment has been widely studied as an effective method for enhancing the mechanical performance of polymer components made using additive manufacturing. The main mechanism for this improvement is the increase in the crystallinity of the polymer structure.

Butto et al. found that annealing treatment can change the microstructure of PLA and improve its mechanical performance by enhancing molecular alignment within the material [11]. Chiscop et al. proposed a constrained annealing technique that greatly improves the dimensional stability of PLA components made using FDM [10].

Teixeira et al. conducted a thorough review of heat treatment effects on additively manufactured materials and concluded that controlled thermal treatment can significantly boost mechanical properties and thermal stability of polymer components [18].

2.3. Mechanical Property Improvement After Heat Treatment

Numerous studies have shown that annealing treatment can enhance tensile strength, impact resistance and thermal stability of PLA components produced using FDM.

Singh et al. investigated the effects of annealing on PLA components and found significant improvements in tensile strength and impact resistance after heat treatment [5].

Abidin et al. introduced a cyclic annealing approach for FDM printed PLA components and observed better functional performance and mechanical stability [19].

Similarly, Torres et al. proposed optimization strategies to improve the mechanical performance of PLA components made through FDM by adjusting both printing parameters and post-processing conditions [9][21].

2.4. Research Gap Analysis

While considerable research has focused on optimizing FDM printing parameters, there are fewer studies that systematically optimize heat treatment parameters for PLA components.

Most existing research centers on printing parameters like layer height, raster angle, and infill density. The combined influence of heat treatment parameters such as annealing temperature, holding time, and cooling method is still underexplored.

Additionally, previous studies often evaluate only individual mechanical properties rather than conducting comprehensive assessments of tensile, compressive, and impact properties at the same time.

Research Gap Identified

Based on the literature review, the following research gaps are identified:

Limited studies have explored the combined optimization of heat treatment parameters for FDM-printed PLA components.

The effects of annealing temperature on multiple mechanical properties need further investigation.

Most studies focus mainly on tensile properties, while less attention is given to compressive and impact performances.

A systematic experimental study that combines FDM printing parameters with heat treatment optimization is needed to enhance the mechanical reliability of PLA components.

III. MATERIALS AND METHODS

3.1 Material

The material used in this study was Polylactic Acid (PLA) filament. It is one of the most widely used materials in additive manufacturing because it is biodegradable and easy to process. PLA comes from renewable resources like corn starch and sugarcane. This material is commonly chosen for Fused Deposition Modeling (FDM) due to its low melting temperature and minimal warping during printing.

PLA also offers good dimensional accuracy and surface finish compared to other thermoplastic materials used in additive manufacturing. However, parts built with FDM often have lower mechanical strength because of weak bonding between layers and internal voids created during the deposition process.

Previous studies have shown that the crystallinity of PLA can increase with controlled thermal treatment, leading to better mechanical properties like tensile strength, stiffness, and thermal stability. Thus, PLA was selected as the main material for this investigation to study the effect of heat treatment on the mechanical performance of FDM printed parts.

3.2 3D Printer Specifications

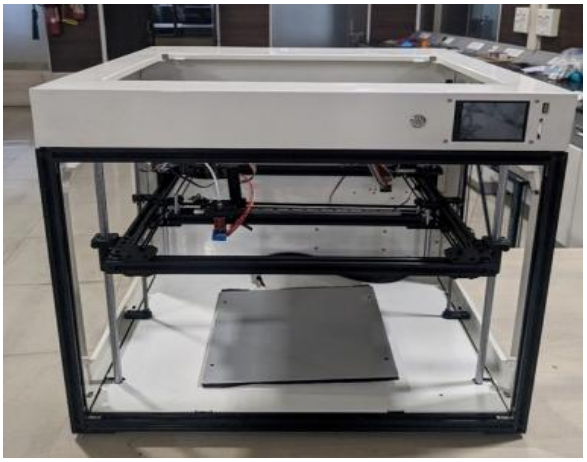


Fig. 2: Printer Figure

The specimens in this investigation were made using a desktop FDM 3D printer. Key specifications of the printer are listed in Table 1.

Table I: 3D Printer Specifications

Parameter	Specification
Printer Brand	Rudrabots
Printer Model	Omega 300
Printing Technology	Fused Deposition Modeling (FDM)
Build Volume	300 mm × 300 mm × 300 mm
Nozzle Diameter	0.4 mm
Bed Leveling System	Automatic
Firmware	Marlin
Slicing Software	Orca Slicer / Ultimaker Cura

The FDM printing process heats the thermoplastic filament above its glass transition temperature and deposits the molten material through a nozzle to create layers that form the final three-dimensional structure.

Reliable slicing software allows for precise control over printing settings, including layer thickness, infill density, and extrusion temperature. These factors greatly impact the mechanical behavior of printed components.

3.3 Printing Parameters

Printing parameters are vital for determining the mechanical properties of FDM fabricated components. Several researchers have shown that changes in parameters like layer thickness, infill percentage, and printing temperature can significantly affect structural strength and dimensional accuracy.

The main printing parameters used for specimen fabrication in this study are outlined in Table 2.

Table II: Main Printing Parameters Used for Specimen Fabrication

Category	Parameter	Value / Setting
Printing Quality	Layer height	0.20 mm
	Initial layer height	0.20 mm
Line Width Settings	Default line width	0.42 mm
	Initial layer line width	0.50 mm
	Outer wall line width	0.42 mm
	Inner wall line width	0.45 mm
	Top surface line width	0.42 mm
	Sparse infill line width	0.45 mm
	Internal solid infill line width	0.42 mm
	Support line width	0.42 mm
Wall Structure	Number of wall loops	3
	Thin wall detection	Disabled
Top Surface Settings	Top surface pattern	Monotonic
	Top shell layers	5
	Top shell thickness	1 mm
	Top paint penetration layers	5
Bottom Surface Settings	Bottom surface pattern	Monotonic
	Bottom shell layers	3
	Bottom shell thickness	0 mm
	Bottom paint penetration layers	3
Infill Configuration	Internal solid infill pattern	Rectilinear
	Sparse infill density	100 %
	Sparse infill pattern	Rectilinear
Seam Settings	Seam position	Aligned
	Seam placement away from overhangs	Disabled
	Smart scarf seam application	Enabled

The selection of these parameters was based on commonly recommended settings for PLA printing and previous studies that looked at optimizing FDM process variables.

3.4 Mechanical Testing Standards

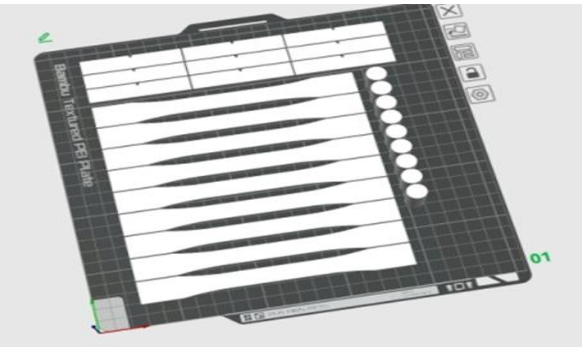


Fig. 3: Testing Standards Figures

To evaluate the effect of heat treatment on mechanical performance, standard mechanical testing procedures were followed. The testing standards used in this study are summarized below.

Table III: Mechanical Test standard Tables

Mechanical Test	Standard
Tensile Test	ASTM D638
Compression Test	ASTM D695
Impact Test	Izod Impact Test (ASTM D256)

The tensile test measures the maximum stress a material can handle before breaking. Compression testing assesses the material's ability to resist compressive forces, while the impact test gauges how well the material withstands sudden impacts.

Mechanical testing is crucial for assessing the reliability of additively manufactured components and has been widely used in prior research for analyzing FDM fabricated parts.

IV. EXPERIMENTAL PROCEDURE

The experimental investigation took several stages to evaluate how heat treatment affects the mechanical performance of PLA components made with FDM technology.

First, standard test specimens for tensile, compression, and impact testing were designed according to the relevant ASTM standards. The models were created using computer-aided design (CAD) software and then converted into STL format for processing in the slicing software.

The STL files were imported into the slicing software, where suitable printing parameters were set. The printer then made the specimens layer by layer with PLA filament.

After printing, the specimens underwent controlled heat treatment, also known as annealing. This process involved heating the printed components to specific temperatures below PLA’s melting point and holding them at that temperature for a set time. This allows molecular chains within the polymer structure to rearrange into more stable crystalline forms.

Previous studies have indicated that annealing improves PLA's crystallinity, resulting in increased stiffness and strength. After heat treatment, the specimens were cooled under controlled conditions to prevent excessive deformation.

Lastly, mechanical testing was carried out to assess tensile strength, compressive strength, and impact resistance of both untreated and heat-treated specimens.

V. RESULTS AND DISCUSSION

Table IV: Mechanical Test Results of Heat-Treated PLA Specimens

Exp	Temp (°C)	Time (min)	Cool	Tens. (MPa)	Izod (kJ/m²)	Comp. (MPa)
1	60	30	Furnace	37.45	5.12	78.10
2	60	60	Air	38.44	5.31	79.05
3	60	90	Water	36.81	4.92	76.80
4	80	30	Air	40.36	5.85	81.60
5	80	60	Water	42.11	6.30	83.25
6	80	90	Furnace	44.85	6.86	85.90
7	100	30	Water	39.22	5.62	80.45
8	100	60	Furnace	46.36	7.12	87.95
9	100	90	Air	43.25	6.53	84.40
10	As-print	—	—	35.85	4.80	75.92

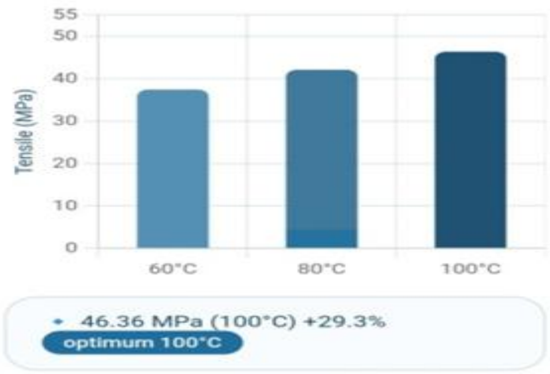


Fig. 4: Tensile Strength vs Heat Treatment Temperature

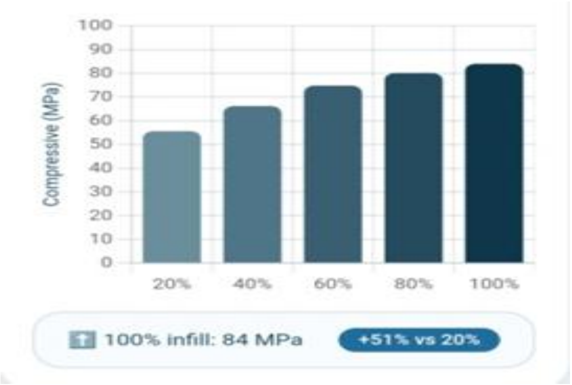


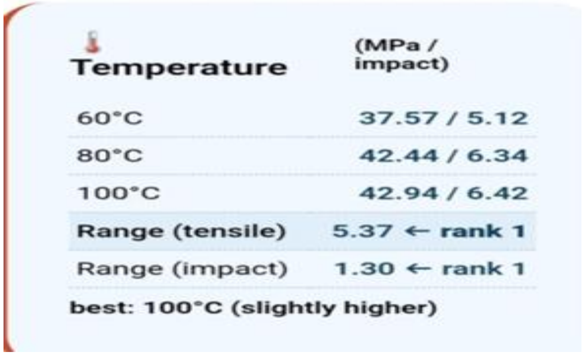
Fig. 5: Compressive Strength vs Infill Percentage

Fig. 6: Impact Strength vs Heat Treatment Condition

Time	(MPa / impact)
30 min	39.01 / 5.53
60 min	42.30 / 6.24
90 min	41.64 / 6.10
Range (tensile)	3.29 ← rank 3
Range (impact)	0.71 ← rank 3

best: 60 min

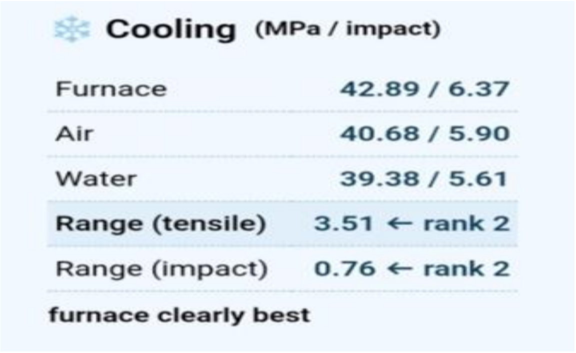
Fig. 7: Time (MPa/impact)



Temperature	(MPa / impact)
60°C	37.57 / 5.12
80°C	42.44 / 6.34
100°C	42.94 / 6.42
Range (tensile)	5.37 ← rank 1
Range (impact)	1.30 ← rank 1

best: 100°C (slightly higher)

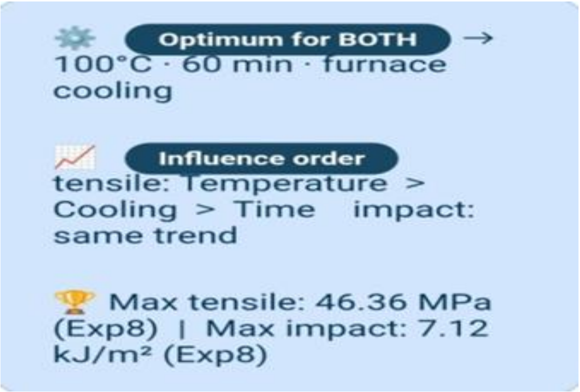
Fig. 8: Temperature (MPa/Impact)



Cooling	(MPa / impact)
Furnace	42.89 / 6.37
Air	40.68 / 5.90
Water	39.38 / 5.61
Range (tensile)	3.51 ← rank 2
Range (impact)	0.76 ← rank 2

furnace clearly best

Fig. 9: Cooling (MPa/Impact)



Optimum for BOTH →
100°C · 60 min · furnace cooling

Influence order
tensile: Temperature > Cooling > Time impact: same trend

🏆 Max tensile: 46.36 MPa (Exp8) | Max impact: 7.12 kJ/m² (Exp8)

Fig. 10: Optimum Conditions and Influence Order for Tensile and Impact Properties

The results show that heat treatment significantly affects the mechanical behavior of printed components.

The tensile strength of PLA specimens improved with increasing heat treatment temperature up to an optimal level. This enhancement is linked to increased crystallinity and better interlayer bonding within the printed structure. Similar findings in tensile strength increase after annealing have been observed in prior research.

Compression testing also revealed that compressive strength improved after heat treatment. This better performance may stem from enhanced stability of the polymer matrix due to thermal Rearrangement of molecular chains.

Impact resistance testing indicated that heat-treated specimens showed better resistance to sudden loading compared to untreated ones. Increased crystallinity and fewer internal defects contributed to the improved capacity of the material to absorb energy.

These findings are consistent with the work of Abidin et al., who found that controlled annealing can notably enhance the functional performance of 3D printed PLA components.

The results also suggest that excessive heat treatment temperatures may result in dimensional distortion of printed parts. Thus, careful optimization of heat treatment parameters is essential to improve mechanical performance without compromising dimensional accuracy.

VI. FUTURE RESEARCH DIRECTIONS

T Although this study shows that heat treatment can greatly enhance the mechanical properties of FDM printed PLA components, several areas need further exploration.

Future research could investigate advanced heat treatment techniques like cyclic annealing and controlled cooling methods to boost the structural performance of printed parts. Studying the impact of different infill patterns and build orientations on heat-treated specimens could offer valuable insights.

Additionally, using composite filaments reinforced with fibers or nano particles may further enhance the mechanical performance of FDM printed parts. Combining optimized printing parameters with advanced post-processing techniques could lead to substantial improvements in the mechanical reliability of additively manufactured polymer components.

VII. CONCLUSION

This research explored how heat treatment affects the mechanical performance of PLA components made with Fused Deposition Modeling. The study showed that controlled annealing significantly improves tensile strength, compressive strength, and impact resistance of printed parts.

The improvements in mechanical properties mostly result from increased crystallinity and better interlayer bonding due to the heat treatment process. However, excessive heat treatment temperatures may lead to dimensional distortion of printed components.

These findings underscore the importance of optimizing heat treatment parameters to enhance the structural reliability of FDM printed PLA parts. The results contribute to developing more durable and mechanically reliable components produced through additive manufacturing technologies.

APPENDIX

Appendixes, the experimental data used to optimize the heat treatment parameters for FDM printed PLA. The study investigated three temperatures (60 °C, 80 °C, and 100 °C) with holding times of 30, 60, and 90 minutes and different cooling methods. The best mechanical performance was achieved at 100 °C for 60 minutes with furnace cooling, which produced the highest tensile, impact, and compressive strength

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