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OPTIMIZATION OF PLA 3D PRINTING PARAMETERS CONSIDERING COOLING RATE AND HARDNESS

Research paper

Dušan Jovanić[1*], Aleksandar Rajić[2], Miodrag Kovačević[3], Ljubica Lazić Vulićević[4]
[1,2,3,4] Technical College of Applied Sciences, Zrenjanin, Serbia

Abstract: This paper presents the optimization of 3D printing parameters for polylactide (PLA) using the Taguchi method, aiming to investigate their influence on the cooling rate and Shore A hardness of the samples. During the 3D printing process, printing temperature, printing speed, and layer height were varied across three levels. A thermographic camera was used to measure characteristic temperatures at a point immediately behind the nozzle and after a specific period of time; these measurements were used to determine the cooling rate, which affects layer hardness. Since lower mechanical properties compared to conventional technologies represent one of the main drawbacks of 3D printing, it is essential to thoroughly investigate these properties to determine the functionality of the working parts. Hardness testing of the PLA samples was performed using an analog durometer in accordance with the EN ISO 868:2015 standard.
Key words: Optimization, Hardness testing, FDM 3D printing of PLA, Thermography, Cooling rate.

INTRODUCTION

Due to the lower surface quality and inferior mechanical properties of polylactide (PLA) parts produced by 3D printing, it is necessary to determine their mechanical characteristics: hardness, tensile strength, impact strength, compressive strength, flexural strength, fatigue strength, creep, aging, friction coefficient, shear resistance, and crack propagation in accordance with the standard ISO 17296-3: Additive manufacturing- General principles- Part 3: Main characteristics and corresponding test methods. Furthermore, this standard defines testing categories for metallic, plastic, and ceramic parts, classifying them into three groups: Group H (testing of highly safety-critical functional parts), Group M (testing of non-safety-critical functional parts), and Group L (testing of parts during design or prototype parts). For all these groups of plastic parts, hardness testing is mandatory (ISO, 2014).
The aim of this work is to determine how the cooling rate measured by a thermographic camera, i.e., the temperature homogeneity of the layers, affects the hardness of the PLA plastic workpiece depending on the 3D printing parameters (printing temperature, printing speed, and layer height), and to determine their optimal values using the Taguchi method**.**
Process parameter optimization studies, such as those published on the platform, show that layer height and printing speed have a dominant contribution of over 50–60% on hardness and dimensional accuracy (Motgi et al., 2023).
A higher extrusion temperature, between 210°C and 220°C, improves interlayer adhesion and reduces porosity, which directly increases surface hardness and shear resistance. However, excessively high temperatures without adequate cooling cause deformations and thermal degradation [Rajabi et al., 2021).
PLA is a semi-crystalline polymer. The cooling rate directly dictates the degree of crystallinity of the material. Research indicates that excessively rapid cooling (strong fans/low ambient temperature) leads to an amorphous structure, which results in lower hardness and strength but better toughness. Slower and more homogeneous cooling allows the formation of crystallites (spherulites), which dramatically increases hardness and elastic modulus (Shbanah, 2023).
The parameters were ranked by their impact on hardness as follows: Layer Thickness, Infill Density, Raster Angle, Printing Speed, and Wall Thickness, from most to least significant.Layer Thickness appears to be the second most important parameter after Infill Density. The effect on impact, hardness and surface roughness tests is significant. Increased

[1] Corresponding author, dusan.jovanic@vts-zr.edu.rs, ORCID: 0009-0001-6058-4074
[2] aleksandar.rajic@vts-zr.edu.rs, ORCID: 0000-0003-3921-1502
[3] miodrag.kovacevic@vts-zr.edu.rs, ORCID:0000-0002-1803-6816
[4] ljubica.lazic@vts-zr.edu.rs, ORCID: 0009-0002-1975-3961:

layer thickness leads to poorer adhesion between layers, resulting in diminished impact strength (Verim et al., 2025).

ADDITIVE MANUFACTURING

According to the ISO 17296-2 standard, additive manufacturing can be classified into:Vat Photopolymerization – laser stereolithography (SLA) and stereolithography based on full-layer exposure (DLP-SLA, LCD-SLA); Powder Bed Fusion – processes using a laser (SLS, SLM, DMLS) and processes using an electron beam (EBM); Material Extrusion (FFF – Fused Filament Fabrication); Material Jetting (PolyJet, PolyJet Matrix); Binder Jetting (3D Printing, Slurry-based 3D Printing); Sheet Lamination (LOM, PSL); and Directed Energy Deposition-DED(ISO, 2017).

Material extrusion process

The material extrusion process, known as FFF (Fused Filament Fabrication)orFDM (Fused Deposition Modeling) – a trademark of Stratasys (Stratasys, n.d.), utilizes a solid thermoplastic material in the form of a filament. The filament is pushed through a heated nozzle, the temperature of which depends on the type of polymer, and is deposited in a semi-molten (pasty) state onto a heated or unheated build platform, where it solidifies to form the desired part layer by layer.
The most significant adjustable parameters for FFF 3D printers include: printing speed, extrusion speed, layer height(for both shell and infill), and the temperatures of the nozzle and the build plate (bed).
In FDM printing, residual stresses occur due to the rapid and uneven cooling of the layers; therefore, temperature control is critical for interlayer bond strength. It is necessary to investigate the temperature homogeneity of the layers, as proper interlayer adhesion is essential to reduce residual stresses (B. Redwood, 2017).

POLYLACTIDE

There is a large number of polymers with various mechanical, physical, chemical, electrical, thermal, and other properties, which have a wide range of applications.Polylactide (PLA) is a thermoplastic, biodegradable plastic derived from organic sources (such as corn starch, sugarcane, or sugar beet) through the fermentation of plant starch, and it exhibits properties similar to polypropylene (PP), polyethylene (PE), or polystyrene (PS). It is used for the production of food containers, films, and medical implants, and it possesses high surface energy, making it ideal for 3D printing. The drawbacks of PLA include low heat resistance and relatively low strength. The properties of PLA are presented in Table 1 (TWI Ltd., n.d.).

Table 1. *Karakteristike Polilaktida-PLA*

The parameters	Values
Density	1,24 g/cm³
Tensile Strength EN ISO 527-1	50 MPa
Flexural Strength EN ISO 178	80 MPa
Impact Strength (IZOD) - EN ISO 180	96,1 (J/m)
Shrinkage rates	0,37-0,41%

TERMOGRAPHY

Infrared thermography (IRT), also known as thermal imaging, can be used for the identification and documentation of irregularities for the purposes of machine condition monitoring, quality control, and non-destructive testing, as well as for monitoring temperatures during various manufacturing processes, such as temperature in the cutting

zone, extrusion temperature in forming processes, casting and cooling temperatures of castings, and thermal phenomena occurring during welding.
Thermography is based on the detection and measurement of the distribution of thermal radiation emitted from the observed surface and its conversion into a representation of radiation intensity differences, i.e., a surface temperature map known as a thermogram.
A significant advantage of infrared thermometers compared to contact temperature measurement methods lies in their extremely fast response time, since the radiated energy is transferred from the object to the sensor at the speed of light, enabling an almost instantaneous response. An additional advantage of these instruments is their high sensitivity, as they are capable of detecting and displaying thermal images composed of very small temperature differences [ISO, 2008].

EXPERIMENTAL RESEARCH

In a series of experiments, a specimen with dimensions of ϕ30 x 4 mm was used as the workpiece. The 3D model of the specimen was created using the SolidWORKS 2016 software package and then converted into the corresponding STL file with the maximum resolution permitted by the software (Figure 1). Subsequently, the relevant parameters were varied according to the experimental design, and a series of specimens with identical external appearances but different properties was produced.

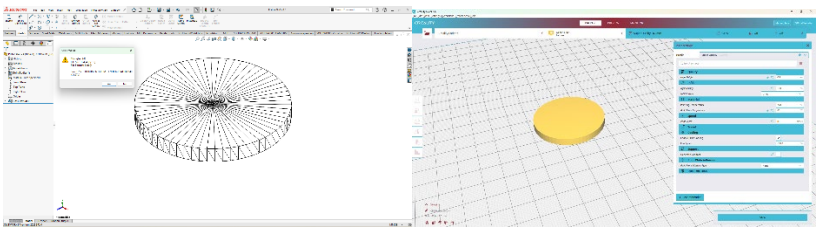


Fig. 1. *3D CAD model and STL file*

Figure 2 shows the Creality Ender-6 Core-XY 3D printer used for the experiment and the Creality CR PLA filament, while its technical specifications are given in Table 2 **(**Creality, n.d.).

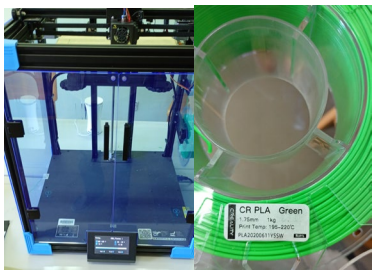


Fig. 2.*Creality Ender-6 Core-XY 3D printer and Creality CR PLA filament*

Table 2. *Technical specifications of the Creality Ender-6 Core-XY 3D printer*

The parameters	Values
Layer Height (mm)	0.1-0.4
Filament Diameter (mm)	1.75
Nozzle Diameter (mm)	0,4
Printing speed (mm/s)	30-150
Nozzle temperature (°C)	180-260
Bed Temperature (°C)	50-100

Creality CR PLA filament was used to fabricate the specimens, and its properties are presented in Table 3 (Creality, n.d.).

Table 3. *Properies of Creality CR PLA filament*

The parameters	Values
Filament Type	PLA
Diameter (mm)	1.75
Print temperature (°C)	195-220
Temperatura stola (°C)	0-60
Print speed (mm/s)	40-100

During the 3D printing of the PLA samples, the cooling rate of the layers was measured using a Testo 860i thermographic camera. The thermographic images were captured from a distance of 30 cm, at an angle of 45° to the workpiece, and with an emissivity setting of 0.95. Figure 3 shows the maximum measured temperature immediately behind the nozzle and the temperature after a time interval of 33 seconds, which were used to calculate the cooling rate (Testo SE & Co. KGaA., 2026).

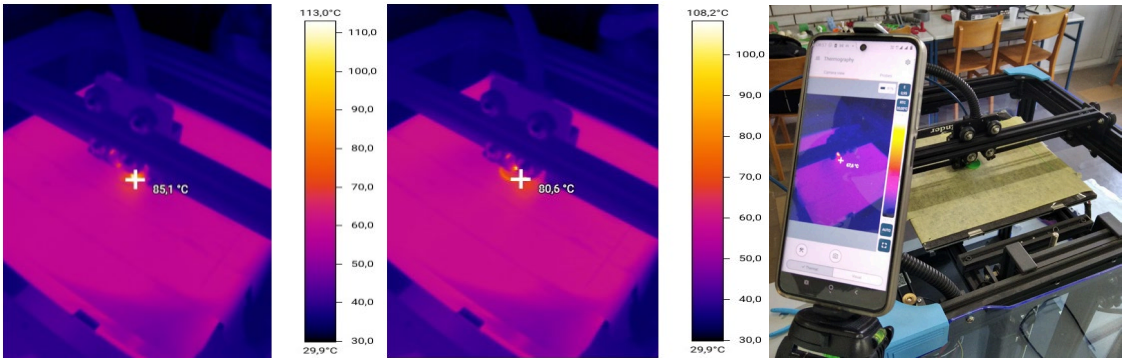


Fig. 3.*Thermograms of temperature immediately after nozzle passage and after a specific time period*

As a measuring instrument, a durometer- hardness meter Sauter A was used, following the Shore A scale, featuring a truncated cone-shaped needle with a 35° angle, requiring a minimum specimen thickness of 4 mm and possessing an accuracy of 1 HS (A) as shown in Figure 4.The test specimen was placed on a hard, horizontal, plane surface.The durometer was held in a vertical position with the point of the indenter at least 9 mm from any edge of the test specimen.The recommended mass was 1 kg for the type Adurometer.The scale of the indicating device was read after 15 s ± 1 s.Five measurements of hardness were taken at different positions on the test specimen, with a minimum separation of 6 mm, and the mean value was determined. The hardness values range from 0 (for full penetration) to 100 (for no penetration) (ISO, 2003).

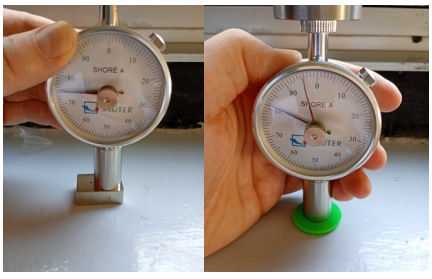


Fig. 4. *Calibration and hardness testing with a durometer*

RESULTS AND DISCUSSION

In the experiment, the values of the most significant 3D printing parameters were varied: Printing Temperature (°C), Printing Speed (mm/s), and Layer Height (mm). The values of the upper, middle, and lower levels of the 3D printing parameters are presented in Table 4. The specimens were fabricated with a 100% linear infill, a bed temperature of 60°C, and all other parameters were kept constant.

Table 4. *Values of the upper, middle, and lower levels of the PLA 3D printing parameters*

The parameters	Values		
	Level 1	Level 2	Level 3
Printing Temperature (°C)	200	210	220
Printing speed (mm/s)	40	60	80
Layer Height (mm)	0,1	0,2	0,3

The Taguchi L9 orthogonal array design of experiments was used for this study. Design of Experiments (DOE) is a systematic approach used to assess how input process parameters influence one or more output responses. By systematically varying input factors, DOE helps determine optimal process parameters and identify key factors and their best levels to meet performance targets. The Taguchi method uses the signal-to-noise (S/N) ratio to achieve the desired results. The S/N ratio method is applied when optimizing a process with multiple responses, using the "larger-the-better" criterion to maximize hardness. The mean hardness values from five measurements, as well as the cooling rate as a function of printing temperature, printing speed, and layer height, are presented in Table 5.

Table 5. *Hardness and cooling rate values for different FDM printing parameters of PLA*

Exp. no.	Printing Temperature (°C)	Printing Speed (mm/s)	Layer Height (mm)	Cooling Rate (°C/s)	Hardness (HS A)	S/N Ratio (dB)
1	200	40	0,1	0,03	88,6	38.9487
2	200	60	0,2	0,07	88,2	38.9094
3	200	80	0,3	0,11	85,6	38.6495
4	210	40	0,2	0,05	90,6	39.1426
5	210	60	0,3	0,09	88,4	38.9290
6	210	80	0,1	0,11	91,0	39.1808
7	220	40	0,3	0,22	86,5	38.7403
8	220	60	0,1	0,19	91,6	39.2379
9	220	80	0,2	0,14	88	38.8897

The mean values of hardness and S/N ratios for each individual parameter are presented in Table 6.

Table 6. *Mean hardness values and S/N ratios for each parameter*

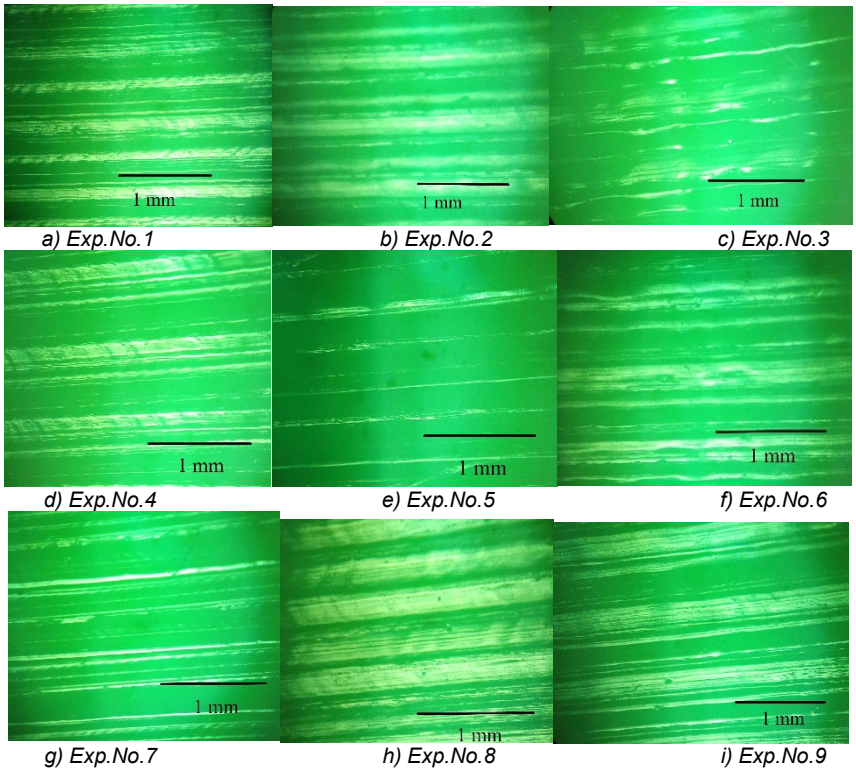
The parameters		Values	
		HS (A)	S/N ratio
Printing Temperature (°C)	200	87.47	38.84
	210	90,00	39.08
	220	88.70	38.96
Printing speed (mm/s)	40	88.57	38.94
	60	89.40	39.03
	80	88.20	38.91
Layer Height (mm)	0.1	90.40	39.12
	0.2	88.93	38.98
	0.3	86.83	38.77

Based on the S/N ratios from Table 6, it can be concluded that the optimal PLA 3D printing parameters for achieving maximum hardness are: a printing temperature of 210°C, a printing speed of 60 mm/s, and a layer height of 0.1 mm.
The influence rank is determined based on the Delta value, which represents the difference between the maximum and minimum mean values for the observed factor. A larger Delta value indicates that the factor has a stronger influence on the final response. The influence ranking for both hardness and process stability is presented in Table 7.

Table 7. *Influence ranking for hardness and process stability*

The parameters	Δ value HS (A)	Rang HS (A)	Δ value S/N	Rang S/N
Printing Temperature (°C)	2,53	2	0,24	2
Print speed (mm/s)	1,20	3	0,12	3
Layer Height (mm)	3,57	1	0,35	1

Based on the ranking of influence and process stability, it can be concluded that layer height has the greatest impact on both hardness and process stability (Rank 1), printing temperature has a moderate impact (Rank 2), and printing speed has the least impact on hardness (Rank 3). As the layer height decreases from 0.3 mm to 0.1 mm, the hardness increases significantly. A lower layer height allows for better compaction and lower material porosity, which directly enhances mechanical resistance.
Microscopic images of the PLA specimens, corresponding to the experimental design and captured at 5x magnification, are shown in Figure 5.



a) Exp.No.1 *b) Exp.No.2* *c) Exp.No.3*
d) Exp.No.4 *e) Exp.No.5* *f) Exp.No.6*
g) Exp.No.7 *h) Exp.No.8* *i) Exp.No.9*

Fig. 5*. Microscopic images of PLA specimens at 5× magnification*

In Figure 5, the darker lines represent the grooves between the layers, which act as stress concentration zones; the wider they are, the rougher the surface. Microscopic inspection revealed that the width of the deposited layer is the largest at the minimum layer height. In Figure 5a, due to the low speed, a high number of continuous lines appear, while the grooves are minimal, resulting in a homogeneous structure.

In Figure 5b, the number of visible lines decreases proportionally as the layer height doubles to 0.2 mm.
In experiment number 3, due to the combination of low printing temperature, high speed, and large layer height, the material failed to flow and fuse properly; consequently, the layer boundaries are indistinct and rough, as shown in Figure 5c.
Experiment number 4, due to the elevated temperature of 210°C and slow printing speed of 40 mm/s, enabled perfectly parallel lines with a layer height of 0.2 mm without any microscopic discontinuities, which can be seen in Figure 5d.
In Figure 5e, very wide grooves dominate, which corresponds to a layer height of 0.3 mm.
Figure 5f shows a fine structure with a high number of thin 0.1 mm layers. Here, due to the speed of 80 mm/s, a slight waviness within the lines themselves is observed compared to Figure 5a, which has the same deposited layer height.
Figure 5g displays wide grooves due to the layer height of 0.3 mm, which appear highly fused because of the high temperature of 220°C and low speed.
The structure in Figure 5h is very smooth and compact, as the high temperature allowed the thin 0.1 mm layers to achieve maximum bonding, making this surface look the most homogeneous among all the samples.
Good material cohesion due to the high printing temperature is shown in Figure 5i, but the grooves are twice as large as in the previous experiment due to the layer height of 0.2 mm and a printing speed of 80 mm/s.
The minimum layer height of 0.1 mm has a dominantly positive impact on hardness. As a rule, a lower layer height means greater compaction of the material, a lower volume of air micropores within the model, and more layer boundaries that sustain the load, which directly increases the surface hardness.

CONCLUSION

3D printing using the material extrusion process (FFF technology) results in a low surface finish quality; regarding hardness, it was determined that the 3D printing parameters—printing temperature, printing speed, and layer height—have a significant influence on this property. Based on the ranking of influence and process stability, it was confirmed that layer height has a dominant impact on both hardness and process stability, followed by printing temperature, which has a moderate impact, while printing speed has the least impact on hardness compared to these parameters. Experiments demonstrated that the highest hardness of the PLA plastic sample is achieved at the minimum layer height of 0.1 mm. A lower layer height allows for better compaction and lower material porosity, which directly enhances mechanical resistance.
A higher printing temperature enables better interlayer adhesion, while faster printing affects the cooling process. The cooling rate, measured with a thermographic camera, should not be excessively high in order to avoid residual stresses and to ensure homogeneous fusion of the layers, which leads to better mechanical properties.
Based on the optimization using the Taguchi method, the optimal PLA 3D printing parameters for maximizing hardness were determined to be: a printing temperature of 210°C, a printing speed of 60 mm/s, and a layer height of 0.1 mm. This configuration is closest to experiment number 8, which, from a microstructural standpoint, exhibits the most homogeneous structure among all samples, appearing highly smooth and compact.

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