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Effect of printing parameters on mechanical properties and processing time of additively manufactured parts

Yahir Enrique Gonzalez[1], Jorge Mario Mendoza[1], Jair Restrepo Durán[1], Luis Carlos Tapia Vertel[1], Jesús David Rhenals-Julio[1]

[1]Universidad de Córdoba, Departamento de Ingeniería Mecánica. Carrera 6, No. 77-305, Montería, Colombia.
e-mail: jesusrhenalsj@correo.unicordoba.edu.co, yahirgonzalez@correo.unicordoba.edu.co, jorge.mendoza@correo.unicordoba.edu.co

ABSTRACT

Fused deposition modeling (FDM) has gained popularity recently due to its versatility and low cost. Considering that the quality of printed parts depends on many variables, a 3^3 factorial design of experiments was conducted, where three influential parameters in the process were studied: layer height (0.15, 0.2, and 0.25 mm), infill percentage (30%, 60%, and 90%), and shell count (2, 3, and 4), using polylactic acid as the material. Their effects on tensile strength, flexural strength, printing time, and interactions were measured. The maximum tensile and flexural stress obtained were 33.5 MPa and 87.3 MPa, respectively, at a 90% infill percentage. It was found that layer height does not significantly affect mechanical strength, while infill percentage has the most significant influence, followed by the number of shells. The latter two factors show a meaningful interaction. Furthermore, all the studied parameters have a significant impact on printing time.

Keywords: Design of experiments; fused deposition modeling; printing parameters; mechanical properties.

1. INTRODUCTION

Additive manufacturing (AM) is a technology that allows the creation of complex pieces and components using the integration of layers [1]. Technological advances have made this technique's implementation possible in producing prototypes. Besides, it is possible to control the shape, which allows for obtaining complex geometries in the products [2, 3]. There are several technologies for the application of AM; one of the most common is fused deposition modeling (FDM), which is widely applied [4].

FDM technology has increased in popularity because it allows the manufacture of non-commercially available parts with a low budget [5]. Some of the manufacturers of this technology publish information about materials and parameters they use in their model prints; however, in most cases, this information is not available or is incomplete [6, 7]. One of the commonly used materials for 3D printing is polylactic acid (PLA) due to its high versatility and the fact that it can be obtained from renewable resources [8].

Although implementing FDM technology in the production sector generates various products, they do not have scientific support for their properties [9]. To perform a printing process, printing parameters must first be set, and these affect the final properties of the printed part [10], so knowing the effect produced by the printing parameters on the mechanical properties is vital in applying these techniques in engineering.

Some research has been carried out to analyze the effects of printing parameters in FDM machines on the mechanical properties of manufactured parts and their performance. In [11], the impact of filler percentage, shell number, and layer height on the ultimate tensile stress was studied. The results showed that the rate of filler has a more significant influence on the tensile strength, and it negatively interacts with the shell number.

In reference to a study conducted in [10], the effect of layer height, printing direction, and printing speed on the tensile and flexural strengths of parts manufactured by FDM was examined. The study revealed that the optimal printing direction is on-edge, and the relationship between layer height and the other factors studied varies.

On the other hand, [4] analyzed the effect caused by the percentage of filler, layer height, and printing speed on the flexural strength of specimens manufactured in FDM; the results show that the layer height presents a statistically significant influence on the flexural strength of the parts.

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The studies presented in the literature focus primarily on studying the effect of printing parameters on the mechanical properties of the parts, and there is a small number of works that investigate the impact of these parameters on the printing time, so studies that simultaneously evaluate all these variables and propose optimization procedures for these processes are needed. This study aimed to determine the effect of filler percentage, layer height, and shell number on the tensile and flexural strengths and printing time of specimens manufactured by FDM in PLA and to propose an optimization technique for these processes based on the design of experiments theory.

2. MATERIALS AND METHODS

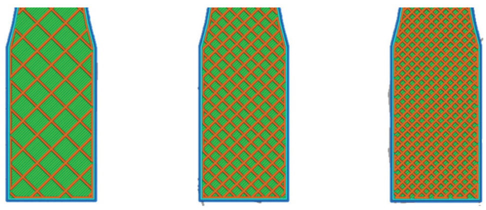
2.1. Printing parameters

Considering the most common variables with the greatest impact according to [12], [13], the following were defined as printing parameters:

1. Percentage of filling, which is defined as the amount of material that is deposited inside the part, its range is 0–100% as shown in Figure 1, with 0% being an internally hollow part and 100% being a fully filled part [14].
2. Layer height, which is defined as the distance the printhead rises in the z-axis from layer to layer [15].
3. Shell number, understood as the number of layers on the outer surface of the constructed part [16], as shown in Figure 2.

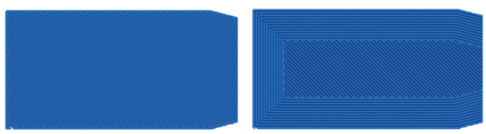
2.2. Design of experiments (DOE)

The mechanical properties of FDM printed parts depend on the printing parameters used [9]. Considering the selected printing parameters, a multilevel factorial design of experiments (N^k) with 3 replicates was chosen. Since it allows to analyze the linear and quadratic behavior of the effects of the printing parameters on the ultimate tensile stress, bending stress and printing time (response variables), as well as the statistical influence of the interactions between factors. Table 1 summarizes the factors and levels chosen for the experimental design.



(a) (b) (c)

Figure 1: Differences in the percentage of infill for a 3D model. a) 30% infill, b) 60% infill, c) 90% infill.



(a) (b)

Figure 2: Representation of shell number. a) Shell number 1, b) Shell number 12.

Table 1: Selected factors and levels.

FACTOR	NAME	LEVELS		
		1	**2**	**3**
A	Layer height (mm)	0.15	0.2	0.25
B	Filling percentage (%)	30	60	90
C	Number of shells	2	3	4

2.3. Specimen fabrication

A Makergear® M2 FDM technology 3D printer with a maximum print size of 250 mm wide, 200 mm long and 165 mm high was used for the construction of the specimens.

PLA+ 3D printing filament with a diameter of 1.75 mm is used as the filler material due to its extensive applications for its low cost. The properties of the printing filament indicated by the manufacturer are shown in Table 2.

The lamination software used to manage the printing parameters is the freely licensed Ultimaker Cura® version 3.6.0. Using SOLIDWORKS® 2020 software, the 3D specimens were modeled with an STL format, following the indications of ASTM D638-14 and ASTM D790-17 standards for tension, and bending, respectively.

Table 3 shows the printing parameters that were kept fixed during the process.

2.4. Mechanical tests

The tests were performed at the Materials and Manufacturing Processes Laboratory of the University of Cordoba with an MTS Criterion® series 40 Electromechanical Test Systems, Model C45.305 universal testing machine with a nominal load of 300 kN (see Figure 3).

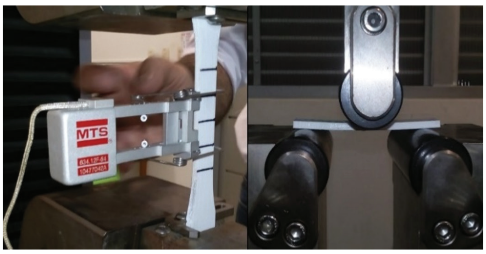
The tests were performed following the procedure of ASTM D638-14 and ASTM D790-17 for tension and bending, respectively. In the tension tests, a preload of 5 kN at a speed of 5 mm/min (0.0833 mm/s) was

Table 2: 3D printing filament properties for polylactic acid [17].

FILAMENT	PRINTING TEMPERATURE (°C)	BED TEMPERATURE (°C)	DENSITY (g/cm^3)	TENSILE STRENGTH (MPa)	FLEXURAL STRENGTH (MPa)
PLA	190–210	60–80	1.24	65	97
PLA+	205–225	60–80	1.24	60	87

Table 3: Fixed printing parameters.

FIXED PRINTING PARAMETERS	NOMINAL VALUES
Extruder temperature	215 °C
Bed temperature	60 °C
Filling pattern	Lines
Printing angle	45°
Printing speed	80 mm/s
Coating fan usage	No
Adhesion to print bed	Skirt
Nozzle size	0.4 mm
Initial layer height	0.2 mm



(a) (b)

Figure 3: Mechanical tests: (a) tension and (b) flexure.

used. For bending tests, a speed of 0.08 mm/s was used. According to ASTM D638-14 and ASTM D790-17 standards and the studies carried out by [10, 18–21].

2.5. Statistical analysis

Statgraphics® software was used to process the experimental data. An analysis of variance (ANOVA) was performed to determine the statistical significance of the factors on printing time, ultimate tensile stress and bending stress.

For the analysis of the relationship between the observed variables and the printing parameters and process optimization, a response surface methodology was used. Other research studies recommend using this methodology, as it provides an efficient way to parameterize the parameters of 3D printing, resulting in time and cost savings and improved printed parts' quality [10, 18, 22].

3. RESULTS AND DISCUSSION

3.1. Effect of printing parameters on ultimate tensile strength

Figure 4 shows the effect of the printing parameters on the ultimate tensile stress of the specimens tested. It is observed that the behavior of the effect of the layer height on the ultimate tensile stress is similar to that found by [10], where with layer height of 0.06 mm, it was obtained the maximum value for the stress, which decreased in the other values they studied and is in agreement with [23] who found that in the layer heights of 0.2 mm, 0.3 mm and 0.4 mm, the maximum value was presented at the midpoint, as in the present study. Other authors found opposite results [23, 24]. This could be due to differences in the type of printer and the internal configuration of the printer.

The variation caused by the percentage of infill is affected by the levels of the other factors, which may be due to different causes, for example, when increasing the number of shells the infill will have less space as shown in Figure 2. This interaction was observed in a similar way in the study by [25].

Figure 5 shows that the effect caused by the layer height when the percentage of filler is 60% and 90% can be considered statistically non-significant. On the other hand, when the percentage of filler is 30%, the layer height presents a slight significant effect. This shows that, as the values of percentage of filler increase, the effect caused by the layer height on the bending stress decreases.

The variations presented by the percentage of infill are affected by the level of the other factors. Therefore, the percentage of filler causes a maximum and minimum increase in the ultimate tensile stress of 24.5 MPa and 9.41 MPa, respectively. Figure 6 shows that when the percentage of filler is at its third level (90%), the values of the ultimate tensile stress can be considered statistically equal. A similar behavior was observed in [26] for high values of filler percentage.

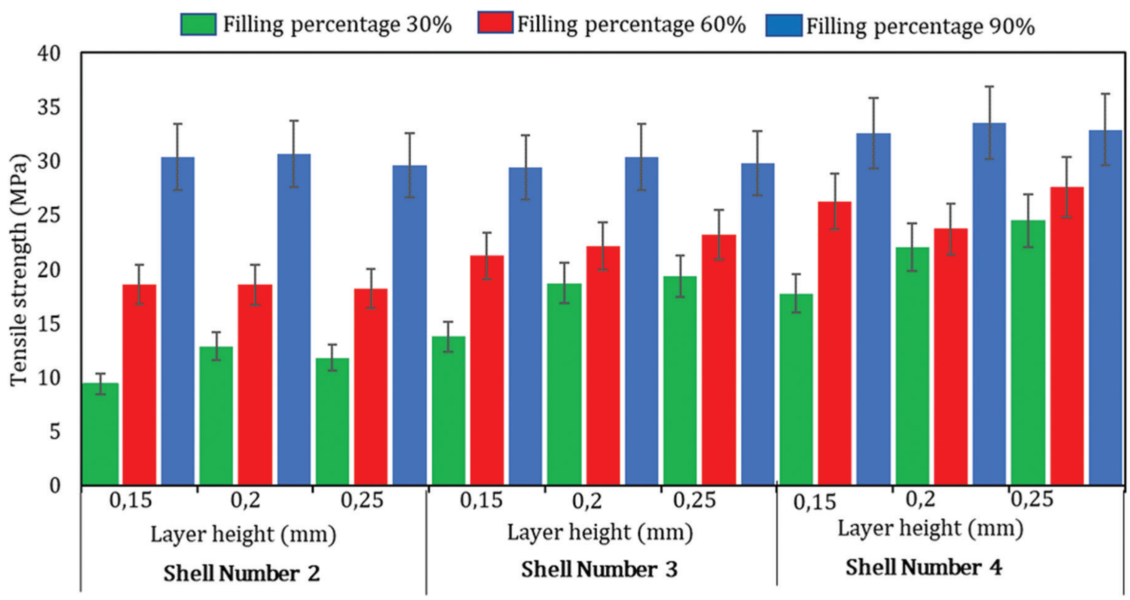


Figure 4: Comparison of printing parameters on ultimate tensile stress.

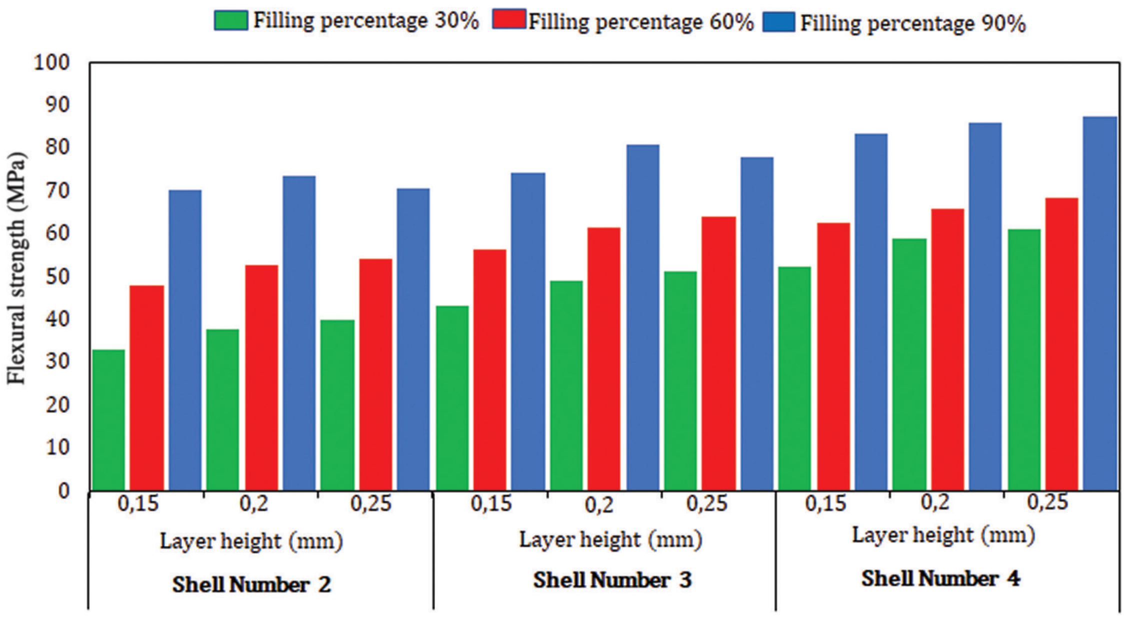


Figure 5: Effect of printing parameters on flexural strength.

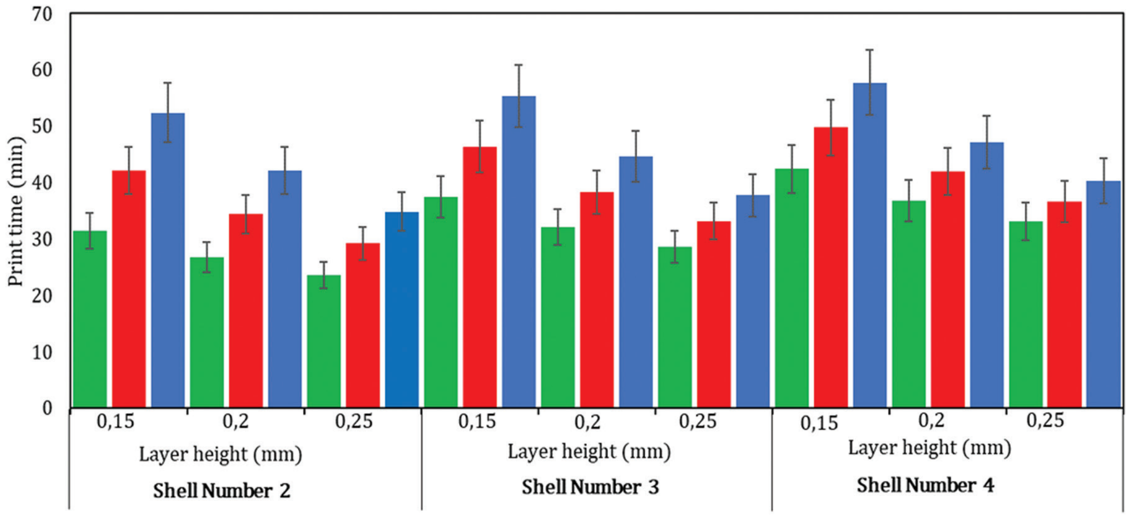


Figure 6: Comparison of printing parameters on printing time in the production of test specimens.

The effect caused by the number of shells presented a close to linear behavior on the ultimate tensile stress as shown in Figure 4(d). As the number of shells increases, the ultimate tensile stress increases proportionally. This was similarly found in [2, 18].

3.2. Effect of printing parameters on flexural strength

The percentage of filler presents a nonlinear behavior. Increasing the value of the levels increases exponentially the value of the response. Authors [27–29] found an increase with exponential tendency of the bending stress when increasing the value of the percentage of filler in a similar way to the present study. On the other hand, when the percentage of filler is 30%, the number of shells presents the greatest increase on the bending stress. This phenomenon was also evidenced by [27]. This interaction can be explained by the fact that increasing the number of shells reduces the internal space of the part.

3.3. Effect of the parameters on the printing time

The maximum time for the specimens (57 min) occurs in both cases when the percentage of filler is 90%, shell number 4 and layer height of 0.15 mm, as can be seen in Figure 6, while the minimum is found with a filler percentage of 30%, shell number of 2 and a layer height of 0.25 mm.

Table 4: Process optimization.

FACTORS			RESPONSES		
LAYER HEIGHT	FILLING PERCENT-AGE	SHELL NUMBER	FLEXURAL STRENGTH	TENSILE STRENGTH	PRINT TIME
0.25	0.6	3	64.13	24.57	33.50

Due to the nature of the process, the layer height is actively related to the other two factors, making its effect on the others easy to observe. When this factor decreases, the number of layers needed to finish the part increases. Thus, by increasing the percentage of filler or the number of shells, the printing extruder must make a longer run in each layer, which increases the time required to manufacture the part. This behavior of the printing time was similarly evidenced in the experiment carried out by [10]. The percentage of filler affects the printing time significantly, which can be seen in Figure 6, which is in agreement with what was reported in [30].

3.4. Statistical analysis of results

The analysis of variance for the bending stress and ultimate tensile stress shows that in both cases the factor with the greatest influence on the response variable is the percentage of filler (factor B), followed by the number of shells (factor C). The interaction between B and C is negative, while increasing B or C decreases the effect caused by the other factor on the response. The layer height (factor A) has a greater effect on the bending stress than on the ultimate tensile stress and is less, in both cases, than that caused by B and C. Printing time B had the greatest effect, followed by A (negative) and C. The AB interaction had the greatest influence, because increasing the B factor requires more extrusion head travel per layer, while the number of layers depends exclusively on the A factor.

Regarding the multiple process optimizations, considering equal importance for all responses, a maximum desirability of 0.06% was found, which is achieved with the printing parameters (Layer height, Filling percentage, Shell Number) shown in Table 4 with their respective responses (Flexural strength, Tensile strength, Print time).

4. CONCLUSIONS

The most influential parameter with respect to ultimate tensile stress, bending stress and printing time was the percentage of filler, followed by the shell number. On the other hand, the layer height had no significant effect on the ultimate tensile stress and bending stress.

All the printing parameters studied influence the printing time. Filling percentage and layer height have greater effect than shell number. On the other hand, when the percentage of infill is 90%, the selection of the other printing parameters will be independent of the ultimate tensile stress and bending stress. The selection of these parameters will depend on other factors such as surface finish and printing time.

The effect of layer height and shell number on ultimate tensile stress and bending stress is greater when the percentage of filler is 30%. However, if mechanical strength is to be maximized, the filler percentage should be set at its highest level, which increases the printing time considerably.

5. ACKNOWLEDGMENTS

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