INFLUENCE OF 3D PRINTING PARAMETERS ON THE MECHANICAL PROPERTIES OF PLA PARTS MANUFACTURED BY FFF

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RESUMEN

La fabricación aditiva (FA) es un proceso productivo que ha ido ganando protagonismo, especialmente en el escenario de la Industria 4.0. Entre las tecnologías FA, tenemos la fabricación por filamento fundido (FFF), ampliamente utilizada por tener principios de funcionamiento sencillos y bajo coste. Con la expansión de la tecnología FFF, ha cobrado importancia el análisis y estudio de las variables que existen en el proceso y los materiales de impresión utilizados. Con un sesgo tecnológico y sostenible, el Poli(ácido láctico) – PLA, basado en materiales vegetales, es uno de los polímeros más utilizados para la técnica FFF. En este estudio se analizó la influencia de variables de impresión como el espesor de capa y el patrón de relleno, además de la variable pigmentación relacionada con el PLA mediante Diseño de Experimentos (DOE) utilizando el diseño factorial 2^k. Las variables de respuesta analizadas fueron el límite de resistencia a la tracción, elongación a la rotura, tiempo de impresión y masa de material utilizado. Las variables de preprocesamiento del proceso FFF, espesor de capa y patrón de relleno, influyen tanto en la resistencia mecánica como en el tiempo y la masa. Estas son más relevantes para las variables de respuesta al compararlas con la variable pigmentación.

Palabras clave: Fabricación aditiva. FFF. PLA. Diseño de experimentos.

ABSTRACT

Additive manufacturing (AM) is a production process that has been gaining prominence, especially in the Industry 4.0 scenario. Among the AM technologies, we have fused filament fabrication (FFF), widely used because it has simple operating principles and low cost. With the expansion of FFF technology, it has become important to analyze and study the variables that exist in the process and the printing materials used. With a technological and sustainable bias, Poly (lactic acid) - PLA, based on plant materials, is one of the most used polymers for the FFF technique. This study analyzed the influence of printing variables such as layer thickness and filling pattern, in addition to the pigmentation variable related to PLA through Design of Experiments (DOE) using the 2^k factorial design. The response variables analyzed were the tensile strength limit, elongation at break, printing time and mass of material used. The pre-processing variables of the FFF, layer thickness and filling pattern, influence both mechanical strength and time and mass. These are more relevant for the response variables when compared to the pigmentation variable.

Keywords: Additive Manufacturing. FFF. PLA. Design of Experiments.

1. INTRODUCTION

Additive manufacturing (AM), also known as three-dimensional (3D) printing, is a group of emerging technologies that create objects based on computer-aided design (CAD) models by adding materials layer by layer. The layer-by-layer approach gives AM processes design freedom and enables the production of conventionally inaccessible geometries, such as topologically optimized, integrated, and functional parts with minimal material waste and reasonable speed. According to ISO/ASTM 52900:2015, there are seven types of AM techniques, including material extrusion, material jetting, binder jetting, sheet lamination, vat photopolymerization, powder bed fusion, and directed energy deposition. Each AM method has its own characteristics in speed, resolution, and cost, thus offering diverse options for users. Material extrusion, also known as fused filament fabrication (FFF), is the most commonly used AM technique that involves the selective deposition of thermoplastic polymer through a heated nozzle. The viscous or molten material is extruded in a build stage to form a predetermined thin layer and subsequently solidifies and bonds with neighboring layers to create a part with dimensional accuracy on the order of 100 µm. Despite its simple operating principle and low precision, the FFF technique offers several advantages over other polymer-based AM techniques such as vat photopolymerization and powder bed fusion, including a wide range of low-cost feedstock materials, versatile build volume to enable small, full-scale parts, and the ability to manufacture functionally graded parts by co-printing multiple compositions. Today, polymer parts manufactured by the FFF technique can meet the demands of many applications, from toys and textiles in daily life, to microfluidics and flexible strain sensors in electronics, and customized implants in biomedicine. More recently, FFF is used in the automotive and aerospace fields, especially for new product development, with its cost and efficiency benefits in the preparation of new tools or molds, prototypes for functional testing and lightweight components [1, 2, 3].

Through 3D models, it is possible to manufacture parts by printing using polymers, with Poly(lactic acid) - PLA being one of the most widely used thermoplastics and still having relative ease of recycling into filament compared to other plastics used for 3D printing. Manufacturing processes seek to advance technologically together with sustainability and, thus, PLA being a biodegradable material and coming from renewable sources has become a viable alternative to polymers derived from petroleum such as Acrylonitrile Butadiene Styrene (ABS), for 3D printer filaments [4, 5]. However, some shortcomings of PLA, such as inherent brittleness, limited elongation to break, and low impact resistance, pose some challenges for the widespread application of the material [6].

It is therefore essential to investigate the FFF process variables applied to the use of PLA as a choice of sustainable technology and, in this way, analyze how such manufacturing or material variables will influence the behavior of parts manufactured by AM.

2. MATERIALS AND METHODS

The materials used were PLA filaments in white and natural colors, both from the supplier 3DFila, with 1.75 mm thickness.

Three factors were selected for analysis: (i) layer thickness, (ii) filling pattern and (iii) pigmentation. Furthermore, two relevant levels were chosen for each factor (Table 1).

Table1. Variation levels for layer thickness, fill pattern and pigmentation.

Factor	**Level of variation**	**Maximum (+)**	**Minimum (-)**
A	Layer thickness (mm)	0.28	0.12
B	Fill pattern	Grid	Triangular
C	Pigmentation	Absent	Present

Layer thickness is a pre-processing variable for slicing and was selected based on the default settings pre-defined by the Ultimaker Cura® 4.7.0. This software enables the transformation of the 3D STL model into g-code format that will be processed by the printer and also the configuration of the pre-processing variables for the FFF technique. Ultimaker Cura® has pre-established default settings for several FFF printers, including the Creality Ender 3, which was used in this study. These pre-defined settings are called profiles and are based on values for the pre-processing variables that deliver good printing results without requiring the operator to perform custom settings. Two profiles were analyzed: super quality and low quality. The most notable difference between these profiles is the layer height, which is why it is the first variable selected. The super quality profile has a layer thickness of 0.12 mm, while the low quality profile uses 0.28 mm, these were the levels selected.

Since there were three factors to be analyzed, a 2^3-factorial design was defined, which were separated into X_1 to X_8 in the test matrix (Table 2).

Table 2. Factorial design test matrix.

Combination	**Layer thickness (mm)**	**Fill pattern**	**Pigmentation**
X_1	0.12	Grid	Absent
X_2	0.28	Grid	Absent
X_3	0.12	Triangular	Absent
X_4	0.28	Triangular	Absent
X_5	0.12	Grid	Present
X_6	0.28	Grid	Present
X_7	0.12	Triangular	Present
X_8	0.28	Triangular	Present

Test specimens were modeled according to ASTM D638 (type IV) [7] standard for tensile testing using the SolidWorks®, with the file generated in STL format. The prefabrication stage of the test specimens with the selected parameters was performed in the Cura® 4.7.0, which allows configuring the desired printing parameters for the process. For this project, the low quality profile (Table 3) was adopted as the default for the Creality Ender 3 printer.

Table 3. Main profile Properties *low quality*.

Property	**Fixed value**	**Unit**
Extrusion width	0.40	mm
Wall thickness	0.80	mm
Top/Bottom layers	4	-
Filling	20	%
Printing temperature	200	ºC
Platform temperature	50	ºC
Flow	100	%
Printing speed	50	mm/s

Five test specimens were made from each combination of the experimental design, totaling 40 test specimens (Figure 1).

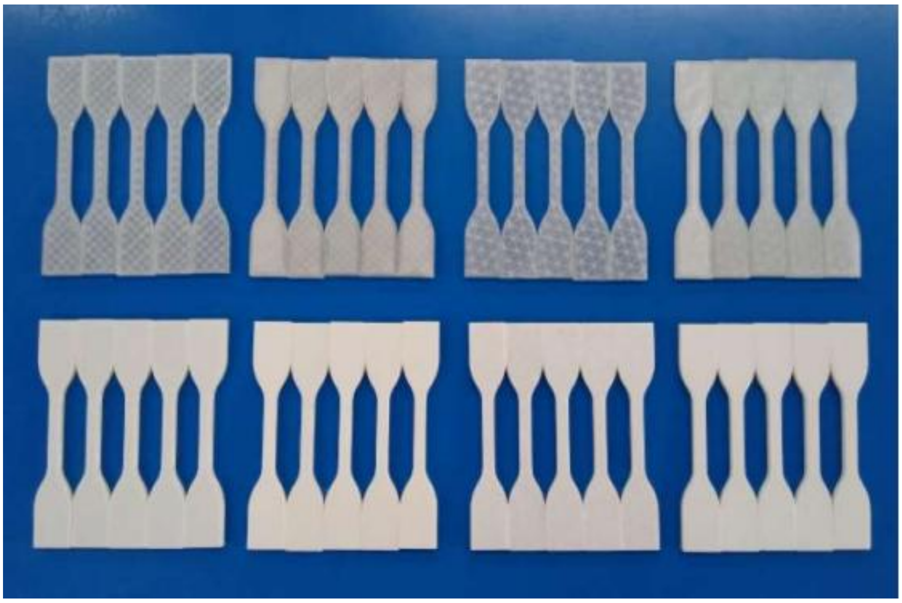

Figure 1. Printed test specimens.

Tensile tests were performed on an Emic DL 100000 universal testing machine. A 25 mm Emic extensometer was used to measure the elongation of the test specimen. The data obtained were manipulated in the Statistica® using ANOVA to verify whether the factors exert influence on the response variables.

3. RESULTS AND DISCUSSIONS

The combination with a layer thickness of 0.28 mm, triangular filling pattern and no pigmentation (combination X_4) was the one that obtained the highest tensile strength limit with 30.01 MPa. The layer thickness of 0.12 mm, grid-type filling pattern and with pigmentation (combination X_5) was the configuration that presented the lowest stress with 16.87 MPa. It can be seen that opposite configurations presented different extremes. The tensile strength probability graph (Figure 2) shows that the layer thickness variable (effect A) is the most significant variable for the tensile strength limit. However, a small influence of pigmentation (effect C) is also noted.

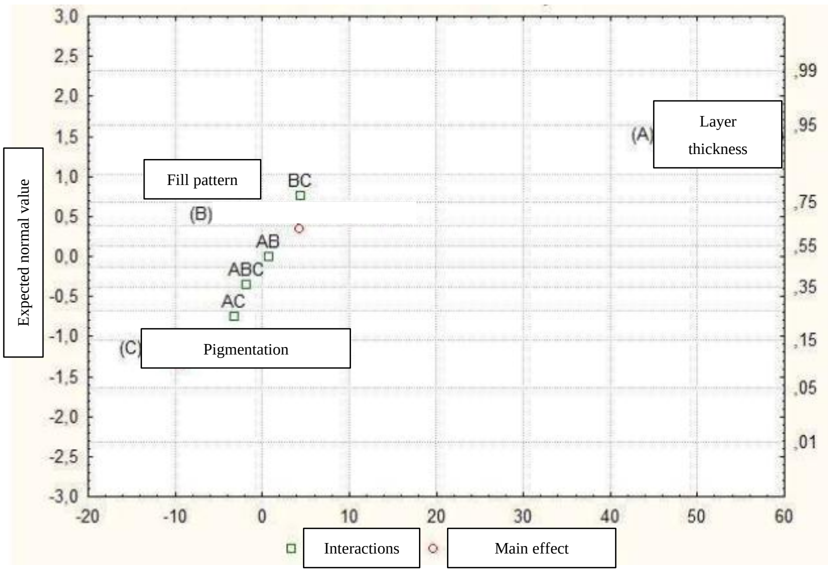

Figure 2. Tensile strength probability plot.

The graphs of average tensile strength limits (Figure 3) allow us to infer that there is a difference between the stress values between all levels for the selected variables. The highest stresses are presented in the layer thickness of 0.28 mm, triangular filling pattern and without pigmentation.

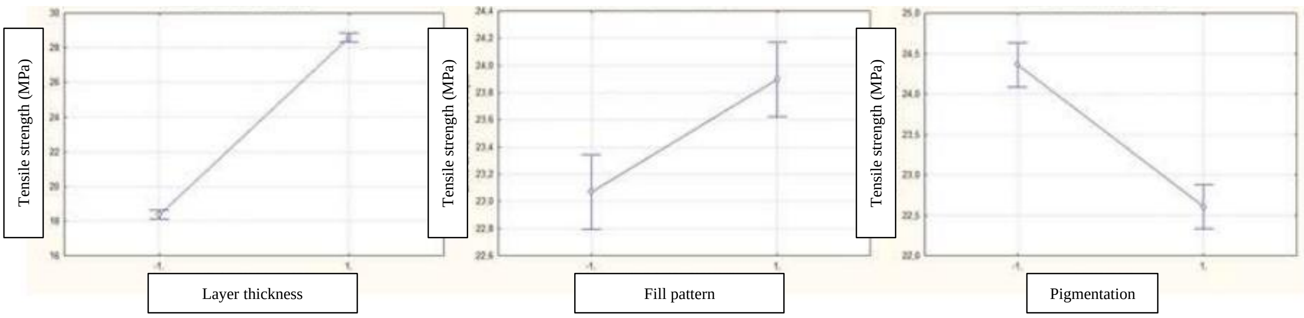

Figure 3. Tensile strength probability plot.

For elongation at break, the combination of layer thickness 0.28 mm, grid-type filling pattern and pigmentation (combination X_6) has the highest value, that is, it has the most ductile combination among those analyzed with 3.40%. However, the configuration with the lowest elongation at break was the layer thickness 0.12 mm, triangular filling pattern and pigmentation (combination X_7) with 1.54%.

The probability graph of elongation at break (Figure 4) shows the layer thickness (effect A) and the filling pattern (effect B) as significant variables for elongation at break, which corroborates the result found in the average geometry.

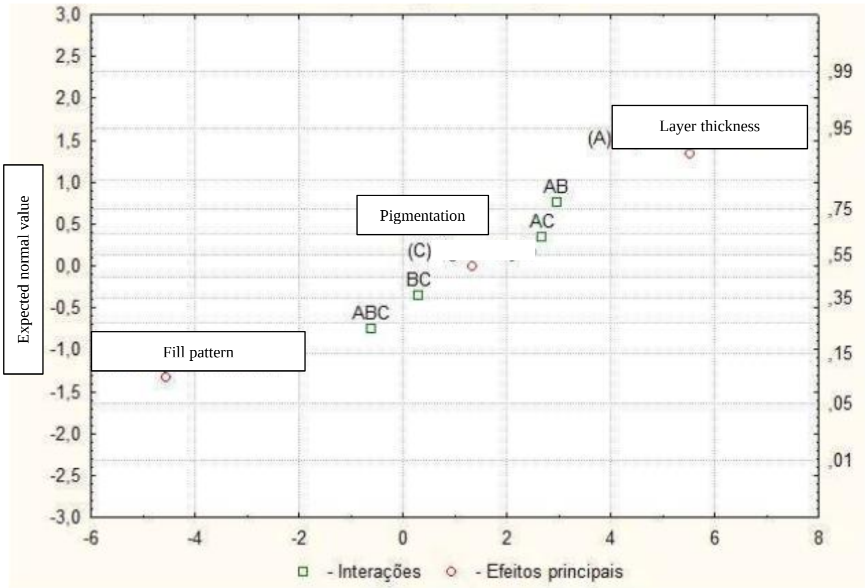

Figure 4. Elongation probability plot at break.

The graphs of average elongation at break (Figure 5) show that the levels of all variables also interfere in the values obtained. We can see that the highest ductility values are seen in a layer thickness of 0.28 mm, grid-type filling pattern and with the presence of pigmentation.

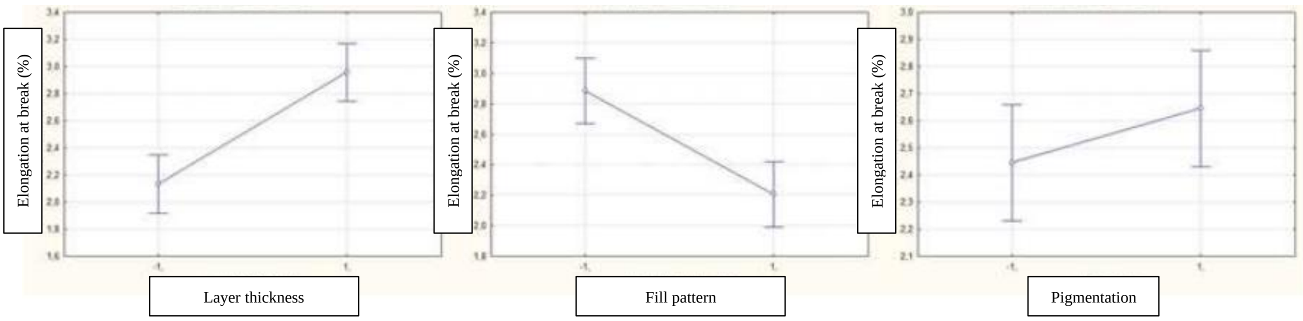

Figure 5. Graphs of average elongation at break.

All combinations with a layer thickness of 0.28 mm achieved better performance, i.e., shorter manufacturing time. Reducing the layer thickness reduces material consumption, as well as the use of the grid filling pattern. The lowest mass consumption occurred with a layer thickness of 0.12 mm. Optimising part orientation, fill density and pattern, layer height, and extruder temperature can result in significant improvements in the strength and stiffness of printed parts [8].

4. CONCLUSIONS

For the tensile strength limit, the layer thickness has a strong relationship with the result and the greater the thickness, the greater the supported tension. There is a small influence of pigmentation, in which natural PLA without pigment has higher tension values. The best configuration found was a layer thickness of 0.28 mm, triangular filling pattern and without pigmentation.

In the elongation at break, the layer thickness and the filling pattern are related to the values obtained. By increasing the layer thickness, the ductility increases. As well as the use of the grid-type filling pattern. The best combination was a layer thickness of 0.28 mm, a grid-type filling pattern and with pigmentation.

In terms of printing time, only the layer thickness is relevant, and increasing this reduces the final time for manufacturing the parts. The mass of material used is influenced by the layer thickness, filling pattern and the interaction between these two factors. This was the only variable in which the interaction between two factors was relevant to the research.

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