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

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RESUMEN

En este estudio se evaluó la influencia de las variables de fabricación altura de capa, densidad de relleno, temperatura de la boquilla del extrusor y velocidad de impresión sobre las propiedades mecánicas (límite de resistencia a la tracción, límite de fluencia, elongación a la rotura y módulo de elasticidad) de piezas de Polietileno tereftalato (PETG) obtenidas mediante el proceso de fabricación con filamento fundido (FFF). Se utilizó el Diseño de Experimentos (DOE) 2^4. Se observó que las variables de respuesta (límite de resistencia a la tracción, límite de fluencia y módulo de elasticidad) son influenciadas principalmente por las variables densidad y relleno, siendo mayor a medida que la densidad de relleno pasa de un nivel bajo a uno alto. En cuanto a la elongación a la rotura, la mayor influencia la presentó la temperatura de la boquilla del extrusor, obteniéndose los mayores valores para el nivel más alto de la variable.

Palabras clave: Fabricación Aditiva. Fabricación con Filamento Fundido. Diseño de Experimentos. PETG.

ABSTRACT

This study evaluated the influence of the manufacturing variables layer height, infill density, extruder nozzle temperature and printing speed on the mechanical properties (tensile strength limit, yield strength, elongation at break and modulus of elasticity) of Polyethylene terephthalate (PETG) parts obtained by the fused filament fabrication (FFF) process. The Design of Experiments (DOE) 2^4 was used. It was observed that the response variables (tensile strength limit, yield strength and modulus of elasticity) are influenced primarily by the density and infill variables, being greater as the infill density goes from a low to a high level. As for the elongation at break, the greatest influence was presented by the extruder nozzle temperature, with the highest values obtained for the highest level of the variable.

Keywords: Additive Manufacturing. Fused Filament Fabrication. Design of Experiments. PETG.

1. INTRODUCTION

During what is called the fourth industrial revolution, also known as Industry 4.0, the production system has been adapting to new needs, seeking greater efficiency in manufacturing processes and increasingly including technologies such as the internet of things and automated machines [1].

In this context, Albertin *et al*. [2] describe that additive manufacturing (AM) plays a fundamental role in Industry 4.0, including being considered as one of its technological pillars, and this is due to the fact that this technology allows for a reduction in the product development cycle, reaching the market more quickly.

AM is a process in which a 3D model created using CAD software is used to manufacture an object. Unlike conventional manufacturing processes that involve material extraction, AM involves the deposition of material consecutively in layers in a specific shape, forming the desired object at the end of the last layer. Because it is a process that involves material deposition, it can reduce waste of raw materials and manufacturing time compared to traditional manufacturing methods, especially when dealing with parts with complex geometries and details.

Within additive manufacturing, there are different manufacturing techniques, including fused filament fabrication (FFF), which is currently one of the most widespread. This technology uses polymers as raw materials, among which acrylonitrile butadiene styrene (ABS), poly(lactic acid) (PLA) and poly(ethylene terephthalate) glycol (PETG) stand out, which are the most widely used. Among the polymers mentioned, PETG stands out for combining some of the advantages of the others, having mechanical resistance and being easy to manufacture, allowing parts to be made with durability and in a practical way.

FFF technology has some advantages over other AM technologies and even over other manufacturing methods, such as a very simple operating principle and relatively low cost, among other factors. In the FFF manufacturing process, the material to be added is heated until melting and deposited according to the desired shape, to obtain the final part after all layers have been deposited. However, this process also has its limitations, such as the fact that parts with lower mechanical strengths are generally manufactured when compared to traditional manufacturing processes such as injection molding [3]. The FFF process involves temperature gradients that may source the residual stresses built up generating undesired part distortion. Residual stresses and distortions mainly result from the polymer evolution from a semi-molten to a solid state throughout the manufacturing process [4]. However, the properties of the resulting parts can be controlled, although they largely depend on the printing process parameters. 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 [5].

Thus, to mitigate such limitations, it becomes essential to evaluate the influence of the different manufacturing parameters of the FFF process on the mechanical properties of artifacts manufactured in PETG, since this will allow the selection of such parameters so that the final part can have the most appropriate mechanical properties for each product design.

2. MATERIALS AND METHODS

The material used was PETG XT filament in metallic blue (blue metal), with a diameter of 1.75 mm, both supplied by the company 3Dfila. Where XT appears after PETG, according to 3DFila, is a classification by the manufacturer for PETG manufactured specifically for the 3D printing process.

In the preparation of the test specimens (Figure 1), a Creality Ender 3 was used with slicing performed in the Ultimaker Cura 4.11.0 software (Figure 1a), totaling 80 test specimens (Figure 1b). The tensile tests (ASTM D638 [6], type IV, Figure 1c) of the test specimens were performed in the Emic DL 100000 universal testing machine, using a 25 mm extensometer (Figure 1d).

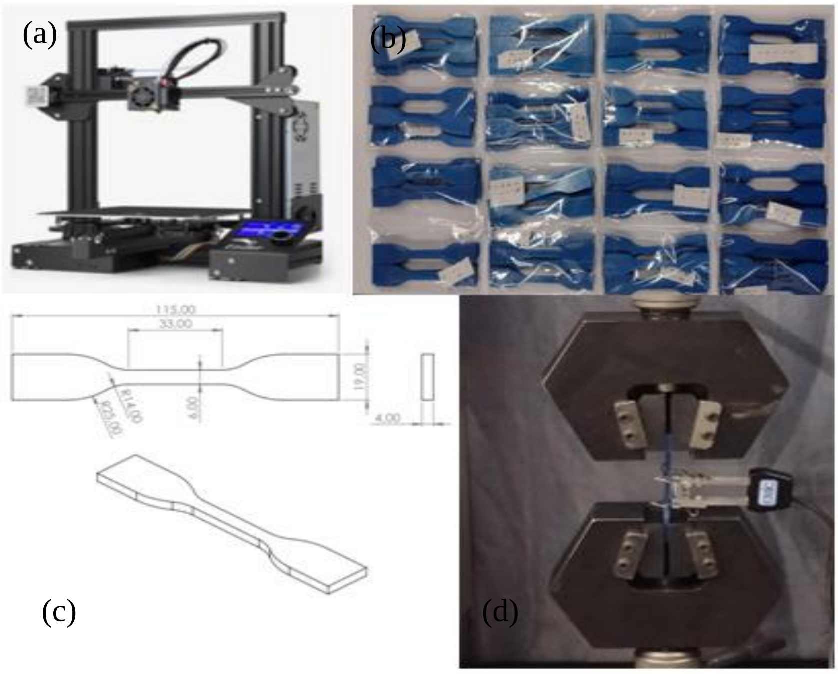

Figure 1. (a) Creality Ender 3 printer, (b) printed specimens, (c) specimen dimensions and (d) tensile test.

The factors chosen for this study were selected based on research and studies observed regarding FFF technology and its manufacturing parameters and PETG material, so that these parameters are relevant to the final strength of the part. The parameters analyzed were: layer height, filling density, extruder nozzle temperature and printing speed, all of which are slicing configurations. To apply the 24 factorial design, two levels were selected for each of the factors (Table 1).

Table1. Printing parameters.

Factor	**Level of variation**	**Maximum (+)**	**Minimum (-)**	**Unit**
A	Layer height	0.28	0.12	mm
B	Fill density	90	70	%
C	Extruder nozzle temperature	260	230	ºC
D	Printing speed	60	40	mm/s

To ensure good print quality and a very constructive comparison, the levels of each factor were based on the values suggested by the filament manufacturer, the Ultimaker Cura slicing software and the values used by Fountas *et al*. [7]. The authors analyzed the influence of the variables layer height, infill density, deposition angle, printing speed and printing temperature on the flexural strength of parts manufactured in PETG using FFF technology.

The two relevant layer height levels were selected from among the predefined parameters of Ultimaker Cura (0.12 mm, 0.16 mm, 0.20 mm and 0.28 mm), but taking as a basis the aforementioned study carried out by Fountas *et al*. [7], selecting the closest to its extreme layer height levels (0.10 mm and 0.30 mm).

For filling density, the maximum level selected was 90% while the minimum level was 70% and the printing speed was 40 mm/s and 60 mm/s, according to Fountas *et al*. [7]. The extruder nozzle temperature was 230°C and 260°C for lower and upper limit values suggested by the filament manufacturer, respectively.

The other parameters of the manufacturing process were kept constant, for example, all parts were printed in the same position in relation to the printing table and the slicing variables were fixed according to the basic settings and parameters of the Ultimaker Cura 4.11.0 slicing software for the Creality Ender 3 3D printer, with the 1.75 mm diameter PETG filament and using the 0.40 mm extruder nozzle. In addition to these variables, the filling pattern was kept in the grid format, and at the suggestion of the filament manufacturer, the temperature of the printing table used was 75ºC.

3. RESULTS AND DISCUSSIONS

The limit averages for tensile strength presented in Figure 2 allow us to note that the greatest variation in the result is obtained with the filling density factor, while the smallest variation is obtained with the printing speed, with the highest values for resistance being obtained for a layer height of 0.12 mm, filling density of 90%, extruder nozzle temperature of 260ºC and printing speed of 40 mm/s.

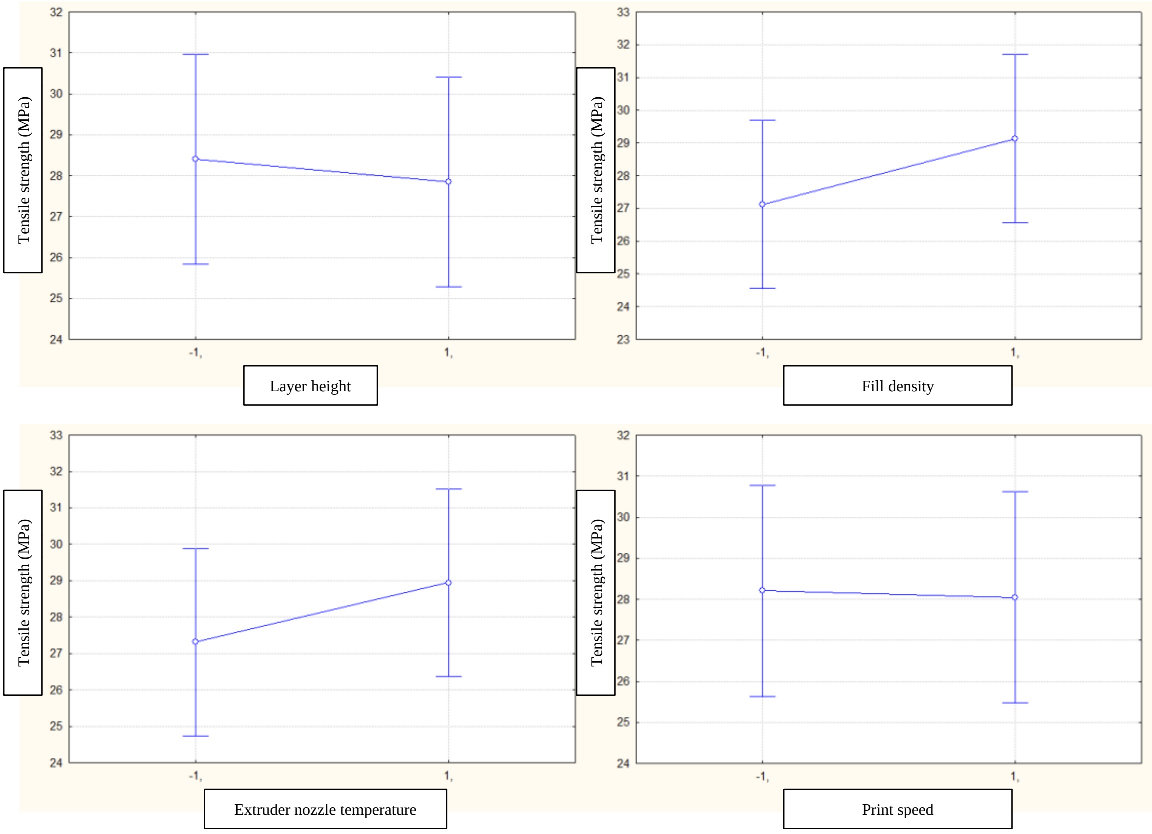

Figure 2. Tensile strength limit averages.

The average yield strengths presented in Figure 3 allow us to observe that the variable filling density leads to the greatest variation in the result obtained, while variation in layer height leads to practically no change. Thus, the highest values for resistance are obtained for a layer height of 0.28 mm, filling density of 90%, extruder nozzle temperature of 260ºC and printing speed of 40 mm/s.

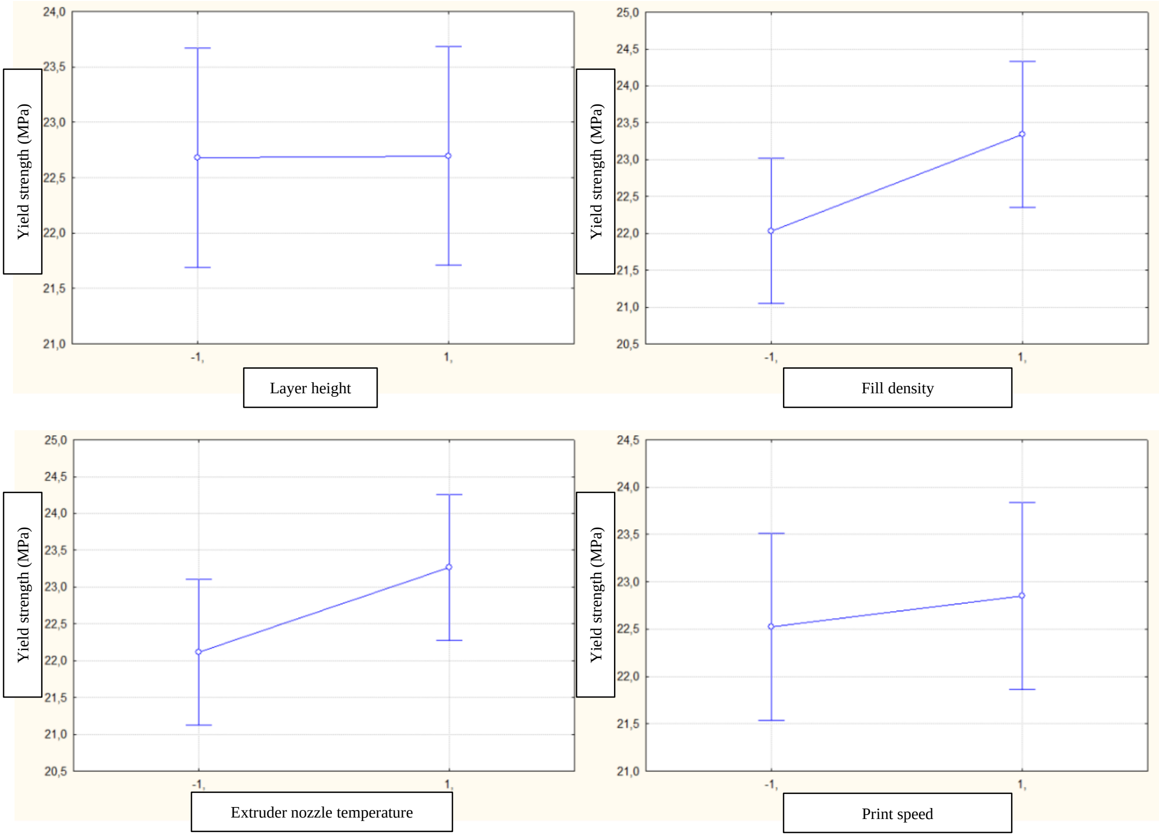

Figure 3. Yield limit averages.

The average limits for elongation at break presented in Figure 4 show that variations in the levels of the factors have little influence on the elongation result, with the greatest variation occurring due to the effect of changes in the extruder nozzle temperature. Thus, the highest values for elongation at break are obtained for a layer height of 0.28 mm, fill density of 70%, extruder nozzle temperature of 260ºC and printing speed of 40 mm/s.

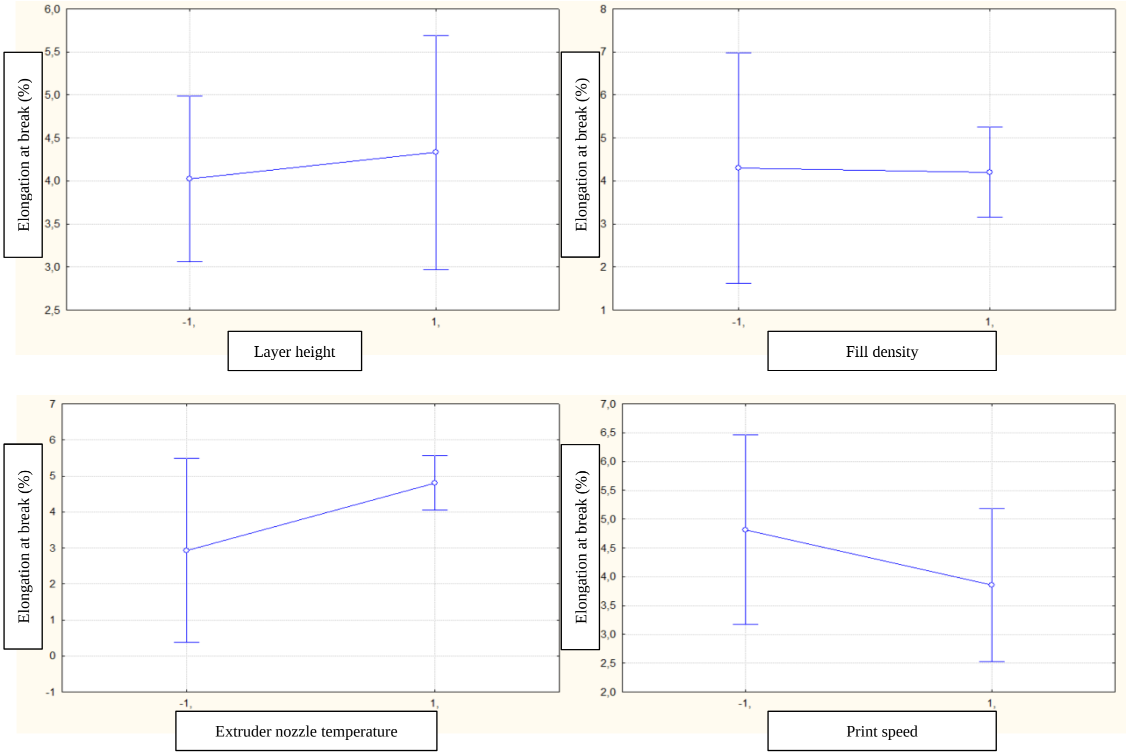

Figure 4. Limit averages for elongation at break.

For the average limits of the modulus of elasticity presented in Figure 5, it is observed that the filling density variable leads to a greater variation in the result obtained, while in the layer height it leads to a practically null change in the modulus of elasticity, and in an intermediate way are the extruder nozzle temperatures and printing speed. Thus, the highest values for resistance are obtained for a layer height of 0.12 mm, filling density of 90%, extruder nozzle temperature of 260ºC and printing speed of 60 mm/s. The ability to adjust these parameters offers considerable flexibility to tailor the mechanical properties of FFF parts to the specific needs of various applications [5].

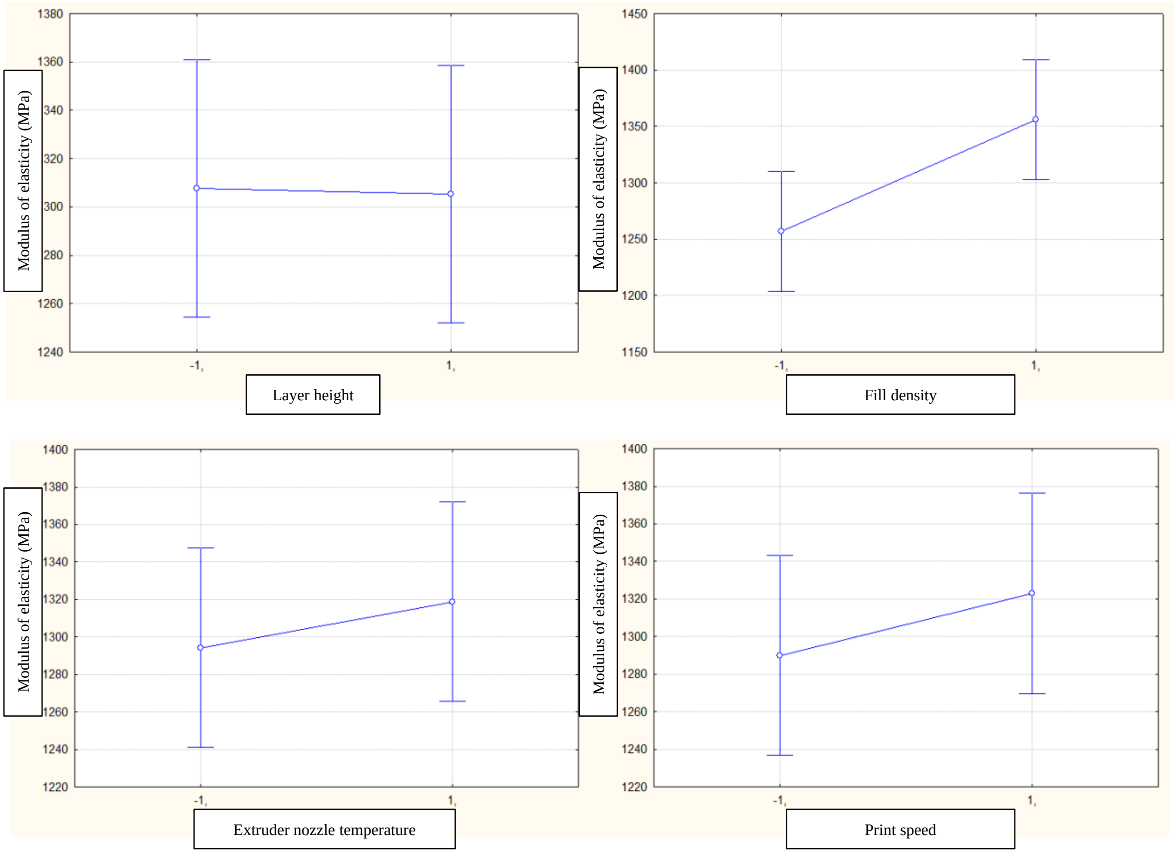

Figure 5. Limit averages for modulus of elasticity.

4. CONCLUSIONS

The tensile strength limit is mainly affected by the infill density factor, followed by the less intense influence of the extruder nozzle temperature and the interaction of the layer height with the printing speed. The maximization of the tensile strength limit within the studied levels is observed when increasing the infill density and the extruder nozzle temperature, and even with less influence, when decreasing the layer height and the printing speed.

Likewise, the increase in the yield point is directly related mainly to the increase in the filling density, and to a lesser extent to the extruder nozzle temperature. Thus, the highest yield point results within the levels studied are obtained with higher levels of filling density and extruder nozzle temperature, and with less representativeness, with high levels of layer height and printing speed.

For elongation at break, the factors that presented the greatest effects on the response were the extruder nozzle temperature and layer height, respectively. Thus, within the variables studied, the samples with greater ductility are obtained when the highest levels of extruder nozzle temperature, layer height, and low levels of infill density and printing speed are used.

In the modulus of elasticity response, it was observed that the filling density variable was again very relevant, followed this time by the interaction between the layer height and extruder nozzle temperature factors. Thus, the elasticity of the parts increases for high levels of filling density, extruder nozzle temperature and printing speed, and for low levels for layer height.

The most relevant variable for both mechanical strength and modulus of elasticity was the filling density, while the extruder nozzle temperature was the most relevant factor for ductility and had some influence on mechanical strength. The layer height variable played a secondary role in the ductility of the parts and was considered irrelevant for the others.

responses. And finally, the printing speed showed influences considered insignificant for each of the results.

The fact that some variables had less influence on the results does not necessarily mean that they do not have this effect, but that proportionally their influence is less than others. Therefore, in a study comparing with other variables, these same factors can be considered influential.

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