A Theoretical and Experimental Research on the Influence of FDM Parameters on Tensile Strength and Hardness of Parts Made of Polylactic Acid

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Abstract-Fused Deposition Modeling (FDM) is a rapid prototyping method, widely used in the manufacture of plastic parts with complex geometric shapes. The quality of the parts manufactured by this process depends on the plastic material used and the FDM parameters. In this context, this paper will present the results of a theoretical and experimental research on how FDM parameters influence the tensile strength and hardness of samples made of PLA (Polylactic Acid).

Keywords-3D printing; experimental tests

I. INTRODUCTION

With the increasing complexity of industrial products and the requirements related to environmental protection and resource conservation, new manufacturing technologies are needed. FDM is the most significant technique in Additive Manufacturing (AM) that refers to the process in which successive layers of material are stored in a computer-controlled environment to create a three-dimensional (3D) object [1]. Since 2009 the demand for FDM has grown steadily and many experts believe that this technology has the potential to revolutionize production in many sectors [2]. The main advantages of FDM are [2]: the manufacturing process is simple, allowing the making of parts with complex geometries and cavities, the dimensional accuracy is good, and it is a more cost-effective method compared to other 3D printing techniques. Additive technologies represent a field that is suitable for the needs of today's society through specific interdisciplinary and application possibilities in various areas such as: medicine, engineering, aeronautics, automotive, architecture, etc. However, there are still some limitations and disadvantages, especially in terms of the lower mechanical properties of FDM parts compared to products by conventional methods, such as injection and compression techniques [2, 3]. Since mechanical characteristics are extremely important for functional parts, it is necessary to investigate the influence of process parameters on the mechanical performance and geometrical qualification [3, 4]. Further research is also needed to determine the printing parameters, such as: deposition orientation, layer thickness, and deposition speed, mainly because the relevant information in the literature is diverse in terms of the values obtained by the mechanical characteristics of parts made with 3D printers. This applies to PLA material, which unlike ABS has not been extensively analyzed [5-10]. The novelty of this paper consists in the comparison of different printing parameters (layer thickness and infill percentage), which can be used in order to optimize the mechanical characteristics obtained for different applications.

II. A COMPARISON OF THE MATERIALS USED FOR 3D PRINTING IN FDM TECHNOLOGY

FDM has the advantage of using a wide range of materials. Table I shows a comparison between the physical and mechanical characteristics of various such materials used. The data were collected from the manufacturers' data sheets specifications. These values are indicative and depend heavily on the printing conditions. The mechanical properties considered refer to the orientation of the horizontal test specimen (XY orientation). Under these conditions, this paper analyzes the influence of technological conditions of deposition on the mechanical characteristics of the deposited material. Economic, environmental, and safety challenges have caused scientists and economic agents to partially replace petrochemical with biodegradable polymers [11] such as the PLA.
TABLE I. PHYSICAL-MECHANICAL CHARACTERISTICS OF THE MOST USED FILAMENTS IN FDM TECHNOLOGY [8-10]

| Material | Extrusion temperature (°C) | Bed temperature (°C) | Density (g/cm³) | Tensile strength (MPa) | Specific Deformation (%) | Charpy impact strength (kJ/m²) | Details |
|----------|---------------------------|----------------------|----------------|------------------------|--------------------------|----------------------------|---------|
| PLA      | 210 ± 10                  | 25-60                | 1.31±0.02      | 15.5-72                | 34.5 ± 8.1               | 5.7 ± 0.4                  | Colored filament |
| PP       | 240 ± 10                  | 80                   | 0.89           | 14                     | >200                     | 10                         | Translucent |
| BVOH     | 210 ± 10                  | 60                   | 1.14           | 45                     | 9                        | 21                         | Soluble in water |
| PETG     | 240                      | 80                   | 1.25           | 31.9 ± 1.1             | 6.8 ± 0.9                | 5.1 ± 0.3                  | Flexible   |
| 316 L    | 240 ± 10                  | 105 ± 15             | 5.6 ± 0.2      | 561                    | 53                       | 1110                       | Stainless steel |
| PETG     | 240 ± 10                  | 150 ± 10             | 1.27           | 81                     | 3.3                      | 6                          | Flexible   |
| ABS      | 210 ± 10                  | 80                   | 1.10           | 33.9                   | 4.8                      | 10.5                       | Very rough |

III. EXPERIMENTAL METHODOLOGY

A. Setting Up Parameters

The mechanical properties of 3D printed parts are important indicators for evaluating print quality. The experimental research program includes tests performed to determine how the technological parameters of the printing influence the mechanical characteristics of the deposited material. In these conditions, the working parameters of the printer used must be taken into account. The initial data targeted in the experimental determinations were grouped into two categories (Table II). The first category refers to process parameters considered as constant quantities: deposition direction, printing speed, filling pattern, and deposition temperature. The second category is the process parameters considered as variable parameters: layer thickness (g), infill percentage (gₖ), flow rate (Fᵢ). Test specimens were made and were grouped on sets of samples, each set of samples consisting of 5 specimens, belonging to a group of process parameters, highlighted in Table III.

TABLE II. CONSTANT AND VARIABLE PRINTING PARAMETERS

| Parameters | Process parameters used (constant quantities) | Variable parameters of the technological process |
|------------|-----------------------------------------------|------------------------------------------------|
| Build orientation X-Y  | Layer thickness (g)                           | Infill percentage (gₖ)                           |
| Print speed (Ps) - 80mm/s | Infill percentage (gₖ)                          | Flow rate (Fᵢ)                                  |
| Deposition temperature (Dt) - 200°C | Layer thickness (g)                           | Infill percentage (gₖ)                           |
| Infill model - lines, 45° orientated | Layer thickness (g)                           | Infill percentage (gₖ)                           |

TABLE III. PROGRAM OF EXPERIMENTAL DETERMINATIONS

| Layer thickness (mm) and infill percentage | Printing parameters |
|-------------------------------------------|---------------------|
|                                           | Flow rate (mm³/s)   | Temperature (°C) | Print speed (mm³/s) |
| 0.2 (100%)                                | 6.4                 | 200              | 80                  |
| 0.2 (75%)                                 | 6.4                 | 200              | 80                  |
| 0.2 (50%)                                 | 6.4                 | 200              | 80                  |
| 0.2 (25%)                                 | 6.4                 | 200              | 80                  |
| 0.15 (100%)                               | 4.8                 | 200              | 80                  |
| 0.15 (75%)                                | 4.8                 | 200              | 80                  |
| 0.15 (50%)                                | 4.8                 | 200              | 80                  |
| 0.15 (25%)                                | 4.8                 | 200              | 80                  |
| 0.1 (100%)                                | 3.2                 | 200              | 80                  |
| 0.1 (75%)                                 | 3.2                 | 200              | 80                  |
| 0.1 (50%)                                 | 3.2                 | 200              | 80                  |
| 0.1 (25%)                                 | 3.2                 | 200              | 80                  |

B. Experimental Set-Up

The adopted material for making the test specimens was PLA. The recommended melting temperature for this material is between 200-220°C, while the temperature of the heated plate has been set to 60°C. The filament used to obtain the test specimens was Creality PLA, with a diameter of 1.75mm [12]. The specimens were made on the Creality CR-X printer, equipped with 2 extruders, with an extrusion nozzle diameter of 0.4mm. Work methodology was applied as in Figure 1. The shape and main dimensions of the specimen are shown in Figure 2. The specimens used in this study to assess dimensional accuracy (Figure 3), repeatability and mechanical properties are modeled on American Society for Testing and Materials ASTM D638, Type IV standards for tensile testing of plastic [13].

Fig. 1. Work methodology.

Fig. 2. Tensile test specimen's dimensional details [13].
Each set of samples consisted of 5 specimens, each belonging to a group of process parameters, highlighted in Table III. A total of 60 specimens were manufactured by 3D printing. The specimens were subjected to mechanical tests to determine the strength characteristics of the material: ultimate tensile strength ($R_u$), elongation at break ($e$), tensile Young's modulus ($E_i$), and hardness (HS). Tensile tests were performed on an electro-mechanical machine with a force cell of 2.5kN, at a speed of 5mm/min (Figure 4). Elongation at break was measured using an axial extensometer (Figure 4). Hardness was measured at the points specified in Figure 3. The values of hardness were determined on 15 specimens, with infill percentage of 50%, 75%, and 100%, in 6 points per specimen (Figure 4), with a Shore D durometer (Figure 5).

IV. RESULTS AND DISCUSSION

The experimental tests were designed to investigate the behavior of plastic parts (PLA), under the action of traction forces, made by 3D printing, taking into account the manufacturing conditions as input factors of the testing process.

A. Tensile Properties Obtained from the Experimental Tests

The initial information for the tensile tests consisted of the shape and dimensions of the test specimen (Figure 2), the type of plastic used (PLA), 3D printing equipment (electro-mechanical machine Lloyd LRX Force Tester - Figure 4), as well as the process parameters considered as constant quantities: deposition direction (X-Y), printing speed (80mm/s), filling pattern (lines), and deposition temperature (200°C). The process parameters considered as variables were: the thickness of the deposited layer ($g = 0.1; 0.15; 0.20\text{mm}$) and the infill percentage ($g_u = 25\%; 50\%; 75\%; 100\%$). The experimentally determined quantities were: ultimate tensile strength ($R_u$), elongation at break ($e$), tensile Young's modulus ($E_i$), and hardness (HS). The test methodology was performed in the conditions in which the variation parameters were the thickness of the deposited material layer $g$ and the infill percentage $g_u$. Graphs were drawn that express the dependence of the mechanical characteristics (CM) of the tested specimens according to the infill percentage $CM = f(g_u)$ for different thicknesses of the deposited layer. Under these conditions, the following dependencies were drawn:

- Figure 6 shows the dependence $R_u = f(g_u)$ for $g = 0.1\text{mm}$ and $g_u = 25\%; 50\%; 75\%; 100\%$.
- Figure 7 shows the dependence $e = f(g_u)$ for $g = 0.1\text{mm}$ and $g_u = 25\%; 50\%; 75\%; 100\%$.
- Figure 8 shows the dependence $E_i = f(g_u)$ for $g = 0.1\text{mm}$ and $g_u = 25\%; 50\%; 75\%; 100\%$.
- Figure 9 shows the dependence $R_u = f(g_u)$ for $g = 0.15\text{mm}$ and $g_u = 25\%; 50\%; 75\%; 100\%$.
- Figure 10 shows the dependence $e = f(g_u)$ for $g = 0.15\text{mm}$ and $g_u = 25\%; 50\%; 75\%; 100\%$.
- Figure 11 shows the dependence $E_i = f(g_u)$ for $g = 0.15\text{mm}$ and $g_u = 25\%; 50\%; 75\%; 100\%$.
- Figure 12 shows the dependence $R_u = f(g_u)$ for $g = 0.20\text{mm}$ and $g_u = 25\%; 50\%; 75\%; 100\%$.
- Figure 13 shows the dependence $e = f(g_u)$ for $g = 0.20\text{mm}$ and $g_u = 25\%; 50\%; 75\%; 100\%$.
- Figure 14 shows the dependence $E_i = f(g_u)$ for $g = 0.20\text{mm}$ and $g_u = 25\%; 50\%; 75\%; 100\%$.
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B. Shore D Hardness

The Shore D Hardness for 50, 75, and 100% $g_0$ can be seen in Figure 15.

V. Conclusions

The objective of the paper was to establish the variation of the mechanical characteristics of the PLA material, deposited by 3D printing, depending on the parameters of the technological process. We have started from the characteristics of the raw material (Table I) which show a wide range of technological process. We have started from the characteristics and for $\varepsilon$, specimen value of $R_m$, test piece of ultimate tensile strength (R$_u$ = 34.5 ± 8.1%). From the analysis of the obtained results it was found that the ultimate tensile strength increases with the infill percentage and the Shore D Hardness, because of the shell layers (thickness of 0.8mm) and bottom and top thickness of the layers applied on all infill types of specimens. Further research and possible modification of the shell structure might reveal different results in this direction.

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