Fabricación aditiva de estructuras 3D reforzadas: efectos de los parámetros de impresión en el comportamiento mecánico

La impresión 3D o prototipado rápido es un método de fabricación aditiva que se emplea para la generación de prototipos y piezas funcionales. FDM (Fused Deposition Modelling) es la más popular debido a su uso extensivo en impresoras 3D para la fabricación de piezas con geometrías complejas, con las ventajas de un bajo coste y sin necesidad de mecanizados. La calidad de las partes fabricadas (acabado superficial, precisión dimensional o propiedades mecánicas) dependen de diversas variables del proceso. El estudio de la influencia de estos parámetros es de gran importancia para entender el funcionamiento de materiales de impresión 3D, y para determinar los desarrollos futuros.

El objetivo de este trabajo es el estudio de la influencia de los distintos parámetros de impresión (orientación, altura de capa y velocidad de impresión) en el comportamiento mecánico de probetas fabricadas con impresoras 3D comerciales. Se han realizado ensayos de tracción y flexión de 3 puntos para evaluar las propiedades mecánicas bajo distintos parámetros del proceso. Finalmente, los resultados obtenidos se han verificado ensayando una estructura funcional como caso práctico.

Palabras clave: Impresión 3D, Orientación, Altura de capa, Velocidad de impresión, Propiedades mecánicas

Additive manufacturing of 3D reinforced structures: effects of process parameters on mechanical properties

Three dimensional (3D) printing or Rapid Prototyping (RP) provides an innovative additive manufacturing method for prototypes and functional components. Fused deposition modeling (FDM) is a fast growing rapid prototyping technology for fabricating thermoplastic parts due to its ability to build functional parts having complex geometrical shapes in reasonable time periods with the advantages of low cost, minimal wastage, and no tooling or touch labour. The quality of a built part (surface finish, dimensional accuracy or mechanical properties) depends on several process variables. Assessing the influence of these process parameters on mechanical properties is vital for understanding the performance of 3D printed materials, and to determine the needs for further research.

The aim of this study is to characterize and assess of different process parameters on the mechanical performance of PLA and ABS samples manufactured with low cost 3D printing. Tensile and three-point bending tests series were carried out to determine the mechanical response of the printed specimens with different process parameters. Finally, the practicality of the results was assessed by testing an evaluation structure as a case example.
1 Background

Additive manufacturing (AM) is one of the most promising areas in the manufacturing of components [1-6]. AM has moved beyond its initial role as prototyping technology to a process that can build finished parts. These technologies are able to accurately form complex 3D parts directly. Furthermore, they enable the manufacture of a large range of prototypes or functional components with complex geometries, which are difficult, if not impossible, to manufacture using conventional methods [7] without tooling or touch labour [8-10]. Compared to conventional methods, AM technologies can shorten the design-manufacturing cycle, reduce production costs, and increase competitiveness [9,11,12]. AM technologies cover a broad spectrum of application such as the aerospace and automotive industry, medicine, architecture, education, and fashion [13-19].

The term 3D printing is often used as synonymous to AM technologies, but it is more commonly associated with low cost desktop 3D printers of polymers and non-metal materials. 3D printing or Rapid Prototyping is a manufacturing process that can reproduce complex geometries, such as those obtained from a topology optimization process [20-21], or generated from a fitting process in Computer-Aided Design [22]. 3D printing is not an entirely new technology, but with the advent of open source, low cost 3D printers has become a widespread manufacturing process. The popularity of 3D printing among researchers and hobbyists for the design and manufacture of complex components has led to the rapid growth of this technology worldwide [23-25].

AM technology is a very broad term encompassing numerous methods such as Stereolithography (STL) of a photopolymer liquid, Fused Deposition Modeling (FDM) from plastic filaments, Laminated Object Manufacturing (LOM) from plastic laminates, and Selective Laser Sintering (SLS) from plastic or metal powders [3,26]. However, the FDM technique is of particular interest due to its association to desktop 3D printers, and it is the most widely used method among all the AM techniques for fabricating pure plastic parts with low cost, minimal wastage and ease of material change [19,27].

FDM, developed by Stratasys in 1988 [10], forms a 3D geometry by assembling individual layers of extruded thermoplastic filament, such as acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA), which have melting temperatures low enough for use in melt extrusion in outdoor non-dedicated facilities [1]. PLA materials offer better thermomechanical characteristics than ABS, but higher mechanical performance, and a lower thermal expansion coefficient. FDM is a complex process with a larger number of parameters that influence product quality and material properties, and the combination of these parameters is often difficult to understand [5,28]. Printing parameters such as build orientation, layer thickness, raster angle, raster width, air gap, infill density and pattern, and feed rate, among others, have a substantial effect on quality and performance of FDM printed parts [1,4,5,7,8,9,12,23,29,30]. Since mechanical properties are crucial for functional parts, it is absolutely essential to examine the influence of process parameters on mechanical performance, so that improvements can be made in selecting the best FDM process parameters settings [11,12,31,32,33].

Moreover, the layered nature of FDM processes has considerable implications on the resulting parts. Thus, further research is required to determine printer parameters such as build orientation, layer thickness and feed rate, particularly since the literature on the mechanical properties of parts processed by low cost 3D printers is somewhat scarce. This applies to the PLA material used in this study that, unlike ABS material, has not been extensively analysed [1,8,34]. Certain studies have specifically focussed on the optimization of FDM process parameters in order to improve ABS thermoplastic performance [28].

To date, anumber of studies have highlighted the impact of build orientation on aspects such as surface quality, geometric accuracy, build time and overall manufacturing cost [30]. However, build orientation has a significant impact on the structural properties of additively manufactured parts. This is often observed in the form of anisotropically printed objects, making structural performance highly dependent on build orientation, in a similar way to composites laminates [35-37]. This effect has been observed and experimentally demonstrated thorough tensile, flexural, impact or compression testing in a limited number of studies [1,4,5,9,10,33,38,39]. These authors agree that the strongest printing orientation is always along the pull direction [6]. A more controversial parameter is layer thickness [1,9,11,32,38]. Several studies have concluded that the optimum selection of parameters for the best mechanical performance includes the minimum layer thickness [6,32]. In contrast, tensile strength and stiffness was found to increase as layer thickness increased [1,9]. Though the effect of feed rate on the mechanical properties of PLA samples is a crucial parameter directly related to manufacturing cost [28], it has not been extensively studied. The inconsistency in the results of mechanical performance is a further indicator of the effects of printing parameters on the mechanical properties of parts, particularly in regard to build orientation, layer thickness or feed rate of PLA samples fabricated by FDM.

In this study, the characterization and assessment of the effect of different process parameters on the mechanical properties of PLA samples fabricated with a low cost desktop 3D printer using FDM technique were examined. Three main process parameters were analysed: build orientation (Flat, On-edge and Upright), layer thickness and feed rate, respectively. These process parameters were selected in order to assess the mechanical response of the printed samples under tensile and flexural loading. The aim was to determine the optimum settings in order to assist users in the correct selection of process parameters. Special attention was paid to the anisotropic response (strength and stiffness) of the printed samples under tensile and flexural loading. Moreover, ABS specimens fabricated by a commercial 3D printer were used for comparative purposes. The results of this study will be useful for defining the best selection of process parameters for optimum mechanical performance and to minimize manufacturing costs. Furthermore, the analysis of the effects of fused deposition modelling process parameters on the mechanical performance of FDM parts are of special interest for the fabrication of continuous reinforced fibre 3D printed structures using the FDM technology [2,3,7,19,40,41]. Finally, the practicality of the previous results was assessed further by
testing an functionally static load-bearing assembly as a case example.

2 Experimental methodology

2.1 Materials, 3D printers and specimen preparation

The goal of this study was to analyse the mechanical performance of PLA samples using different process parameters. Furthermore, ABS plus™ P430 samples were used for comparative purposes. Typical values of the main mechanical properties of PLA and ABS materials fabricated by FDM technology [8,26] are presented in Table [1]

<table>
<thead>
<tr>
<th>Properties</th>
<th>PLA</th>
<th>ABS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>15.5-72.2 MPa</td>
<td>36-71.6 MPa</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>2020-3550 MPa</td>
<td>99.8-2413 MPa</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>0.5-9.2%</td>
<td>3-20%</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>52-115.1 MPa</td>
<td>48-110 MPa</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>2392-4930 MPa</td>
<td>1917-2507 MPa</td>
</tr>
</tbody>
</table>

Table 1. Typical range of mechanical properties for PLA and ABS materials fabricated with FDM technology

These samples were fabricated using a WitBox desktop 3D printer, manufactured by BQ [42]. WitBox is a low cost desktop printer that uses PLA material with a 0.4 mm nozzle size. WitBox can be controlled with any open source software. In this study, Cura software [43] was used to generate G-code files and to command and control all the process parameters. Furthermore, ABS samples were fabricated using the industrial 3D printer Dimension Elite, developed by Stratasys. The Dimension Elite is a high performance industrial printer that uses ABS material and is controlled by CatalystEX Software [44], a specific software that can modify only a limited number of process parameters.

There are no standard test methods for tensile and flexural properties of parts fabricated using FDM. In this work, the ASTM D638 [45] and D790 [46] methods were applied for testing tensile and flexural specimens, respectively. The geometry of the 3D printed specimens were modelled using SolidWorks software, exported as an STL file and imported to the 3D printing software. The geometry of the tensile and flexural specimens are shown in Figure [1].

One of the most important and controversial parameters to determine the quality of a part fabricated using FDM is the layer thickness (Lt), see Figure 2b. Rankouhi et al. [6] stated that, although layer thickness has been studied extensively, see for examples References [1,9,11,32,38], it should be further analysed, due to the disparity of results. In this work, different layer thickness values were considered in order to analyse the influence of this parameter. These values were selected according to the Witbox 3D printer range. In comparison, in the case of the Dimension Elite 3D printer, only two layer thickness values were analysed due to restrictions in the selection of this parameter. In both cases, layer thickness was measured in the Z direction.

The influence of the raster pattern, air gap, raster angle or raster width in the mechanical performance of FDM printed parts has been extensively studied [23,28]. There is a broad spectrum of infill patterns, making it difficult to analyse the influence of raster pattern. In this work, solid samples filled with a perimeter raster were analysed, which is where the tool paths are the offsets from the perimeter with a distance of the nozzle size, see Figure 2b. Hence, the selected shell thickness
was selected long enough to fill the sample, with a raster angle of 0°.

Furthermore, the effect of feed rate (Ff) in the mechanical performance of PLA or ABS samples has not been extensively studied [28]. This process variable is also directly related to build time, and consequently, to manufacturing cost. In a FDM process, if the feed rate is modified, the flow rate of the extruded material must be changed in order to keep a constant width of the perimeter lines. In this study, the influence of the feed rate on mechanical properties was evaluated. Three different feed rates were considered for the WitBox printer. Flow rate was adjusted accordingly. In the case of the Dimension Elite 3D printer, feed rate could not be modified and a fixed feed rate of 43 mm/s was selected. Some parameters, such as air gap, raster angle or temperature, were fixed for all the samples in order to focus on the influence of the previous three parameters (build orientation, layer thickness and feed rate). A complete set of 5 specimens of each of the combinations of variables was printed on both 3D printers.

2.3 Experimental set-up

The experimental series were carried out at the University of Castilla-La Mancha (Spain). Each sample set consisted of five specimens for a given group of process parameters, with a total of 420 specimens (tensile and bending specimens), 360 PLA and 60 of ABS, respectively. Average strength and stiffness values of the mechanical test were taken as the results. Since the physical properties of many materials (especially thermoplastics) can vary depending on ambient temperature, tests were carried out according to the standards for room temperature.

The uniaxial tensile tests were performed following the standard ASTM D638-10 standard [45]. A 50 kN universal electro-mechanical testing machine at a fixed loading rate of 2 mm/min was used for the tensile test, see Figure 3a. Figure 3b shows the set-up of a tensile specimen and test fixture. Strain was measured using a MTS 634.14 high-performance axial extensometer. The experimental data were processed following the recommendations of the previous standard, for the determination of the maximum tensile strength and the tensile Young’s modulus. Young’s modulus was determined considering the linear part of the stress-strain curve and the slope was estimated by a linear fit. Tensile strength was calculated as a ratio between the maximum load reached during the test and the cross-sectional area.

The 3-point bending tests were performed following the ASTM D790-10 procedure [46] using a three point bending test fixture. Figure 3c shows the set-up of a 3-point bending specimen and test fixture, where the radius of the loading nose and the radii of the support noses were 3 mm. The flexural modulus of elasticity was determined following the previous standard.

3 Results and discussion

An extensive test series was designed to assess the effects of different ranges of three main process parameters (build orientation, layer thickness and feed rate) on the mechanical properties of printed specimens under tensile and flexural loading. Average and standard deviation of the test results of the maximum strengths and stiffnesses for the printed PLA samples are tabulated for the tensile tests and for 3-point bending tests in Table 2 for Fr=43 mm/s.

Table 2. Average tensile and 3-point bending test results of PLA and ABS samples with a feed rate of 43 mm/s.

<table>
<thead>
<tr>
<th>Build O.</th>
<th>σs (MPa)</th>
<th>E (MPa)</th>
<th>σf (MPa)</th>
<th>E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upright</td>
<td>41.1 (1.7)</td>
<td>3726.7</td>
<td>40.5 (3.3)</td>
<td>3451 (175.5)</td>
</tr>
<tr>
<td>On-edge</td>
<td>64.9 (1.8)</td>
<td>4004.3</td>
<td>78.1 (0.3)</td>
<td>4025.5 (58.5)</td>
</tr>
<tr>
<td>Flat</td>
<td>77.3 (0.8)</td>
<td>4017.3 (37.1)</td>
<td>72.3 (0.2)</td>
<td>3769.9 (34.8)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Build O.</th>
<th>σs (MPa)</th>
<th>E (MPa)</th>
<th>σf (MPa)</th>
<th>E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upright</td>
<td>29.9 (0.8)</td>
<td>1402 (2.5)</td>
<td>31 (0.4)</td>
<td>1339 (18)</td>
</tr>
<tr>
<td>On-edge</td>
<td>62 (1.5)</td>
<td>1447 (208)</td>
<td>61.7 (3.9)</td>
<td>1717.6 (130.4)</td>
</tr>
<tr>
<td>Flat</td>
<td>53.4 (3.6)</td>
<td>1550 (100.6)</td>
<td>46 (0.5)</td>
<td>1546.3 (84)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Build O.</th>
<th>σs (MPa)</th>
<th>E (MPa)</th>
<th>σf (MPa)</th>
<th>E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upright</td>
<td>21 (0.99)</td>
<td>1931 (21)</td>
<td>21.9 (0.8)</td>
<td>1999.5 (22.5)</td>
</tr>
<tr>
<td>On-edge</td>
<td>38.5 (0.29)</td>
<td>2417 (20)</td>
<td>39.4 (0.1)</td>
<td>2373 (16)</td>
</tr>
<tr>
<td>Flat</td>
<td>26.4 (0.3)</td>
<td>1541.7 (29.1)</td>
<td>26.9 (0.4)</td>
<td>1557.5 (53.5)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Build O.</th>
<th>σs (MPa)</th>
<th>E (MPa)</th>
<th>σf (MPa)</th>
<th>E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upright</td>
<td>19.5 (0.5)</td>
<td>642.6 (2)</td>
<td>18.6 (0.9)</td>
<td>648 (20.4)</td>
</tr>
<tr>
<td>On-edge</td>
<td>33.4 (0.9)</td>
<td>961 (13.5)</td>
<td>30.9 (2.7)</td>
<td>883.6 (41)</td>
</tr>
<tr>
<td>Flat</td>
<td>25.4 (0.2)</td>
<td>712.3 (27)</td>
<td>26.3 (0.9)</td>
<td>758.3 (50.5)</td>
</tr>
</tbody>
</table>
ABS tensile and flexural specimens were fabricated with the industrial 3D printer Dimension Elite for comparative purposes. Due to the limitation of this industrial 3D printer, only a feed rate of 43 mm/s and two different layer thickness (L_t=0.18 mm and 0.24 mm) could be selected. A total of 60 ABS specimens were fabricated and tested. Average and standard deviation of the tensile and flexural test results for the ABS samples are shown in Table 2. The results have shown that PLA samples exhibited strength and stiffness values that are about twice the values of ABS samples. However, even if PLA samples were stronger than ABS samples, they were more brittle. Indeed, the deformation at fracture was about 2-4% for the tensile PLA samples and more than 8% for the ABS ones, see Figure 4. PLA offers better thermomechanical characteristics than ABS, having a stronger mechanical resistance and a lower thermal expansion coefficient. On the other hand, the most important disadvantage of PLA compared with ABS is the lower durability due to its biodegradability [5].

![Figure 4](image)

**Figure 4.** Comparison of the stress-strain behaviour of PLA and ABS samples printed with different build orientations, with the same layer thickness and feed rate.

### 4 Functional structure test results

A two-part arbitrary functional structural assembly was designed and manufactured using the process parameters selected for the 3D printed samples described in the previous section. The goal of this section was to demonstrate the practicality of the previous results in terms of the selection of the optimum process parameters for maximizing the mechanical performance of a structural functional component and to minimize manufacturing costs. This assembly was selected as a functional static load-bearing structural component. Figure 5 depicts the geometry of the proposed structural assembly and its main dimensions. Table 3 shows the average and standard deviation of the maximum load at failure for the selected combinations of build orientation, layer thickness, and feed rate process parameters, respectively.

As expected from the tensile test results of Table 3, functional load-bearing samples with L_t=0.06 mm depicted higher mechanical strength compared to samples with L_t=0.24 mm.

![Figure 5](image)

**Figure 5.** Functional load-bearing structural assembly. (a) Details of individual parts, (b) Assembly. Dimensions are in mm.

**Table 3.** Average maximum load of tensile test results of the PLA functional assembly with different process parameters ranges. Standard deviation is show in brackets.

<table>
<thead>
<tr>
<th>Build Orientation</th>
<th>L_t=0.06 mm</th>
<th>Fr=20 mm/s</th>
<th>Fr=50 mm/s</th>
<th>Fr=80 mm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upright</td>
<td>194 (26.3)</td>
<td>163 (22.1)</td>
<td>149 (19.6)</td>
<td></td>
</tr>
<tr>
<td>On-edge</td>
<td>341 (32.7)</td>
<td>339 (20.7)</td>
<td>328 (14.5)</td>
<td></td>
</tr>
<tr>
<td>Flat</td>
<td>335 (26.9)</td>
<td>329 (21.2)</td>
<td>320 (53.4)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Build Orientation</th>
<th>L_t=0.24 mm</th>
<th>Fr=20 mm/s</th>
<th>Fr=50 mm/s</th>
<th>Fr=80 mm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upright</td>
<td>223 (29.7)</td>
<td>192 (18.9)</td>
<td>174 (17.6)</td>
<td></td>
</tr>
<tr>
<td>On-edge</td>
<td>334 (31.9)</td>
<td>328 (5.3)</td>
<td>323 (23.6)</td>
<td></td>
</tr>
<tr>
<td>Flat</td>
<td>327 (10.5)</td>
<td>321 (19.1)</td>
<td>317 (31.9)</td>
<td></td>
</tr>
</tbody>
</table>
5 Conclusions

In this work, the characterization and the assessment of the effect of different process parameters on the mechanical properties of PLA samples fabricated with a low cost desktop 3D printer using FDM technique were examined. Evaluation of the mechanical properties is necessary if functional parts are manufactured using low cost 3D printers. The purpose of this study was to provide practical suggestions for optimal process parameter selection to improve the mechanical performance of 3D printed parts. The literature review has underscored the amount of research aimed at improving the mechanical properties and part quality of ABS parts fabricated by FDM. However, the relationship between process parameters and the quality and mechanical properties of parts has received little attention, particularly for PLA printed materials fabricated with FDM technology. In addition, very little work has been done both in terms of material characterization and FDM process optimization. In this study, different ranges of three main process parameters were analysed: build orientation, layer thickness and feed rate. In addition, manufacturing costs were evaluated as a function of the printing time. Tensile and three-point bending test series were carried out to determine the mechanical response of the printed specimens following the ASTM standard recommendations.

The analysis of the experimental results reveals the impact of process parameters on the mechanical performance of PLA samples. The results have shown that components printed using FDM technology are anisotropic in nature, and build orientation had a significant impact on the mechanical properties of the PLA samples. Therefore to maximize part strength and stiffness, an on-edge orientation is desirable, where possible, as it has been shown to have the highest strength and stiffness, the best failure performance (ductile fracture and maximum plastic strain) and optimum manufacturing costs as a function of the printing time. Furthermore, in this case, the optimal selection of process parameters to maximize failure performance was high feed rate values with low layer thickness values or the opposite combination (low feed rate values with high layer thickness values). In both cases, tensile and flexural strength and stiffness, failure behaviour and manufacturing costs were very similar. Whereas, if the upright orientation is selected, high layer thickness values and low feed rate values are recommended in order to maximize strength and reduce manufacturing costs.

As the geometry of parts fabricated by FDM technology may be complex, it is desirable to select a combination of process parameters that provide the resulting mechanical properties as isotropic as possible with the lowest printing time. This conclusion was also corroborated by testing a functional structural assembly as a practical 3D printed part.

The lack of experimental data in the literature as well as the study of potential variables such as extruder temperature, shell thickness or build material, underscore the need for further research to improve our understanding of the optimal settings and the mechanical behaviour of 3D printed components. Moreover, studies are required to assess the impact on strength, wear or thermal and electrical properties of 3D printed materials in order to determine the applicability to high-performance 3D printed parts. Finally, the analysis of the effects of process parameters on the mechanical performance of FDM parts is of special interest for the fabrication of continuous fibre reinforced 3D printed structures using FDM technology [2,3,7,19,40,41].

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