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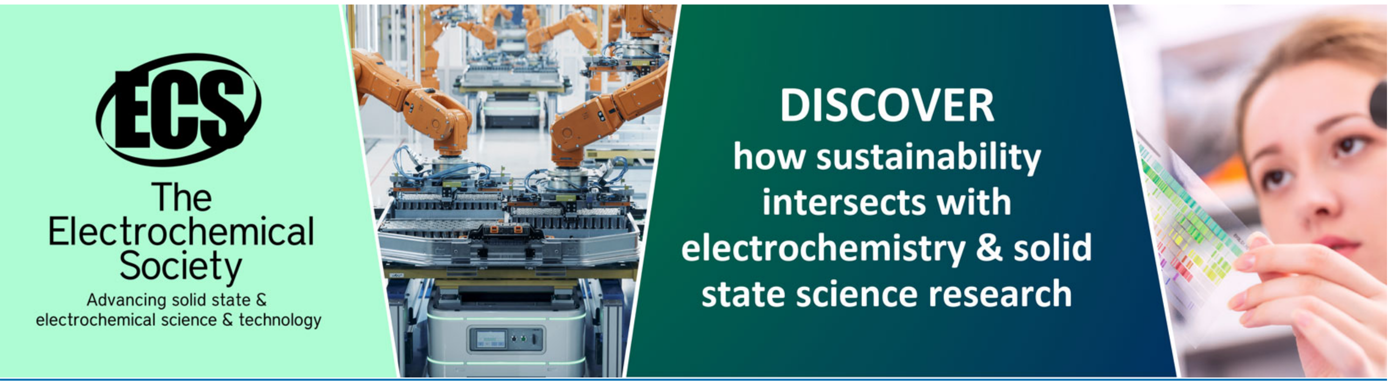

Evaluation of mechanical properties of FDM components reinforced with fibre

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Abstract: This research analyses the influence of different parameters of the Fused Deposition Modelling process with continuous carbon fibre reinforcement upon tensile strength of manufactured parts. For that, the appropriate behaviour of specimens designed according to ISO 527 standard was verified, in a preliminary test. Hereafter, a full factorial Design of Experiment was proposed with five parameters and two levels. After manufacturing and testing the specimens, a regression including all possible interactions of the parameters was performed with their tensile results. This model was optimized, considering the terms with the highest statistical significance (p-value less than 0.05), so that a simplified model of 14 terms with an r-squared of 97.5% was obtained. Thanks to this research the tensile response of a printed part as a function of the chosen manufacturing parameters can be predicted in advance.

Keywords: Additive Manufacturing, Fused Deposition Modelling, Carbon Fibre, Design of Experiments, Tensile Strength.

1. Introduction

Additive Manufacturing (AM) is considered a high impact manufacturing process in many different industries, such as the automotive and aerospace industries, as well as in other sectors as biomedical [1]. Some qualities that make 3D printed materials attractive are easy and inexpensive manufacturing of complex parts, very low percentage of waste, high specific strength and resistance to corrosion [2]. The most commonly used AM process is Fused Filament Fabrication or Fused Deposition Modelling (FDM), which is based on extruding thermoplastic filament through a heated nozzle to generate a 3D solid, layer by layer. Commonly used polymers include polylactic acid, acrylonitrile butadiene styrene for general purpose, and polycarbonate, and polyamide for engineering applications [3].

Emerging 3D printers have the capability to produce composite materials; carbon, glass and Kevlar fibres are combined with thermoplastic polyamide matrices to create 3D solids [4]. Two main categories of fibres are used: short (discontinuous) and long (continuous) fibres.

Different parameters have been tested to improve the mechanical response to 3D printing parts, such as printing pattern orientation [5], layer thickness and fibre volume content [6]. Hu et al. [7] analysed the flexural response of printed parts when process parameters such as layer thickness, printing temperature and printing velocity, were modified. The authors observed that reducing the layer height and printing velocity had a high benefit on flexural strength, while increasing the layer thickness and printing temperature produced average results.

Jiang et al. [8] concluded that the addition of continuous carbon fibre oriented at 0 degrees provided the printed samples with high tensile strength. On the other hand, Blok et al. [9] affirmed that the addition of continuous fibre further increases the tensile strength, compared to nylon filaments premixed with carbon fibre. Tavcar et al. [10] investigated service life tests for various types of materials and reinforcement materials used in 3D printing. The results showed that reinforced materials could survive more cycles when lubrication was applied.

Numerous works discusses the use of specific materials and individual factors values. However, it is difficult to find works that carry out a complete investigation on the influence of different matrix materials, printing parameters and continuous fibre reinforcement. In this research, the influence of these parameters on the tensile strength of the printed parts is analysed.

First, a tensile specimen geometry was defined following the recommendations of ISO 527 [11]. After testing this design, two levels of five FDM factors were defined: categorical (material and infill pattern) and numerical (filling percentage, skin thickness and number of layers reinforced with fibre). Using a full factorial design of experiments (DOE) with two replicates, the specimens were printed and tested. Subsequently, a model composed of linear factors and statistically significant interactions was fitted for the output variable "tensile strength". With this model, the influence of each parameter, as well as their interaction on the tensile strength, were analysed.

2. Materials & Methods

2.1. Materials

The FDM machine used in this research was the Mark1 (MarkForged, USA), which main characteristics are shown in table 1. This machine has two extruders. One of them is used to manufacture parts using the FDM technique, while the other one is used to reinforce the chosen layers of the manufactured parts with continuous fibre. To define the printed parameters and the reinforcement of the layers, Eiger software, provided by the manufacturer [12], must be used. The working materials that this machine can handle are Nylon and Onyx [12], the latter is also offered in a flame resistant version. Onyx is a composite material consisting of a Nylon matrix reinforced with carbon fibre whiskers. The main tensile properties of Nylon and Onyx are shown in table 2. As can be seen, Onyx is less strong and rigid than Nylon. However, Onyx shows a much lower ductility than the Nylon, both at yield and break situations. This allows a better control of deformation in mechanical components printed in this material.

Table 1. Main specifications of Mark1 [12].

Specification	Units	Value
Build volume (x, y, z)	mm	320, 132, 154
Extruder #1	-	Thermoplastic
Extruder #2	-	Reinforcement fibre
Maximum layer height (Def.)	μm	200 (125)

Table 2. Main tensile properties of matrix materials used by Mark1 [12].

Property	Units	Nylon	Onyx
Tensile Modulus	GPa	1.7	1.4
Tensile Stress at Yield	MPa	51	36
Tensile Strain at Yield	%	4.5	25
Tensile Stress at Break	MPa	36	30
Tensile Strain at Break	%	150	58

The continuous reinforcement fibres offered by the manufacturer are carbon, Kevlar and glass fibres [12], being the latter also offered in a high temperature resistant version. Table 3, shows the main properties of this fibres. The higher performance of carbon fibre compared to the other two can be remarked. In addition, all these materials have a more fragile but resistant behaviour than the matrix materials, (table 2). Due to the fragility and the difference in mechanical properties between the reinforcement fibres options, the *Eiger* software allows different distribution strategies, specific to each type of fibre to be defined.

Table 3. Main tensile properties of reinforcement fibres used by Mark1 [12].

Property	Units	Carbon	Kevlar	Fiberglass
Tensile Modulus	GPa	60	27	21
Tensile Strength	MPa	800	610	590
Tensile Strain at Break	%	1.5	2.7	3.8

To determine the tensile properties of the parts obtained with the Mark1, a universal testing machine ME-402 (Servosis, Spain) equipped with a 50kN load cell, was used. Thus, the influence of the different combinations of FDM parameters on the tensile strength of the printed parts were assessed. As there is no specific standard for composite materials obtained by AM, according to ISO 17296 [13] and ISO 527 [11] a type 1B specimen with 4 mm thick, was designed. Finally, tensile tests were carried out following the recommendations of ISO 527 [11].

2.2. Methods

The main objective of this research is to analyse the influence of different parameters of the FDM process with fibre reinforcement on the tensile strength of the obtained printed parts. Before defining the considered parameters, the proper behaviour of the designed tensile specimen was verified by means a preliminary test. Furthermore, this test revealed the strong influence of some printing parameters (the pattern and infill density) on the tensile strength.

After the preliminary test, a full factorial DOE was carried out. The factors chosen are shown in table 4. In order to ensure the reliability of the results, two replicates were proposed to this DOE. Therefore, a total of 64 specimens were manufactured and tested. In addition, all specimens were printed with the same spool of each material. The rest of the FDM parameters were configured by default in the CAM software [14]. These values are recommended by the manufacturer of the system.

Table 4. Factors and levels considered in the full-factorial DOE.

Factor	Type	Units	Level 0	Level 1
Material	Categorical	-	Nylon	Onyx
Infill density	Numeric	%	20	60
Infill pattern	Categorical	-	Linear	Hexagonal
Wall thickness	Numeric	Loop	2	4
C Fibre Reinforced	Numeric	Layer	0	2

3. Results and discussion

Preliminary tests proved that the specimen design worked properly, as the specimens broke within the calibrated length, figure 1(a). In addition, the influence of both the chosen specimen infill pattern and the infill density on the tensile strength was tested, with the former being a more significant factor, figure 1(b). This permitted to explore the expected strength values for this type of specimens, confirming the feasibility of the tests to be carried out later.

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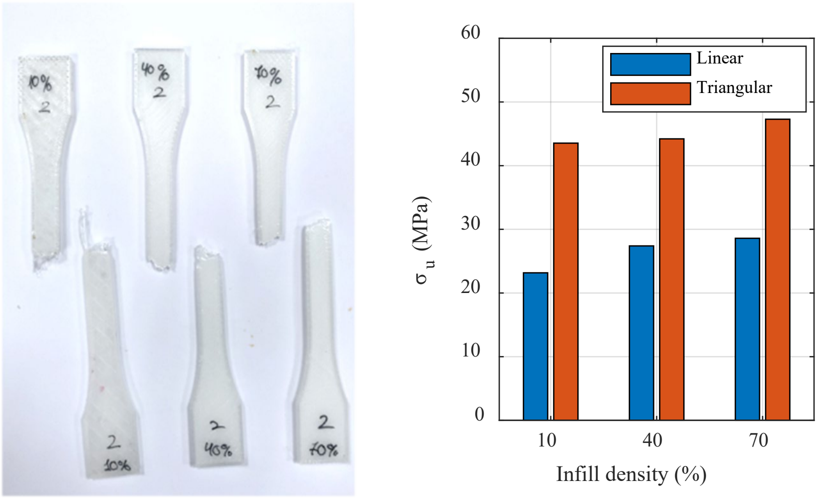
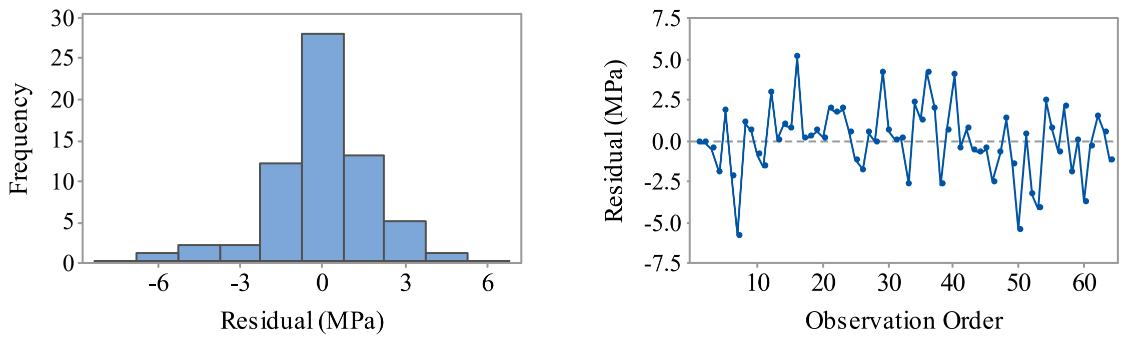


(a) (b)

Figure 1. Preliminary test results: **(a)** Linear pattern specimens used. **(b)** Tensile Strength.

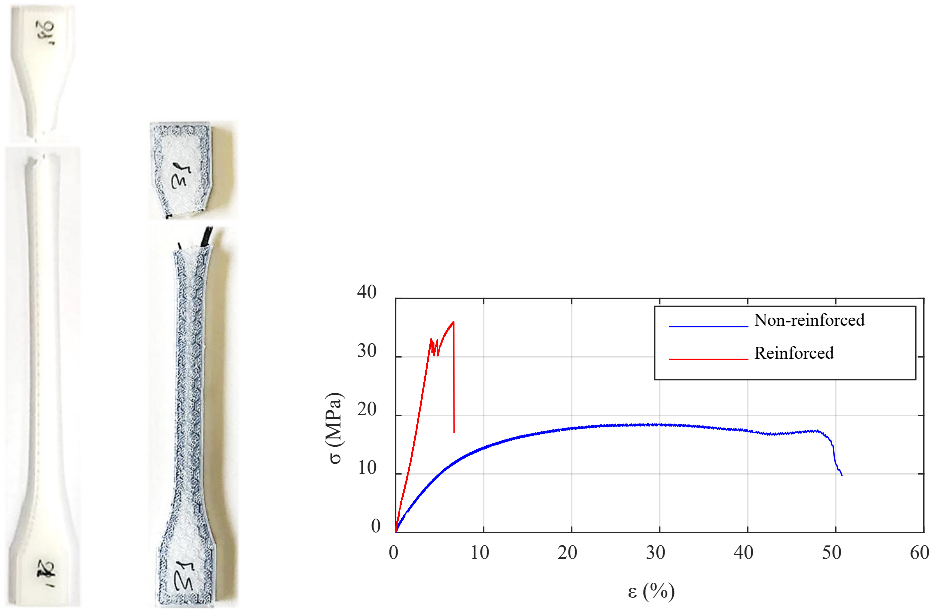
Subsequently, the specimens were manufactured with the combinations of the proposed factorial DOE and tested. In these tests, tensile strengths between 15 and 70 MPa were obtained. The strength values registered for each specimen were processed using Minitab software, fitting a linear model and considering up to third order interaction terms with statistical significance (considering factors obtaining a p-value below 0.05), so that an optimization of the first fitted model was executed. This model shows an r-squared value of 97.5%. Its residual values are shown as a frequency representation in figure 2(a). As can be noticed, with the exception of some extreme isolated values, the histogram of these residues has a normal distribution, which indicates that the model fitted correctly. Most of the differences observed between the actual and the fitted values are due to the characteristic variability of the analysed objective parameter, i.e. tensile strength.



(a) (b)

Figure 2. Fitted model residuals: **(a)** Frequency graph. **(b)** Residual for each run.

The residual values for individual runs are shown in figure 2(b). A distinction can be seen between runs with low residual values (±2.5MPa) and high residual values (out of±2.5MPa). The runs with high residual values, corresponding in all cases with carbon fibre reinforced specimens, were most of them manufactured with Nylon matrix as well. These high residual values can be explained due to the tensile strength variation observed between the two replicates tested. While carbon fibre reinforcement increases the tensile strength, it also reduces the ductility of the material, making it more fragile and unpredictable. This behaviour can be observed in the degree of ductility shown by the specimens during the test, figure 3(a) and 3(b), as well as in the stress-strain behaviour obtained, 3(c). Furthermore, in the case of the reinforced specimens, fluctuations in the stress near the breaking point, were observed. These fluctuations, which coincided during the test with clicking sounds emitted by the material, are due to the rupture of the different reinforcement fibres. This sudden rupture of the fibres causes the specimen to break unpredictably introducing variability in the tensile strength of the reinforced specimens.



(a) (b) (c)

Figure 3. Effect of the fibre reinforcement in the tensile behaviour of the material: **(a)** Non-reinforced, **(b)** Reinforced broken specimens, **(c)** Stress-strain behaviour obtained.

Table 5. Coefficients obtained for the fitted model.

Fitted Model						
Linear factors				Interactions		
Factor	Cod.	Coeff.	p-value	Factor	Coeff.	p-value
Material	A	4.915	<0.0005	A*C	-1.037	0.001
Infill density	B	3.345	<0.0005	A*D	1.094	0.001
Infill pattern	C	-3.096	<0.0005	A*E	3.182	<0.0005
Wall thickness	D	1.837	<0.0005	B*C	-1.409	<0.0005
Fibre Reinforced	E	10.443	<0.0005	B*E	0.760	0.014
Constant	-	31.724	<0.0005	C*D	-1.057	0.001
				C*E	-1.041	0.001
				A*C*E	-0.758	0.015

Table 5 shows the coefficients obtained, the degree of statistical significance (p-value) of the factors and the interactions considered for the model after the initial optimization. This fitted model permits to analyse the influence of the different factors considered on the strength of the manufactured parts. To analyse the importance of the linear factors (table 5), the main effect graph can be used (figure 4). This graph shows that the highest strength is obtained with the combination of the Onyx material, the highest infill density, the linear infill pattern, the highest wall thickness and with carbon fibre reinforcement. On the other hand, this graph analyses the importance of the different linear factors, being more important those whose effect produces a greater variation of the response. In this case, the carbon fibre reinforcement is the most important factor, increasing the tensile strength 20 MPa on average. To

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analyse the importance of the rest of coefficients, including the interactions between factors, the Pareto representation can be used (figure 5). In this case, the linear terms, together with the interaction between material and reinforcement, A*E, are the most important terms. This interaction is due to the lower strength increase obtained by using carbon fibre reinforcement in the specimens manufactured in Nylon matrix, compared to that obtained in case of Onyx matrix. This indicates that the discontinuous fibres of the Onyx material permit a better performance of the continuous fibre reinforcement. This phenomenon had been highlighted previously, when the residuals of the model were described.

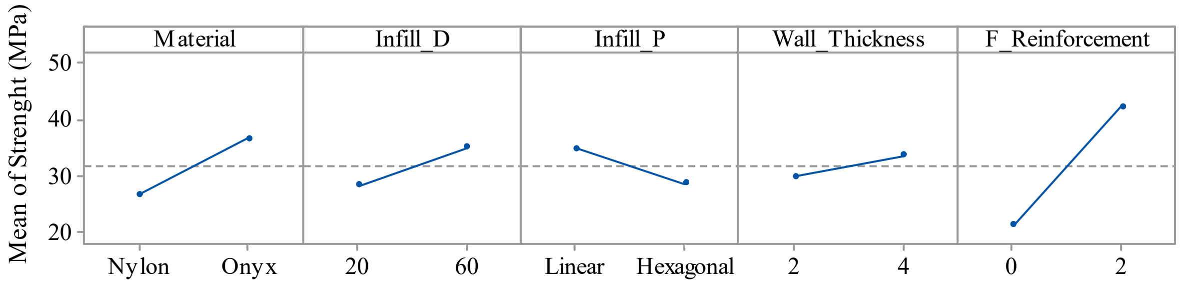

Figure 4. Main effects of the model.

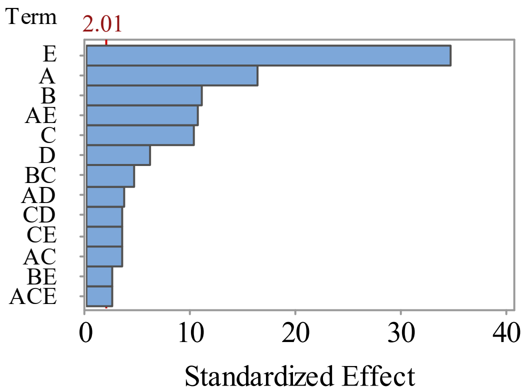

Figure 5. Pareto representation of the model.

Finally, the interaction graph of the model can be analysed (figure 6). The interactions between infill density and pattern, B*C, as well as the interaction of the wall thickness with infill pattern and also with material, D*C and D*A, respectively, can be noticed. The interaction between infill density and pattern can be related to the close relationship of the infill pattern distribution strategy by the control software depending on the selected infill density. Thus, a higher strength increase was achieved using the 60% infill density in the case of the linear pattern than in case of using the hexagonal. An increase in the infill density results in a more direct variation of the amount of material in the specimen whether linear pattern is used. Similarly, the interaction between wall thickness and infill pattern can be explained. On the other hand, the interaction between material and wall thickness indicates that increasing the wall thickness has a greater effect in case of Onyx than in Nylon. Onyx has carbon fibre whiskers so, for this material, increasing the wall thickness increases the amount of reinforcement, which enhances the strength improvement.

Third order interactions with statistical significance have only been detected for the interaction between material, infill pattern and fibre reinforcement, A*C*E. This interaction can be related to the A*E interaction, whose effect can be enhanced by using the linear infill pattern. In any case, this third order interaction has lower significance within the model than others of second order.

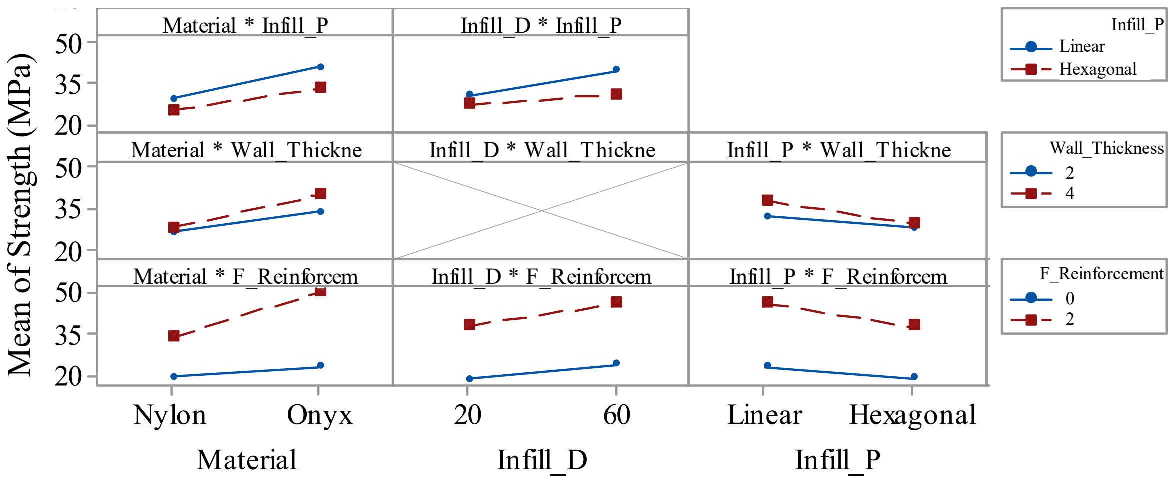

Figure 6. Non-linear interactions of the model.

4. Conclusions

This work analyses the influence of various parameters of the FDM process with continuous carbon fibre reinforcement, on the tensile strength of the 3D printed parts. After the analysis of the proposed model, the main conclusion that can be stated is the grade of importance of the parameters upon the tensile strength of the 3D printed parts. These are, from highest to lowest grade of importance: fibre reinforcement, material, infill density, infill pattern and wall thickness. Regarding the non-linear terms, the following can be stated:

- Material - fibre reinforcement: the whiskers present in the Onyx allow to amplify the benefits of the continuous carbon fibre reinforcement.
- Wall thickness - infill pattern and infill density - infill pattern: the increment of the wall thickness permits to increase the tensile strength more in case of linear pattern than in the hexagonal one, due to the lower dependent of the distribution of the former inside the part regard to the wall thickness than in case of the latter. That is, the wall thickness affects the distribution of the pattern more in case of the hexagonal, so it does not practically allow to increase the strength. Similar reasoning can be applied to the case of infill density and pattern. Infill density permits to improve more the tensile strength in case of the linear pattern.
- Wall thickness - material: an increase of the wall thickness permits a higher increase of strength in the case of Onyx. This is due to the fact that Onyx has carbon fibre whiskers inside the matrix. Therefore, the increase in strength associated with the increase in wall thickness is amplified with the Onyx material compared to that achieved with Nylon.

These conclusions permits to state that the mechanical strength is maximised when Onyx, higher infill density, linear infill pattern, higher wall thickness and carbon fibre reinforcement are used. On the other hand, unpredictable tensile behaviour was detected in the case of Nylon reinforced with carbon fibre, near the tensile strength due to the rupture of the different reinforcement fibres. This effect was reduced when using the Onyx. Due to this issue, it is recommended to use Onyx as the matrix material instead of Nylon, whether carbon fibre reinforcement is required.

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