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CORRELATION BETWEEN PRODUCTION PARAMETERS AND MECHANICAL PROPERTIES OF ABS PLUS p430 FUSED DEPOSITION MATERIAL

M. Corsi[1], S. Bagassi[1], M. C. Moruzzi[1], L. Seccia[1]

(1) Department of Industrial Engineering, Università di Bologna, Italy

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Corresponding Author
Marzia Corsi
Department of Industrial Engineering
Università di Bologna
e.mail: marzia.corsi2@unibo.it

Abstract

Fused Deposition Modeling (FDM), is one of the most popular and widely used Additive Manufacturing filament based technology employing materials such as Acrylonitrile Butadiene Styrene (ABS), Polycarbonate (PC), Thermoplastic Polyurethane (TPU) and Polylactic Acid (PLA). In this technique, the part is built up layer-by-layer, affecting, both the resolution along the z-axis, and the mechanical properties dependent on the mesostructure, controlled by a large amount of production parameters such as layer thickness, raster orientation, number of contour and air gap. When dealing with functional and structural printed parts, a deep understanding of these tunable building parameters and their influence on the mechanical properties is of the utmost importance and over the years many experimental studies have been carried to investigate this need. This study is intended to explore specimens realized through FDM technique with different combinations of printing parameters to analyse their effect on the mechanical properties of ABS Plus p430. To this aim, tensile and compression specimens, had been designed and tested. Sixteen different types of tensile specimen had been realized by varying four different parameters, namely, layer thickness, part interior style, infill orientation and number of contours. Whereas, the number of compression specimens had been limited to four considering the variation of two parameters: layer thickness and part interior style. Three samples for each specimen had been produced in ABS Plus p430 using a Stratasys Fortus 250mc FDM printer and tested with a universal testing machine through tension and compression tests to analyse the correlation between printing parameters and material properties. Test results had led to important conclusions on the consistency and homogeneity of the mechanical properties and on the variation of the material's performances in accordance with the different combinations of production parameters.

1 Introduction

Fused Deposition Modeling (FDM), developed in the late 80s, is one of the most popular and widely used Additive Manufacturing filament based technology employing materials such as Acrylonitrile Butadiene Styrene (ABS), Polycarbonate (PC), Thermoplastic Polyurethane (TPU) and Polylactic Acid (PLA). In this technique, a thin filament of plastic material is melted at a temperature slightly higher than its melting point and extruded by a movable head and nozzle. Once melted, the material is laid down on the modelling base, it cools down and solidifies [1]. To anchor the object to the build platform and support overhanging parts, a support structure might be necessary; a second nozzle is used to build the support in a different material. The support material may be soluble so after manufacturing, the build job is washed with a solution that dissolves the support. The part is built up layer-by-layer, affecting not only the resolution along the z-axis (staircase effect) but also the mechanical properties dependent on the mesostructure which is controlled by a large amount of production parameters such as layer thickness, raster orientation, number of contour and air gap.

These parameters are tunable so many experimental studies had been carried out having regard to the need of a full understanding of building parameters and their influence on the mechanical properties which is crucial in functional and structural printed parts. Ahn et al. [2] tested flat specimens under axial load to investigate the effects of air gap, bead width, raster orientation and ABS colour on tensile and compressive strength. Their results determined, on one hand, that air gap and raster orientation were the factor with a dominant effect on tensile strength; the tensile strength was enlarged with a raster orientation normal to the applied force and with a negative air gap. On the other hand, none of the factors investigated showed a significant effect on compressive strength. While Anitha et al. [3] focused on the surface roughness of the printed parts and investigated the effect of the layer thickness, raster width and speed of deposition; by decreasing the layer thickness, the mechanical performance increased. Fodran et al. [4] performed tensile tests on ABS specimens with different flow rates and fiber layouts and observed an important effect on tensile strength and modulus. Moreover, during the study, the specimens were post-processed with adhesive impregnation improving the mechanical properties. Es-Said et al. [5] examined the effect of layer orientation through tensile test and demonstrated how this factor affected the mechanical properties of the specimens. Moreover, Croccolo et al. [6] dealt with the effect of contouring on the static strength and stiffness of FDM processed parts; an analytical model to predict the above mentioned properties was developed proving a good accuracy in accordance with the experimental results. Lee et al. [7] studied the effect of build orientation, layer thickness, air gap and raster angle on the compressive strength of cylindrical parts fabricated through three different technologies, FDM, 3D printer and nano-composite deposition. Transverse FDM specimens exhibited a lower compressive strength with respect to axial specimens. Lastly, Montero et al. [8], through the use of Design of Experiment methodology, estimated the effect of design and process parameters on the tensile strength of FDM specimens. Among the five factors taken into consideration, namely, air gap, bead width, raster orientation, model temperature and ABS colour, the two with a significant effect on tensile strength were air gap and raster orientation. A more exhaustive review on the influence of FDM process parameters over the mechanical properties of polymer specimens was presented by Popescu et al. [9].

The study performed during the work presented, fits into this experimental framework and in particular it is intended to explore specimens realized through FDM technique with different combinations of printing parameters such as: layer thickness, part interior style, infill orientation and number of contours, to analyse, not only the effect of printing parameters on build time, material volume and surface quality, but also, through the use of ASTM regulations and Design of Experiment method, the mechanical properties of ABS Plus p430 material. To this aim, tensile and compressive specimens, had been designed and tested according to, respectively, ASTM D-638 and ASTM D-695 Standards. In order to reach the goal, the work was divided into different steps. The first step of the work was the design of the specimens and the determination of the printing parameters to analyse. The tensile specimens had been designed according to the ASTM D-638 Standard, with reference to the geometry of type I. Sixteen different types of specimen had been realized by varying four different parameters, namely, layer thickness, part interior style, infill orientation and number of contours. The compressive specimens had been designed in a cubic shape both for simplifying the testing procedure and for making faster the set up of the samples. In this case, the number of specimens had been limited to four considering the variation of two parameters: layer thickness and part interior style. Three samples for each of the tensile and compressive specimens had been produced in ABS Plus p430 using a Stratasys Fortus 250mc and all the parts were tested with a universal testing machine through tension and compression tests to analyse the correlation between printing parameters and material properties. Test results had been processed, according to the aforementioned ASTM standards and the Design of Experiment method, leading to important conclusions.

The Design of Experiment (DOE) method, is a branch of applied statistics that deals with planning, conducting, analysing, and interpreting controlled tests to evaluate the factors that control the value of a parameter or group of parameters [10]. This methodology is especially useful when designing a product, it is necessary to identify the optimal value of the control parameters i.e. the variables that affect the behaviour of the system. The DOE allows to identify the control parameters, $factors$, and their relative combinations that optimize the process results in terms of an index of quality. The aim of the DOE is to characterize the system and to comprehend the relation of cause and effect between input and output variables, obtaining a system which is robust even in case of factors that cannot be predicted or controlled [11]. By exploiting the DOE method, it is possible to manipulate multiple input factors (X) and relative $levels$ (n) at the same time to identify interaction that might be missed when the levels of a variable are modified and other factors are fixed (*one factor at a time* approach). However, it is evident how the usage of a *full factorial* approach, investigating all the possible combination (X^n) when the number of factors or levels is high, would lead to a high amount of test to perform, costs and time would accordingly increase. In those cases, the best approach could be the *fractional factorial* that allows the investigation of only a part of the possible combinations; the response can be interpolated with mathematical methods to get its value even in untried combinations ensuring the same results of a full factorial analysis [12].

2 Materials and Methods

2.1 Apparatus design

The first step of the experimental plan was the design of the tensile and compressive specimens, to be realized with a Stratasys Fortus 250mc FDM machine [1] in ABS Plus p430 material, and the determination of the production parameters. Acrylonitrile Butadiene Styrene (ABS) is a thermoplastic polymer with an amorphous structure composed by Acrylonitrile, Butadiene and Styrene. When combined, these three monomers lead to the formation of two co-polymer phases to make up the ABS [13]. Strength and rigidity of Acrylonitrile and Styrene combined with the toughness of Polybutadiene, lend toughness and resistance to the ABS; the amount of each monomer can be adjusted to manipulate the mechanical properties of ABS [14]. This material is widely exploited in AM and in particular it is used in fused deposition modeling (FDM) technology. In this work, the material that had been used is the ABS Plus p430; ABS Plus is a true production-grade thermoplastic that is durable enough to perform virtually the same as production parts. When combined with FDM 3D Printers, ABS Plus is ideal for building

[1] https://support.stratasys.com/en/printers/fdm/fortus-250mc

3D models and prototypes in an office environment [15]. The mechanical properties of ABS Plus p430 are listed in Table 1.

Table 1: ABS Plus p430 mechanical properties [15].

	Test method	**Metric XZ axis**
Tensile Strength, Ultimate (Type 1, 0.125", 0.2"/min)	ASTM D638	33 MPa
Tensile Strength, Yield (Type 1, 0.125", 0.2"/min)	ASTM D638	31 MPa
Tensile Modulus (Type 1, 0.125", 0.2"/min)	ASTM D638	2,2 GPa
Tensile Elongation at Break (Type 1, 0.125", 0.2"/min)	ASTM D638	6%
Tensile Elongation at Yield (Type 1, 0.125", 0.2"/min)	ASTM D638	2%

The tensile specimen, in figure 1, had been designed with reference to the geometry of type I of the ASTM D-638; for the compressive specimen (figure 2), on the contrary, a cubic shape, with a side of $E = 25,4\ mm$ had been chosen both for simplifying the testing procedure and for a faster set up of the samples.

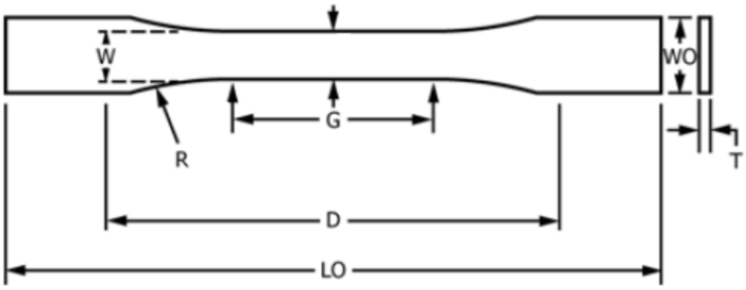

Figure 1: ASTM D638 specimen type I.

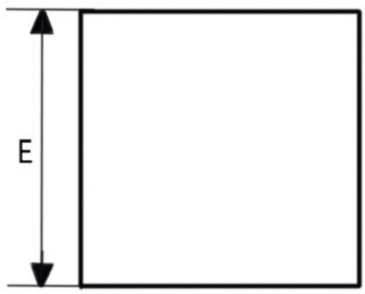

Figure 2: Compression specimen.

- LO: Length overall – *165 mm*
- D: Distance between grips – *115 mm*
- G: Gage length – *50 mm*
- R: Radius of fillet – *76 mm*
- W: Width of narrow section – *13 mm*
- T: Thickness – *7 mm*
- WO: Width overall – *19 mm*

Subsequently, considering the tensile specimen, the parameters to characterize the parts to be printed were chosen. This was not easy both for the large number of possible alternatives and for the estimate to be made a priori about the influence that the various parameters would have on mechanical characteristics. The main "sensitive" variables and possible levels are listed below.

- *Layer thickness*: measure of the layer height of each successive addition of material
  1. 0.1778 mm
  2. 0.254 mm

3. 0.3302 mm

- *Part interior style*: manner in which the beads are deposited in each layer
  1. Solid
  2. Sparse, high density
  3. Sparse, low density
  4. Sparse, double dense
- *Infill orientation*: orientation that the various layers have for each pass
  1. Standard (45°)
  2. Longitudinal (according to the direction of the applied force - 0°)
- *Number of boundary curves*: number of external contours made during the printing process
  1. Single
  2. Multiple

Two levels for each of the four parameters were selected; the layer thickness was chosen in the two most common values *0.1778 mm* and *0.254 mm* that guarantee a better distribution of the material, by decreasing the thickness of the layers, the filling of the parts will be improved, both from a volume and topological point of view. Moreover, with a smaller layer thickness the so-called staircase effect is reduced. As part interior style, *Solid* and *Sparse high density* were chosen. The first guarantees the best possible volume filling and therefore the piece will be almost "full" inside. Sparse high density mode, on the other hand, minimizes the material used by creating a one-way lattice structure. In this way the part does not have the same volume filling as the previous hypothesis but still manages to maintain a good solidity optimizing the amount of material used.

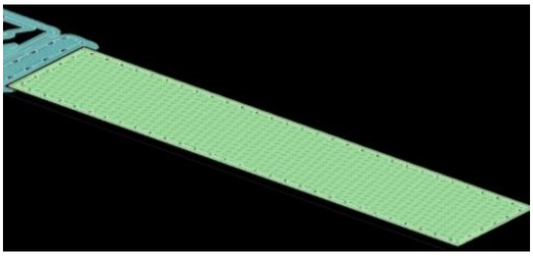

Figure 3: Part interior style: Solid.

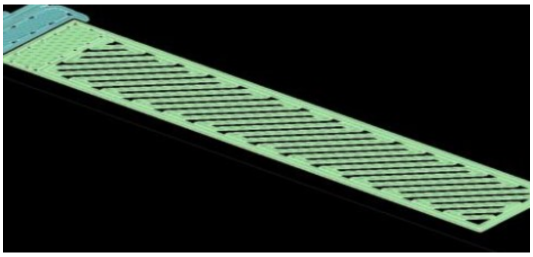

Figure 4: Part interior style: Sparse high density.

As already addressed, since the ABS obtained with additive techniques is an orthotropic material, that is, it has different mechanical characteristics depending on the direction considered, the *standard* infill orientation was chosen to obtain a specimen as dense as possible even if this means an orientation between the various layers of 45°. Secondly, in order to comply with the demands of the regulations, the *longitudinal* orientation was exploited. This should generate more resistance since fiber and force are parallel, but the machine finds it more difficult to make the specimen in this way and therefore there is no perfect distribution of material between internal layers and longitudinal outer faces.

Finally, consider the number of contours: *single* (standard) or *multiple* (two). Therefore, given the four factors and the relative levels, the samples to be tested were $4^2 = 16$ as listed in Table 2.

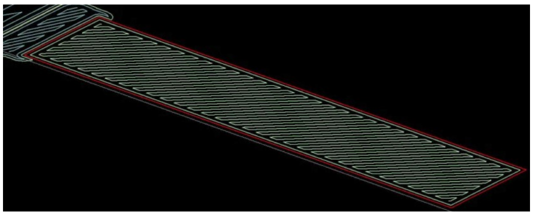

Figure 5: Infill orientation: Standard.

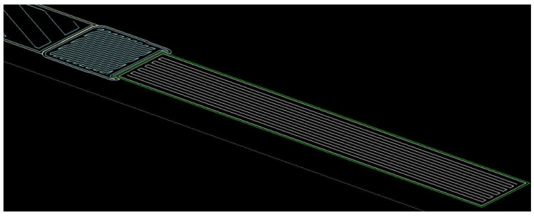

Figure 6: Infill orientation: Longitudinal.

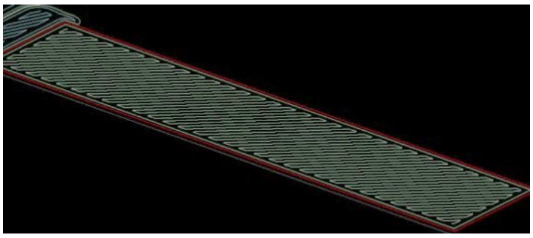

Figure 7: Number of contours: Single.

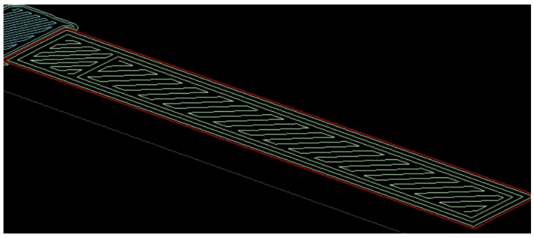

Figure 8: Number of contours: Multiple.

Table 2: Tensile test samples: Layer thickness - Part interior style - Infill orientation - Number of contours - Build time - Model volume (from Insight software) - Support volume (from Insight software).

N	L. t. [mm]	Part int. st.	Inf. orient.	Num. c.	Build t.	Mod. V.[cm^3]	Sup. V.[cm^3]
1	0.1778	Solid	Standard	1	2h 31min	19.106	2.860
2	0.1778	Solid	Longitudinal	1	2h 15min	18.533	2.834
3	0.1778	Solid	Standard	2	2h 37min	19.109	2.860
4	0.1778	Solid	Longitudinal	2	2h 19min	18.861	2.834
5	0.1778	Sparse HD	Standard	1	2h 01min	14.567	2.860
6	0.1778	Sparse HD	Longitudinal	1	1h 47min	13.617	2.834
7	0.1778	Sparse HD	Standard	2	2h 24min	15.225	2.860
8	0.1778	Sparse HD	Longitudinal	2	1h 57min	14.846	2.834
9	0.254	Solid	Standard	1	1h 20min	19.079	3.038
10	0.254	Solid	Longitudinal	1	1h 10min	18.304	2.966
11	0.254	Solid	Standard	2	1h 24min	19.079	3.038
12	0.254	Solid	Longitudinal	2	1h 12min	18.697	2.966
13	0.254	Sparse HD	Standard	1	1h 16min	15.243	3.038
14	0.254	Sparse HD	Longitudinal	1	1h 07min	14.682	2.966
15	0.254	Sparse HD	Standard	2	1h 25min	16.028	3.038
16	0.254	Sparse HD	Longitudinal	2	1h 10min	15.158	2.966

When dealing with the compressive specimen, only two parameters (layer thickness and part interior style) were taken into account since the compression test is less affected by the possible variables. the cross section increases during the test and therefore it is difficult for cracks to compromise the resistance of the specimen, moreover, there is almost never a real breakage but the analysis of the data reveals when the material has yielded. Even in this case two levels per factor had been considered leading to a four different samples (Table 3).

The build orientation of tensile and compression samples is shown in Figure 9.

2.2 Test methodology

To analyse the ABS plus p430 material, three ASTM standards had been considered:

Table 3: Compression test samples: Layer thickness - Part interior style - Build time - Model volume (from Insight software) - Support volume (from Insight software).

N	Layer thick. [mm]	Part interior style	Build time	Model Vol. [cm^3]	Support Vol.[cm^3]
1	0.1778	Solid	1h 28min	16.769	0.737
2	0.1778	Sparse HD	1h	11.753	0.737
3	0.254	Solid	41min	16.749	0.746
4	0.254	Sparse HD	38min	12.099	0.746

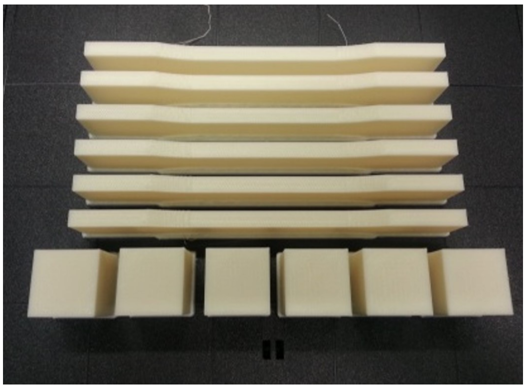

Figure 9: Build orientation of the samples.

- ASTM D-618 Standard practice for conditioning plastics for testing [16];
- ASTM D-638 Standard test method for tensile properties of plastics [17];
- ASTM D-695 Standard Test Method for Compressive Properties of Rigid Plastics [18].

For reasons of both cost and reduction of the test time, 3 samples for each of the sixteen combinations for the tensile specimen and of the twelve for the compressive ones, will be evaluated instead of the 5 required by the standards.

Uniaxial tension test is commonly used to evaluate the material response to static and quasi-static loading and it is performed with a universal testing machine. Testing procedures and parameters are specified in the ASTM Standards. In case of plastic materials, the Standard exploited are the D-638 and D-618. All the tests had been performed with a Crosshead Speed of 6 mm/min and a loading cell of 10 kN; the area of the resistance cross-section of the specimens is 91 mm^2 and considering tensile yield strength given in the material datasheet, an applied load of about 3 kN is needed to lead the specimen to the yielding point.

Quasi-static compression tests were performed, using a universal testing machine, according to ASTM D-695 and D-618 Standards to obtain the yield compressive properties of the material. This type of test presented many difficulties staring from the choice of the specimen's geometry. To obtain the most precise measurements, a load cell of 100 kN was used; in this case, the load to lead to the yielding point fluctuated approximately between 30 and 50 kN. In this case the crosshead speed was 1.3 mm/min.

The test execution was divided in different batches according to the specimens and the typology of test to execute, the outcome of the tests was a Force-Displacement curve with the same trend for all the samples of the same typology. For sake of clarity, an example of Force-Displacement curve for both tension and compression tests is reported respectively in Figure 10 and Figure 11.

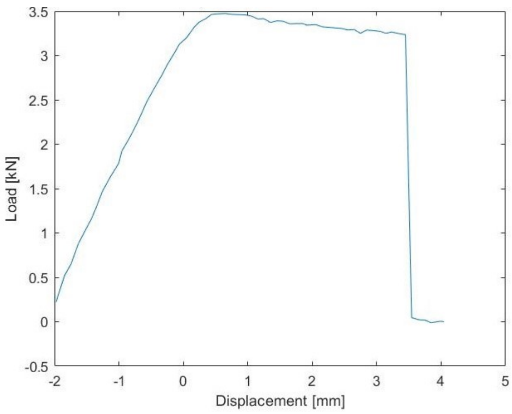

Figure 10: Force-Displacement curve of tension test.

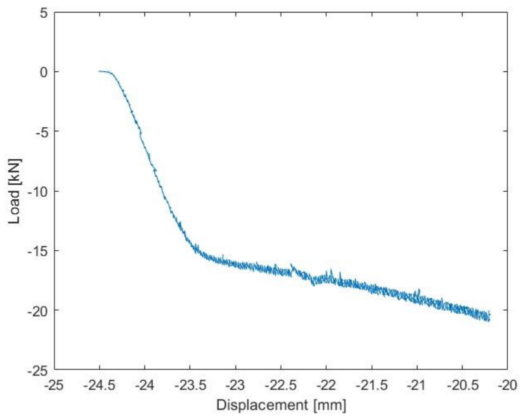

Figure 11: Force-Displacement curve of compression test.

3 Results and discussion

This section presents the results related to displacement and load of the samples and analyses the results of the tensile tests in terms of ultimate tensile strength (UTS), nominal strain at break (ε_{tb}), Young modulus(E) and of the compression ones in terms of compressive yield strength (σ_y) and modulus of elasticity (E) according to the above mentioned regulations and the DOE methodology. These results are summarized in Table 4 and Table 5. Firstly, with reference to Table 2 and Table 3 in section 2, it is possible to note that among the tensile specimen made using more material and the one with less material, N3 and N6 respectively, the volume difference is significant; $19,109\ cm^3$ for the first one and $13,617\ cm^3$ for the second one, that means a difference of $28,9\%$. Moreover, the layer thickness of these specimens ($0,1778\ mm$) ensures a better filling and surface finish, but the building time is considerably lengthened; $2h37min$ for N3 (Solid part interior style) and $1h47min$ for N6 (Sparse High Density part interior style) with a percentage difference of $32,5\%$. Looking at the compression specimens, the greatest difference in material volume and building time can be observed between the specimens with a layer thickness of $0,1778\ mm$ N1 and N2 with $16,769\ cm^3$ and $1h28min$ in the first case and $11,753\ cm^3$ and $1h$ in the second one; resulting in a percentage difference of $29,9\%$ in terms of material and $31,8\%$ in terms of time.

When considering, instead, the experimental results of the tensile tests, the highest values of mechanical properties moduli are the ones of the specimens with the lower value of layer thickness ($0,1778\ mm$): an Ultimate Tensile Strength of $43,56\ MPa$ for the sample N6-A, a Nominal strain at break of $5,23\%$ for the sample N1-A and a Young modulus of $2,97\ GPa$ for the sample N2-B. Dealing with the compression specimens, the highest values of Compressive yield strength and Modulus of elasticity are observed in those specimens with part interior style *Solid*.

For a first analysis of the results, in compliance with the requirements of ASTM D638 and ASTM D695 standards, the standard deviation was calculated for all the results using the Formula:

$$s = \delta = \sqrt{\frac{\Sigma x^2 - nX^2}{n-1}} \tag{1}$$

Where:

- s: Estimated standard deviation

- x: Value of the single observation
- n: Number of observations
- X: Arithmetic mean of the observed set of samples

After completing this first analysis, the attention has to be paid to the parameters required by the Design of Experiment method. The standard deviations for the number of repeated tests was defined as:

$$\delta_y = \frac{\delta}{\sqrt{m}} \tag{2}$$

Where:

- δ_y: Standard deviation for the number of repeated tests
- δ: Standard deviation
- m: Number of repetitions

Standard deviations s and Standard deviations for the number of repeated tests δ_y of tensile and compression tests are listed in Table 4 and Table 5.

Table 4: Experimental results, Standard deviation (s) and Standard deviation for the number of repeated tests (δ_y)- Tensile test.

N		UTS **[MPa]**	UTS $mean$ **[MPa]**	ε_{tb} **[%]**	ε_{tb} $mean$ **[%]**	E **[GPa]**	E $mean$ **[GPa]**	s UTS **[MPa]**	s ε_{tb} **[%]**	s E **[GPa]**	δ_y UTS **[MPa]**	δ_y ε_{tb} **[%]**	δ_y E **[GPa]**
	A	38.18		5.23		2.09							
1	**B**	36.38	36.64	4.32	4.74	2.10	2.10	1.43	0.51	0.065	0.83	0.29	0.037
	C	35.36		4.68		2.10							
	A	40.17		2.45		2.61							
2	**B**	40.08	39.96	2.15	2.32	2.97	2.71	0.28	0.15	0.22	0.16	0.08	0.12
	C	39.64		2.37		2.55							
	A	33.10		5.01		2.90							
3	**B**	33.51	33.60	4.59	4.65	2.59	2.57	0.54	0.33	0.35	0.31	0.19	0.20
	C	34.18		4.35		2.21							
	A	41.71		3.04		2.31							
4	**B**	40.58	40.77	2.84	2.75	2.16	2.35	0.87	0.34	0.22	0.50	0.19	0.20
	C	40.01		2.38		2.59							
	A	17.80		3.92		0.90							
5	**B**	17.54	17.63	3.38	3.44	1.12	1.00	0.15	0.31	1.01	0.08	0.18	0.58
	C	17.54		3.03		0.98							
	A	43.65		3.90		2.53							
6	**B**	40.43	40.95	2.91	3.01	2.01	2.38	2.44	0.85	0.32	1.41	0.49	0.18
	C	38.76		2.21		2.61							
	A	35.65		4.19		2.13							
7	**B**	35.24	35.40	4.86	4.17	2.41	2.28	0.22	0.71	0.14	0.12	0.41	0.08
	C	35.32		3.45		2.31							
	A	23.08		1.87		1.49							
8	**B**	23.51	23.27	1.61	1.84	1.92	1.73	0.22	0.21	0.22	0.12	0.12	0.12
	C	23.21		2.03		1.77							
	A	36.02		4.72		2.69							
9	**B**	40.94	37.59	3.17	3.95	2.83	2.60	2.90	0.75	0.23	1.67	0.43	0.13
	C	35.81		3.95		2.28							
	A	38.13		2.76		2.08							
10	**B**	35.32	37.36	1.95	2.49	2.08	2.15	1.79	0.47	0.12	1.03	0.27	0.07
	C	38.64		2.77		2.30							
	A	35.91		4.64		2.39							
11	**B**	36.25	36.27	4.89	4.82	2.28	2.28	0.37	0.15	0.10	0.21	0.08	0.06
	C	36.65		4.93		2.18							
	A	35.94		3.14		2.28							
12	**B**	36.48	34.51	3.55	3.23	2.23	2.22	2.96	0.28	0.07	1.71	0.16	0.04
	C	31.10		3.01		2.14							
	A	21.63		4.14		1.32							
13	**B**	21.46	21.50	3.10	3.43	1.30	1.32	0.16	0.62	0.02	0.092	0.36	0.011
	C	21.41		3.05		1.34							
	A	40.97		3.61		2.24							
14	**B**	40.78	40.79	2.73	2.97	2.06	2.11	0.92	0.61	0.18	0.53	0.35	0.10
	C	40.61		2.56		2.04							
	A	24.81		3.71		1.41							
15	**B**	24.85	24.81	3.89	3.71	1.44	1.43	0.03	0.18	0.02	0.02	0.10	0.02
	C	24.78		3.52		1.45							
	A	26.70		2.00		1.57							
16	**B**	26.63	26.66	1.98	2.07	1.81	1.67	0.03	0.14	0.12	0.02	0.08	0.07
	C	26.66		2.24		1.62							

Table 5: Experimental results, Standard deviation (s) and Standard deviation for the number of repeated tests (δ_y) - Compression test.

N		σ_y [MPa]	σ_y *mean* [MPa]	E [GPa]	E *mean* [GPa]	s σ_y [MPa]	s E [GPa]	δ_y σ_y [MPa]	δ_y E [GPa]
1	**A**	49.03	50.71	0.99	0.91	1.69	0.07	0.97	0.04
	B	50.67		0.90					
	C	52.42		0.85					
2	**A**	23.38	23.87	0.70	0.72	0.44	0.04	0.25	0.02
	B	24.20		0.70					
	C	23.05		0.76					
3	**A**	51.32	51.70	1.02	1.00	0.45	0.02	0.26	0.01
	B	52.20		0.99					
	C	51.59		0.98					
4	**A**	22.83	22.77	0.73	0.72	0.14	0.02	0.08	0.01
	B	22.61		0.73					
	C	22.88		0.70					

Analysing the values of Standard deviation and Standard deviation for the number of repeated tests, it is easy to see how the values related to the input variables considered are very low and rarely exceed the unit. This indicates that the dispersion of the experimental results with respect to the position index (arithmetic mean) is extremely low and therefore the output values have great homogeneity. On one hand, this means that the material exhibits consistent and homogeneous mechanical characteristics; on the other hand, that the tests were performed in such a way to ensure the repeatability of the results. This first analysis of the results in terms of Standard deviations, was followed by study of interaction between the various printing parameters to evaluate the variation in material's performances in accordance with the different combinations in the settings of the FDM prototyping machine. Production parameters were compared by using a direct comparison through factorial plans of 2 factors and 2 levels for repeated tests, considering the factors sorted in order of importance. Once the mean of both rows and columns, and the corresponding "great mean" were calculated, the main effects of the factors, i.e. the variation in the response of the system produced by a change in factor levels, A (influence of the first independent variable x_1 on the dependent one) and B (influence of the second independent variable x_2 on the dependent one) and the interaction effect AB (combined effect of both independent variables) had been found as:

$$A = \frac{a + ab}{2} - \frac{1 + b}{2} \tag{3}$$

$$B = \frac{b + ab}{2} - \frac{1 + a}{2} \tag{4}$$

$$AB = \frac{ab - b}{2} - \frac{a - 1}{2} \tag{5}$$

With 1,a,b, ab that are defined by the position indicated by the coordinates -1;+1 (see Table 6).

The purpose of this approach was intended to make the statistical processing of data easier and more efficient, avoiding the use of overly complex factorial plans. For the tensile tests, five different factorial plans with 2 factors and 2 levels had been studied considering the other factors involved as set by default. The only parameter taken into account during this analysis was the UTS, in fact this is the most binding limit for the usage of the material. For the compression ones, only one factorial plan had

Table 6: a, b, ab variables definition.

		x_2	
		-1	+1
x_1	-1	1	b
	+1	a	ab

been considered since the only parameter to take into account was the compressive yield strength. For sake of clarification, an example of factorial plan is reported in Table 7.

Table 7: Factorial plan: Layer thickness-Part interior style (Infill orientation:Standard - Number of contours:1).

		Part interior style	
		Sparse HD (-1)	Solid (+1)
Layer thickness	0.1778 (-1)	1=17.62	b=36.64
	0.254 (+1)	a=21.5	ab=37.59

The results of the different factorial plans of the tensile tests are listed below:

- Layer thickness - Part interior style (Infill orientation: Standard - Number of contours: 1):
  A=2.41 B=17.55 AB=-1.46
  The output variable is strongly affected by the independent variable *Part interior style*, with an effect of almost an order of magnitude bigger than the one of the *Layer thickness.*
- Layer thickness - Infill orientation (Part interior style: Sparse HD - Number of contours: 1):
  A=9.04 B=21.28 AB=-1.99
  The independent variable *Infill orientation* has a predominant effect with respect to the *Layer thickness.*
- Layer thickness - Number of contours (Part interior style: Sparse HD - Infill orientation: Standard):
  A=-2.45 B=9.65 AB=-6.33
  In this case, the only useful effect is given by the independent variable *Number of contours*, the only one with a positive increase of the response.
- Part interior style - Infill orientation (Layer thickness: 0.1778 mm - Number of contours: 1):
  A=9.04 B= 13.29 AB=-9.97
  Both factors influence the output, even if the *Infill orientation* is preponderant.
- Part interior style - Number of contours (Layer thickness: 0.1778 mm - Infill orientation: Standard):
  A=8.61 B= 7.36 AB=-10.41
  Both variables exhibit an influence over the output.

In all the above mentioned factorial plans, the difference in response between the levels of one factor is not the same at all levels of the other factor, which means that an interaction effect, mild in the first two cases and stronger in the last three, is present.

Looking at the compression tests, the factorial plan involving the Layer thickness and the Part interior style was studied resulting in the following values: A=-0.05 B=27.88 AB=1.04.
That means that the *Part interior style* has a strong preponderance over the *Layer thickness* and their combined effect.

4 Conclusions

The study presented in this work, was intended to analyse the influence of printing parameters and their interactions on the mechanical properties of parts produced with FDM technique in ABS Plus p430 material. To this aim, tensile and compressive specimens were designed and tested according ASTM D-638 and D-695 standards. The tensile specimens had been designed according to the ASTM D-638 Standard, with reference to the geometry of type I. Sixteen different types of specimens had been realized by varying four production parameters: layer thickness, part interior style, infill orientation and number of contours. The compression specimens had been designed in a cubic shape both for simplifying the testing procedure and for making faster the set up of the samples. Moreover, the number of specimens had been limited to four considering the variation of layer thickness and part interior style. Even if, according to the standards, five samples for each specimens should had been produced and tested, it was decided to limit the number of samples to test to three. Tension and compression tests were performed with a universal testing machine and the results had been processed according to the aforementioned standards and the Design of Experiment method. While some results were desirable, others were completely unforeseen to confirm the utility of this characterization.
First of all, an analysis of standard deviations was performed to assess the dispersion of results, highlighting how the values, being mutually consistent, indicated a good executive method and precision when conducting the experimental tests.
Afterwards, The study and comparison carried out with the DOE method underlined the interactions among the various production parameters in relation to the values found during the experimental tests. Moreover, even if the purpose of this study was beyond the search for the best compromise between the various combinations of printing parameters, the analysis of different factorial plans allowed to draw up some guidelines to optimize the performance of most of the parts produced through FDM technique in ABS material. With regard to the tensile specimens, part interior style *Solid* prevails over layer thickness significantly and less over the number of contours. However, it requires a longer build time of up to 32,5%. Layer thickness is a parameter that has little influence on the mechanical properties of the specimen, however as in the previous case the build time with a thickness of *0.1778 mm* takes significantly longer than the case *0.254 mm*, with time differences exceeding 50%. Infill orientation *Longitudinal* is favourable both with respect to the use of higher layer thickness, and with respect to the use of a *Solid* part interior style, moreover the importance of this parameter can be further emphasized by carrying out a manual revision of the part. The number of contours was found to be the least influential parameter of the four, with predominant function only in certain combinations of layer thickness and part interior style, however some specimens made in this way showed a greater extent of the plastic area than the single contour. Considering the compressive specimens, the part interior style used, *Solid*, is of fundamental importance for the performance detected compared to the layer thickness, almost irrelevant.

An interesting development of this work could be the analysis of material's performances when the machine trajectories are manually modified. In fact, the distribution of internal raster could be improved to better adhere to the contours, which the FDM machine does not do by default in all the considered settings, especially in Sparse High Density mode, but needs to be done by acting on the toolpath parameters in the processing software. Moreover, as already proposed by Croccolo et al. [6], an analytical model taking into account the production parameters should be developed to predict the mechanical properties of the printed parts.

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