A Statistical Approach of the Flexural Strength of PLA and ABS 3D Printed Parts

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Abstract-The need for rapid obtaining parts has made researchers to widely study 3D common printing technologies like FDM (Fused Depositing Modeling), SLS (Selective Laser Sintering), SLA (Stereolithography). Although FDM can provide high geometrical complexity of parts at convenient costs and with efficient delivery logistics, a set of printing parameters of the raw materials used for manufacturing needs to be optimized accordingly. Therefore, this study reveals the influence of printing parameters on the flexural strength of PLA (Polylactic Acid) and ABS (Acrylonitrile Butadiene Styrene) printed samples, by applying the Taguchi method and ANOVA (Analyisis of Variance) of 3-point bending tests results.

Keywords-3D printing; experimental tests; 3-point bending; Taguchi method

I. INTRODUCTION

Additive technologies can accomplish technical tasks like complex geometrical part manufacturing with minimum cost and less complex technology by using a single step fabrication process. FDM is the most common 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 object [1, 2]. However, in order to achieve the needed mechanical characteristics in industries such as bioengineering, aerospace, and automotive, several specific printing parameters must be adapted and optimized [2, 3]:

- Building orientation: usually testing specimens are flat, on edge, and upright oriented.
- Temperature conditions: environment, extrusion, bed and platform temperature.
- Slicing parameters: layer thickness, nozzle diameter/ bead/ road width, flow rate, deposition speed, infill percentage.

The considaration of several printing parameters can ensure the quality of products, improving dimensional precision, avoiding the production of waste and large amount of scraps, and increasing productivity rates [3-7]. For the optimization of the process conditions of FDM rapid prototyping technology, several statistical optimization techniques have been successfully used. Applying the Taguchi method to determine the design of experiment, signal to noise (S/N) ratio and ANOVA are commonly used to identify the influence of the determinant factors [3, 4, 8]. The novelty of this paper consists in the comparison of the flexural strength of the most common materials used within the FDM technology (PLA and ABS) and the behavior of printed parts related to process variables (layer thickness and infill percentage). This matter can be used to optimize the specific mechanical characteristics used for various technical applications.

II. MATERIALS, METHODS AND PROCEDURES

A. Setting Up Process Parameters

Beside process parameters, the materials used to manufacture the parts by the FDM process also significantly affect their mechanical properties. The most widely used raw materials are thermoplastics such as ABS, PLA, polyethylene, teflon, and polypropylene, High-impact Polystyrene resin (HiPS), Polyethylene Terephthalate Glycol (PETG), and Polyamide (PA). For PLA and ABS the specifications collected from filament producers are shown in Table I. Each 3D printed sample results from a combination of signal factors such as layer thickness and infill percentage as shown in Table II.

B. Sample Preparation

A total of 45 samples (5 samples of each combination of 3 layer thicknesses and 3 infill percentages) with standard

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dimensions [9, 14, 15] (Figure 1) were fabricated from PLA and ABS, with a Raise E2 3D printer, with a volume capacity of 330×240×240mm and then were tested on a Lloyd LRX Force Tester electro-mechanical testing machine (Figure 2). Autodesk Inventor was used for designing the samples and the drawing was converted in STL format. Process parameters were adjusted with the Idea Maker software, including internal structure pattern (Figure 3), layer thickness, and infill percentage.

TABLE I. FDM FLEXURAL STRENGTH SAMPLE PARAMETERS

Parameters	Material specifications	
	PLA	ABS
Nozzle diameter	0.40 mm	0.40 mm
Build orientation	Flat	Flat
Layer thickness	According to Table II	According to Table II
Top solid layers	4 layers	4 layers
Bottom solid layers	4 layers	4 layers
Outline/perimeters shell	3 outlines	3 outlines
Internal fill pattern	Lines	Lines
External fill pattern	Rectilinear	Rectilinear
Internal fill percentage	According to Table II	According to Table II
Internal infill angle offsets	180◦	180◦
Extruder temperature	210 ◦C	240 ◦C
Heated bed temperature	60 ◦C	110 ◦C
Default printing speed	70 mm/s	40 mm/s
Filament diameter	1.75 mm	1.75 mm
Filament density	1.24 g/cm3	1.05 g/cm

TABLE II. FDM VARIANCE OF SIGNAL FACTORS

Signal factor selection		
Levels	Layer thickness (A)	Infill percentage (B)
1	0.1	50%
2	0.2	75%
3	0.15	100%

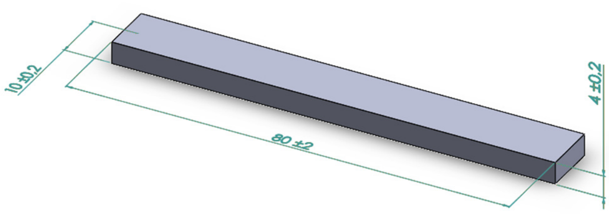

Fig. 1. Flexural specimen according to ISO 178 [9].

C. *Flexural Strength Experimental Tests*

The method is used to investigate the flexural behavior and to determine flexural strength. The deformation of the specimen gets to the point of maximum deflection, so, the maximum bending stress can be named flexural strength. The loading speed of the test was 1mm/min and the distance between the supports was calculated and measured at 64mm (L=16h, where h is the specimen's height [9]). Tests were performed at room temperature (20℃) and the samples were allowed to acclimatize for at least 24h. Flexural strength was calculated with [9]:

$$\sigma_f = \frac{3FL}{2bh^2} \quad (1)$$

where σ_f is the flexural stress parameter in question, F is the maximum bending load (N), L is the span length (mm), b is the width of the specimen (mm), and h is the height of the specimen (mm). The results for each material are listed in Tables III and IV.

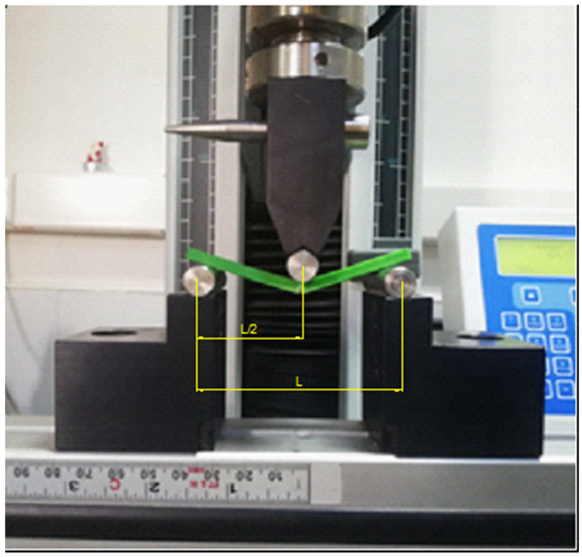

Fig. 2. Electro-mechanical machine Lloyd LRX Force Tester.

Fig. 3. Internal and external infill pattern of the samples for the 3 point bending test.

III. RESULTS AND DISCUSSION

A. *Taguchi Method and S/N Ratio*

The actual results were analyzed with the Minitab statistical software. With the Taguchi method, parameter design converts the objective value to S/N ratio, which is known as the relation of S/N ratio in terms of the experimentally quality characteristic evaluation index [10-12]. S/N ratio represents a statistic reference that makes a comparison between the level of positive signal variables to the level of background noise parameters. In this study, the aim is to improve the mechanical properties of 3D printed parts and to transform signal parameters into system control factors. Therefore, in Minitab, the larger-the-better criterion is used, and S/N ration (η) is calculated with [4]:

$$\eta = -10\log\left[\frac{1}{p}\sum_{i=1}^{p}\frac{1}{w_i^2}\right] \quad (2)$$

where η is the S/N ratio, w_i is the i position result of the experiment, and p is the repeated times of a trial.

The two experimental results in S/N ratio are shown in Tables III and IV. η_1, η_2 are the S/N ratio for flexural strength both for PLA and ABS samples.

TABLE III. MEANS OF FLEXURAL STRENGTH (PLA)

Layer thickness (A)	Infill (B)	Maximum flexural strength (MPa)	η_1
1	1	106.9575	40.5842
1	2	110.9040	40.8989
1	3	107.9085	40.6611
2	1	95.4525	39.5957
2	2	110.9805	40.9049
2	3	113.5380	41.1028
3	1	101.1675	40.1008
3	2	109.1985	40.7643

TABLE IV. MEANS OF FLEXURAL STRENGTH (ABS)

Layer thickness (A)	Infill (B)	Maximum flexural strength (MPa)	η_2
1	1	71.9184	37.1368
1	2	75.3567	37.5424
1	3	77.7345	37.8123
2	1	52.5024	34.4036
2	2	56.1318	34.9842
2	3	78.4725	37.8943
3	1	50.2539	34.0234
3	2	55.4201	34.8733

By analyzing the S/N ratio, the significance of signal factor can be determined. The infill percentage ranks first (Table V), so the layer thickness has a smaller significance, as shown in Figure 4, in the Pareto Chart for PLA samples.

TABLE V. RESPONSE TABLE FOR S/N RATIOS (PLA AND ABS)

Level	Layer thickness (PLA)	Infill (PLA)	Level	Layer thickness (ABS)	Infill (ABS)
1	40.71	40.09	**1**	37.50	35.19
2	40.59	40.86	**2**	34.62	35.80
3	40.53	40.89	**3**	35.76	36.89
Delta	0.18	0.80	**Delta**	2.88	1.70
Rank	2	1	**Rank**	1	2

B. ANOVA

ANOVA [13, 14, 16] was performed in order to identify the importance of factors and the influence on flexural strength. The results of the ANOVA analysis applied to the PLA test specimens are listed in Table VI and express the total sum of square deviation (SS), total degrees of freedom (DF), the variances or square means (MS), F-Value ratio, and P-Value. The level of confidence was considered 95% which relates to a P-Value smaller or equal to 0.05 to accept or reject the initial hypothesis that all means are equal. Consequently, a P-Value of 0.838 confirms the level of significance of the signal factor layer thickness, but the F-Value, which represents a ratio between the variance of the category groups related to the variance of the entire group suggest more pronounced influence of the infill percentage signal factor to the results of flexural strength of PLA 3D printed test samples.

In comparison, the relative influence of factors and interactions is determined by the applied ANOVA to the flexural strength means of ABS 3D printed samples. The results are listed in Table VII. As it can be also seen in Table V, in the case of using this raw material, the signal factor layer thickness is ranked first. The influence of the factor is also highlighted by the corresponding F-Value (7.18) and can be observed in a graphical form in Figure 5. However, a less significant difference, compared with the PLA ANOVA results, between the influences of the factors can be observed.

TABLE VI. ANOVA FOR PLA SAMPLES

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Layer thickness	2	0.05082	0.02541	0.19	0.838
Infill	2	1.22012	0.61006	4.45	0.096
Residual error	4	0.54861	0.13715	-	-
Total	8	1.81954	-	-	-

TABLE VII. ANOVA FOR ABS SAMPLES

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Layer thickness	2	677.7	338.86	7.18	0.047
Infill	2	243.9	121.95	2.59	0.190
Residual error	4	188.7	47.17	-	-
Total	8	1110.3	-	-	-

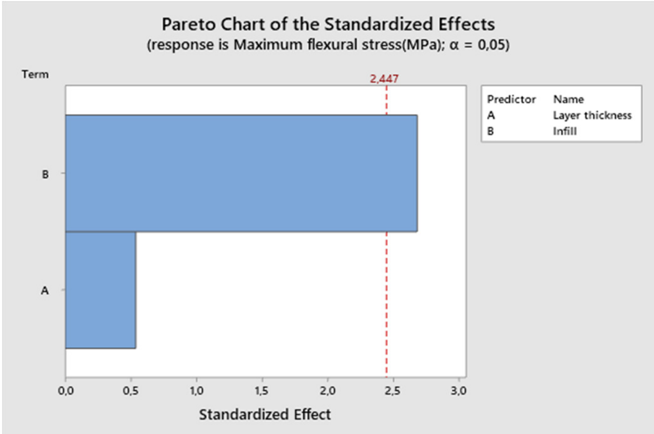

Fig. 4. Pareto chart for PLA samples with predictors: Infill and layer thikness.

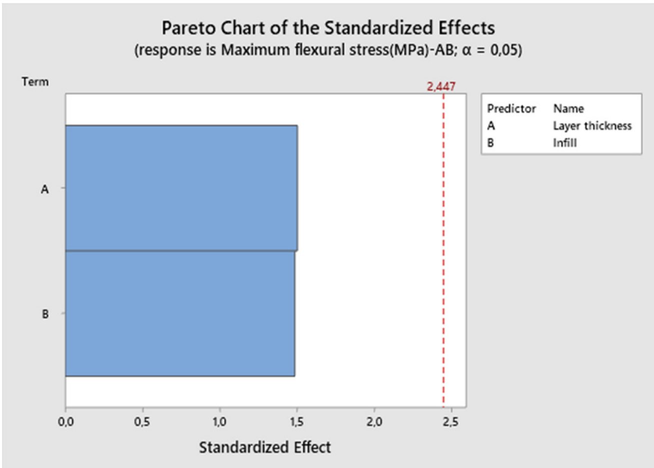

Fig. 5. Pareto chart for ABS samples with predictors: Infill and layer thikness.

Finally, regarding the initial assumption, all P-Values are greater than 0.05 (the initial hypothesis is confirmed and all means are equal), beside the one corresponding to the factor layer thickness for ABS samples which reveals that the initial hypothesis is rejected, so the means are not equal.

C. Graphical Analysis

The graphical representation of the significant factors layer thickness and infill percentage is displayed in the interaction plot for maximum flexural strength (Figure 6). Data means for PLA 3D printed test samples reveal a correlation with the ANOVA results and a similarity between the graphs concerning factor A is being observed. By comparison, the graphical representation of the interaction plot for maximum flexural strength for ABS 3D printed test specimens reveals a higher level of significance in 0.10mm layer thickness, that can be distinguish in Figure 7. As can be seen, for PLA, the signal factor B (infill percentage) has a higher influence on the means of flexural strength, as for the ABS, the layer thickness (signal factor B) is more significant.

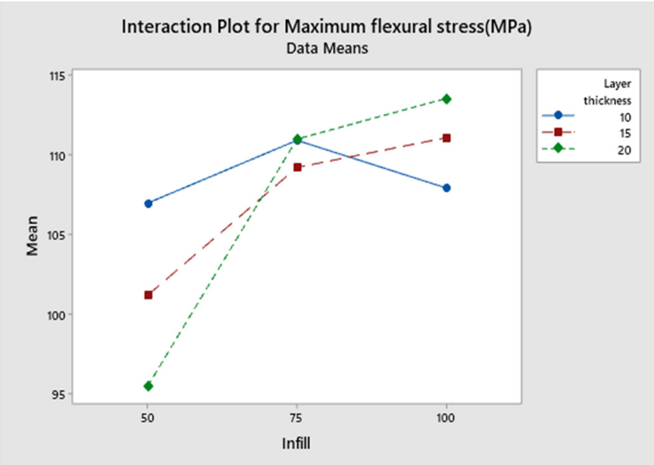

Fig. 6. Interaction plot between data means (PLA).

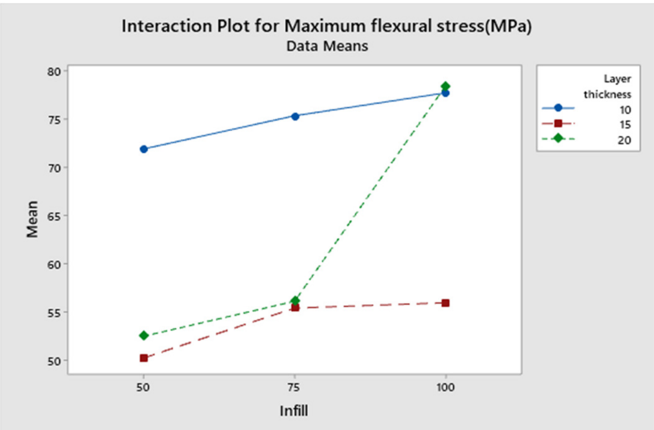

Fig. 7. Interaction plot between data means (ABS).

From the main effect plot for S/N ratio in Figures 8 and for PLA and ABS 3D printed test specimens respectively, the optimum levels of the two main signal factors for each response of the part can be obtained intuitively.

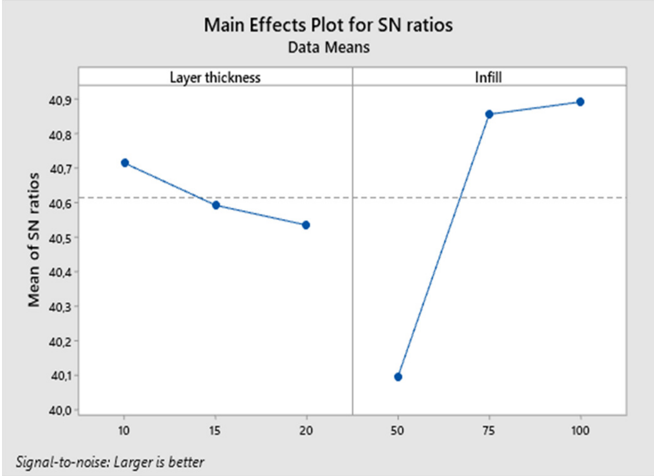

Fig. 8. Main effect plot for S/N ratio (PLA).

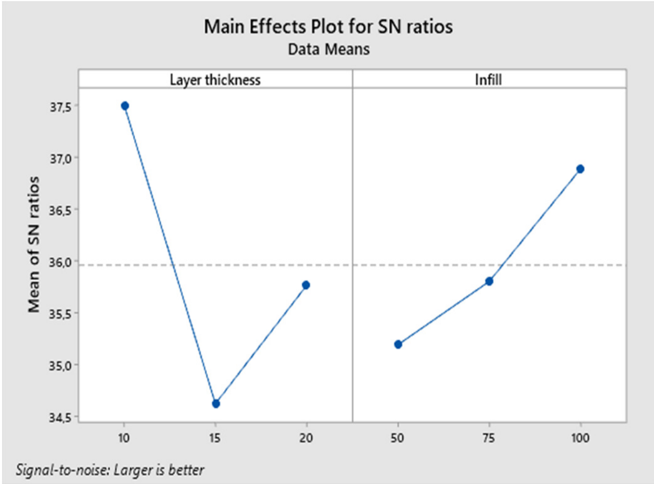

Fig. 9. Main effect plot for S/N ratio (ABS).

IV. CONCLUSIONS

In this study, the effect of layer thickness and infill percentage on the flexural strength of parts fabricated by FDM technology was conducted to compare PLA and ABS, the most commonly raw plastic materials used. The parts obtained with this technology have a different anisotropic behavior than those fabricated by injection [17]. In conclusion, the flexural strain results of the test specimens have been analyzed and processed with statistical software, performing S/N ratio and ANOVA with the aim of obtaining the final significant factors and optimal printing parameters. Thus, by processing the results it can be observed that layer thickness and infill parentage, as process variables, affect differently the performance of PLA and ABS printed parts in terms of flexural strength. Infill percentage as a signal factor has a greater influence than layer thickness regarding the PLA material while layer thickness is more significant for the ABS material.

PLA has a better performance regarding the flexural strength (maximum value reached was 122.5125MPa and the average value was 107.4643MPa) in comparison with ABS (maximum value reached 80.2350MPa and average value was

63.7516MPa). For several applications and technical fields the use of PLA is constrained by its low thermal resistance, low impact resistance, and glass transition temperature (55 and 60◦C) [1]. So, this study can be taken into consideration when choosing the appropriate material and adapting convenient printing parameters, but also considering other mechanical characteristics for the specific type of application.

In [4], several different signal factors have been taken into account, so flexural strength has a range of values between 51.31 to 90.13MPa. The result of [1] reveals flexural strength with values ranging between 31.1 to 59.1MPa. The difference between the values obtained in this article and the values obtained in other studies can be explained by signal factors such as deposition orientation, deposition style, raster width, raster gap as well as using variations of plastic materials. In this regard, further studies will be conducted for a better understanding of the most significant factors and materials that can influence the main mechanical properties.

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