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Fatigue lifespan study of PLA parts obtained by additive manufacturing

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ABSTRACT

Currently, additive manufacturing (AM) is not limited to prototype manufacturing, but is also used to generate parts with final applications. This paper considers this aspect of 3D printing, and aims to characterize fatigue life of parts manufacturied through fused filament fabrication. This is one of the most complex AM technologies, due to the high number of parameters that must be taken into account. The knowledge of the influence of the different manufacturing parameters on the mechanical behavior of the parts has been previously considered for static forces, but so far, dynamic working regimes have not been explored. In this paper, a design of experiments through Taguchi orthogonal arrays is applied to analyze the influence of five factors on fatigue life on PLA specimens. Five fatigue tests are performed for each combination of parameters. Results show that fill density, nozzle diameter and layer height are the most influential factors on fatigue lifespan. Finally, honeycomb proves to be the most beneficial infill pattern with regards to fatigue life.

Keywords: Additive manufacturing, Fused filament fabrication, PLA, Fatigue life

1. Introduction

3D Printing is a generic term used to define any kind of additive or layered manufacturing process, that is, a group of techniques used to obtain final parts or prototypes in a short period of time from a CAD file by progressive addition of a raw material [1]. One of the most difficult feature to define in parts manufactured by additive manufacturing methods, is their mechanical behavior. The complexity to characterize these kind of parts lies in the number of variable parameters involved in their manufacturing process, and in not knowing how they interact with each other.

The main characteristic common to all AM methods is the fact that pieces are constructed by stacking layers [2]. This feature causes the manufactured parts to exhibit anisotropic mechanical behavior, due to the existence of a preferential bearing direction, with coincides with the manufacturing direction along which the material is deposited. On the other hand, there is a considerable difference between the binding forces between layers, and between the particles of the same layer. There are many factors that influence this phenomenon, and most of them are determined by the way the pieces are made. The manufacturing process is governed by different parameters, which are those that in any case must be controlled and defined to obtain good properties in the final pieces.

One of the factors to be taken into account is the manufacturing direction, as was concluded by several studies on additive manufacturing using samples made with fused deposition modeling [3-9] and other AM technologies [10-13]. This parameter determines how the different layers are joined to each other, and which is the preferential bearing direction with respect to the direction of application of the stresses to which the pieces are subjected during their work.

Another important factor that defines the mechanical behavior of the piece is the layer height or thickness of each layer, given by the transverse dimension of each of the stacked layers [3-5]. Its main influence is in the strength of union between them, but also in other parameters such as the surface finish and the cost of the piece [14], since the lower layer height plus manufacturing time will be necessary.

Another factor of great relevance for the final characteristics and production of the piece is the manufacturing strategy. This is influenced by the combination of the selection of various parameters such as the building style or manufacturing pattern, the diameter of the raw material which in turn determines the diameter of the nozzle to be used in the extruder and the rate of material deposition. The types of patterns to use, depend on the software and the machines used. For example, a rectilinear grid is the most popular and the one used by default on most printers. As for the diameter of the extruded material, regardless of the diameter of the starting material, it can be varied by placing nozzles of different dimensions. Finally, the extrusion speed determines how fast a layer is printed on top of the other; that is, in what state of solidification is a layer of material when it is placed another one over and with how strong they are joint with each other. This together with other parameters acts on the minimization of distortion [4,15,16].

There is a variety of parameters, and it is not easy to choose these for a part for final use with mechanical requirements. Usually, operators choose these parameters under their experience and acquired knowledge, but there is not enough comprehensive information to determine suitable manufacturing parameters. This is why the main objective of this paper is the study and analyze o the mechanical properties of the parts manufactured by FFF subjected to dynamic loads in PLA pieces, according to four process parameters: layer height, fill density, extruder diameter, and the velocity of the extrusion head. The level of each parameter have been chosen considering the studies published by different researchers already referenced in this text.

Because of this study, the best levels for the mentioned parameters are obtained, within the intervals chosen, so that the best results in terms of fatigue life are found in the pieces tested. This study presents a notable interest for the manufacturing process by FFF, since it provides certain guidelines in selecting the parameters of the manufacturing process of the pieces in a suitable way.

2. Experimental setup

The specimens have been manufactured in PLA, and their geometric shape, in the absence of a standard fatigue test for laminated polymer materials, has been adapted to that defined by the manufacturer of the machine used to perform the tests (Figure 1A). A Prusa i3 printer, based on RepRap technology, was used to manufacture the specimens. They were subjected to a rotating fatigue test, by fixing them to a spindle head, and applying a punctual force at the cantilever specimen, giving way to an oscillating maximum bending moment at its fixed section (Figure 1B).

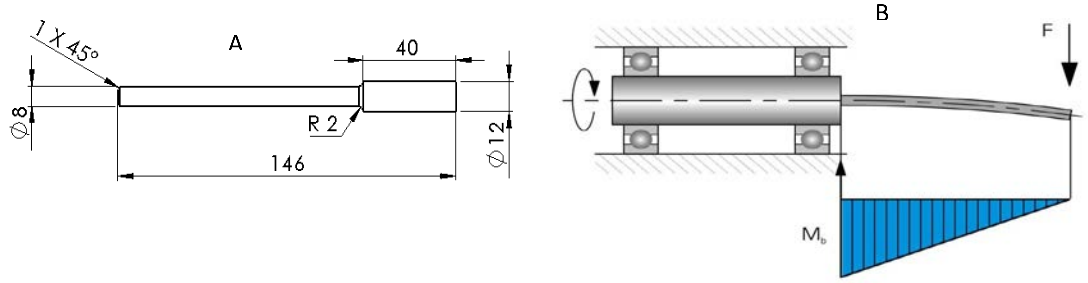

***Figure 1. A.** Dimensions of fatigue specimens. **B.** Fatigue test diagram, and maximum bending moment at the fixed section of the workpiece.*

The machine used to test the specimens has been a GUNT WP 140. This machine allows to fix the specimen with a clamp at one end, attached to the spindle of the engine. At the other end, a punctual force can be applied through a spring mechanism, and regulated by a loading cell that allows to control the magnitude of the force applied. It can be manually adjusted by a thread that moves the end of the specimen vertically (Figure 2). All specimens have been tested with a force of 15 N (what derives in a maximum bending stress of 53.8 MPa).

The specimen rotates at a speed of 2800 min^{-1}. The load, applied in the direction perpendicular to the axis of rotation, generates a load of sinusoidal shape in the fibers of the specimen. This test piece generally breaks in a critical section, which is the zone of greatest bending moment and is also the section in which a change of diameter is performed (Figure 1B). After a series of charge cycles, the specimen fails as a result of the symmetrical cyclic charge, and the machine stops automatically, showing the number of cycles. They are electronically counted, and are displayed digitally.

Figure 2. *GUN WP 140 machine used to perform the different fatigue tests 1: Protective cover, 2: drive motor, 3: control center, 4: tools, 5: test pieces, 6: support, 7: test piece, 8: device to apply the load by rotating the black wheel on top.*

2.1 Taguchi Experimental design

A DOE approach was selected to perform this study, based on a Taguchi orthogonal array. This partial DOE method allows to combine numerous factors and levels and reduce the number of experiments drastically, to assess the influence of a broad parameter combination. The main objective is to find the most significant manufacturing parameters of the parts, to increase their fatigue life. To decide which parameters will be taken as variables in the experimental design, we have considered results from previous studies [17,18]. These parameters also influence other aspects of 3D printed parts, such as the surface finish or cost, so the decision to take these and not other parameters has also been for a global analysis. Therefore, the following four parameters will be considered in the model:

1. **Layer Height**. It defines the thickness of the layers, and greatly affects the manufacturing time, as the thinner the layers, the longer the print head will have to work.
2. **Nozzle Diameter**. It determines the thickness of the thread to be extruded. It can be achieved by changing physically the nozzle for each test.
3. **Fill density**. It defines that controls the density of fill material in the different layers, and therefore the distance between threads inside the piece. It affects the material consumed.
4. **Extrusion head velocity.** The printing velocity can be varied for the different layers, but for these experiments, the same velocity value was fixed for all layers.

For each factor, three levels were studied in order to assess with a certain resolution the influence of each factor on the final behavior. These factors and levels, shown at Table I, are combined in a L27 Taguchi array (Table II). In addition to the individual influence of parameters, the L27 array allows to study the interactions between three of them have, and have therefore been included in the model, except for the extrusion head velocity. For each Taguchi run specified at Table II, five identical specimens have been printed and tested under equal conditions.

There are many other manufacturing parameters to define when printing a part. In this study they have been fixed for all the samples (Table III). Specimens have been printed using a honeycomb infill pattern, and with a brim layer to ensure adherence of the specimen to the printing base during the addition of material (Figure 3). A 1,75 mm filament has been used to manufacture the specimens, heated up to 200ºC, and with no bed heating.

Table I. *Factors and levels included in the Taguchi array*

Factor	**Level**			**Unit**
	1	2	3	
Layer Height	0,1	0,2	0,3	mm
Nozzle Diameter	0,3	0,4	0,5	mm
Fill density	25	50	75	%
Printing velocity	25	30	35	mm/min

Table II. *Taguchi Design of experiments*

Exp.	Layer height	Nozzle diameter	Fill density	Printing velocity	Exp.	Layer height	Nozzle diameter	Fill density	Printing velocity
1	0,1	0,3	25	25	**15**	0,2	0,4	75	30
2	0,1	0,3	50	30	**16**	0,2	0,5	25	25
3	0,1	0,3	75	35	**17**	0,2	0,5	50	30
4	0,1	0,4	25	30	**18**	0,2	0,5	75	35
5	0,1	0,4	50	35	**19**	0,3	0,3	25	35
6	0,1	0,4	75	25	**20**	0,3	0,3	50	25
7	0,1	0,5	25	35	**21**	0,3	0,3	75	30
8	0,1	0,5	50	25	**22**	0,3	0,4	25	25
9	0,1	0,5	75	30	**23**	0,3	0,4	50	30
10	0,2	0,3	25	30	**24**	0,3	0,4	75	35
11	0,2	0,3	50	35	**25**	0,3	0,5	25	30
12	0,2	0,3	75	25	**26**	0,3	0,5	50	35
13	0,2	0,4	25	35	**27**	0,3	0,5	75	25
14	0,2	0,4	50	25					

Table III. *Other printing parameters, kept constant for all specimens.*

Parameter	Valour
Speed for non-print moves	130 mm/s
Brim width	5 mm
Filament Diameter	1.75 mm
Extruder Temperature	200° C
Bed Temperature	0º C
Infill pattern	Honeycomb

Figure 3. *Printing tray with 5 test pieces printed with the same parameters*

3. Results discussion

Each group of five specimens have been tested, and fatigue life has been registered. Outliers inside the collected data were filtered and discarded by applying the Chauvenet's criterion. In Table IV, the results of cycles to failure of the manufactured specimens can be observed.

2.1 Average effect of each factor

The experimental results were analyzed by an analysis of variance (ANOVA), to find the influence of the manufacturing factors on the fatigue strength or number of expected cycles for each part, as well as the interactions that exist between factors. As can be seen in Figure 4, the layer height has the most significant impact on fatigue life. By increasing the layer height, better results of number of cycles have been obtained until failure. The diameter of the nozzle also has an increasing tendency influence on the number of cycles that resist the specimens, but is not so influential as layer height. The larger the nozzle size, better results are obtained. The fill density seems to be the one that has the greatest influence on the resistance, growing drastically this, when the percentage of filling of the pieces increases. Finally, the printing velocity does not seem to have a significant influence on fatigue life. Thus, maximum velocity should always be chosen to increase the productivity of the process.

Table IV. *Results of number of cycles until test failure*

Exp.	Average number of cycles	Exp.	Average number of cycles
1	724	**15**	344
2	778	**16**	772
3	1385	**17**	1332
4	611	**18**	1593
5	851	**19**	703
6	1667	**20**	749
7	914	**21**	1794
8	1047	**22**	954
9	2044	**23**	1244
10	727	**24**	3231
11	1229	**25**	1161
12	2880	**26**	3327
13	778	**27**	4666
14	1511		

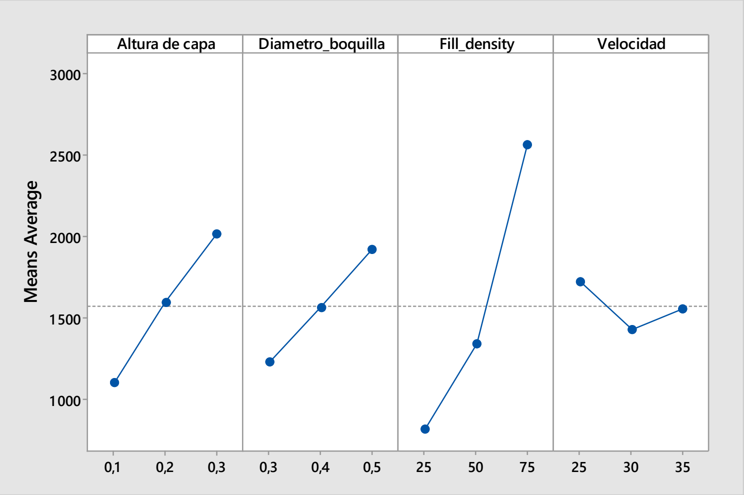

Figure 4. *Main effects plot for means of number of cycles until failure.*

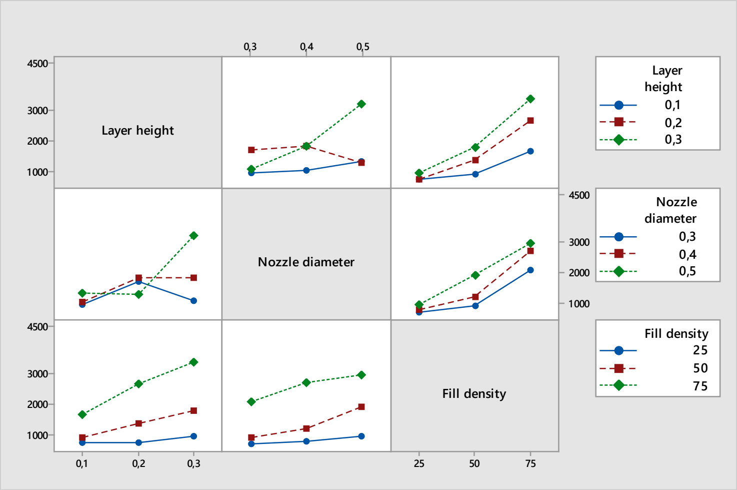

Figure 5. *Interaction plot for means of number of cycles until failure*

As for statistical results, a 10% significance level α = 0.1 was taken to check the p-values associated to the ANOVA hypothesis tests. The p-values for the layer height is 0.055; for nozzle diameter 0.140; for fill density 0.003 and for printing velocity 0.629. These p-vales confirm what can be observed graphically, as the layer height and the fill density have a statistically significant influence on the fatigue strength. However, the nozzle diameter and the speed do not show any influence, in the range of values tested.

Two factors interact between them, when one has influence on the effect of the other factor and vice versa. This interaction describes a situation in which, the simultaneous influence of the two variables on output is not additive. Figure 5, shows that there is only one interaction between the parameters found as statistically significant; it is between the layer height and the nozzle diameter, which is confirmed if p-values associated to the ANOVA are checked. For the interaction Layer Height / Nozzle Diameter, this value is 0.086. The Layer Height / Fill density interaction shows a p-value of 0.429, and the Nozzle Diameter / Fill density value is 0.783. Therefore, they are not significant.

The layer height and nozzle diameter interaction being significant confirms what can be thought of intuitively, which is that as the layer height is increased, so should be done with the nozzle diameter. Using high nozzle diameters with low layer heights has a detrimental effect on the fatigue resistance of the specimen, probably due to an overfilling, and a consequent harmed material matrix inside the part.

2.2 Robustness presented by each factor

The signal-to-noise ratio (SN) measures the robustness of each factor on the response variable, as it is the ratio between the value of the output signal of a parameter and the noise or the associated error. Figure 7 shows how the infill density, the layer height and the nozzle diameter are robust parameters (from highest to lowest robustness), with an increasing SN ratio, in the same way as the graph of means.

Regarding the last parameter, the extruder velocity behaves in the same way as before and reaffirms that it is not influential in the fatigue resistance in the range of study speeds. This behavior is again corroborated with the calculation of the p-values for the SN ratios. Values are for Layer Height 0.015; for the Nozzle Diameter 0.029, for the Fill density 0 and for the Extrusion head speed 0.753. Therefore, the most influential parameters are also the most robust ones if fatigue life is taken as response variable.

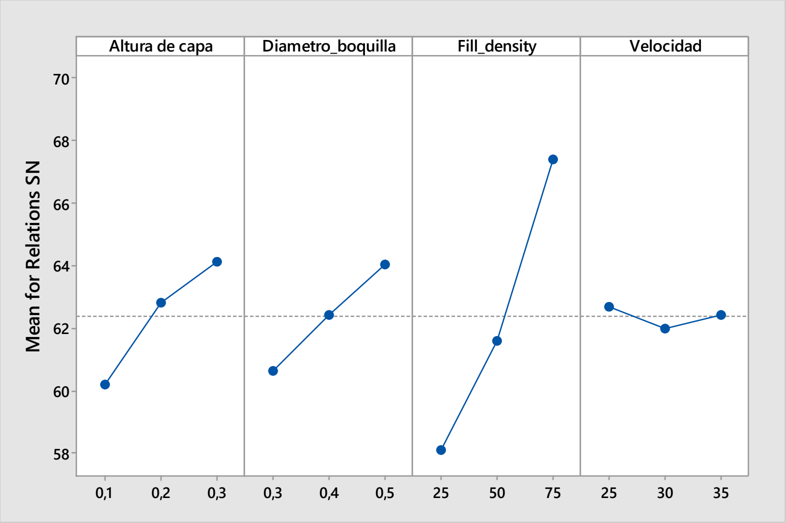

Figure 6. *Signal-to-noise ratios of each factor*

3.3 Technological recommendations for 3D printing

The results obtained in the experiments presented above allow obtaining the optimal configuration of parameters (for the analyzed ranges in all factors) for a longer fatigue life in the parts (Table V).

Table V. *Optimal parameters for greater resistance to fatigue, within the studied range of values*

Parameter	**Optimal level for greater resistance to fatigue**
Fill density	75 %
Nozzle Diameter	0.5 mm
Layer Height	0.3 mm

3.4 Wöhler curve and fatigue limit

Once the technical recommendations where found, a second set of specimens was manufactured to elaborate the S-N curve associated to that parameter combination. For that purpose, specimens where tested by applying the forces specified at Table VI. Three specimens where tested for each stress level, and the resulting S-N curve derived from the point cloud is represented at Figure 9. Figure 9. Taking infinite life at 10^5 cycles, the fatigue limit was not found, but can be concluded that it should be slightly under 45 MPa. This is a reference value that could be taken to work with.

Table VI. *Stress levels tested to draw the S-N curve*

F (N)	M_{max} (N·mm)	σ_{max} (MPa)
10	1040	35.8
13	1352	46.6
15	1560	53.8
18	1872	64.5
20	2080	71.7
22	2288	78.8

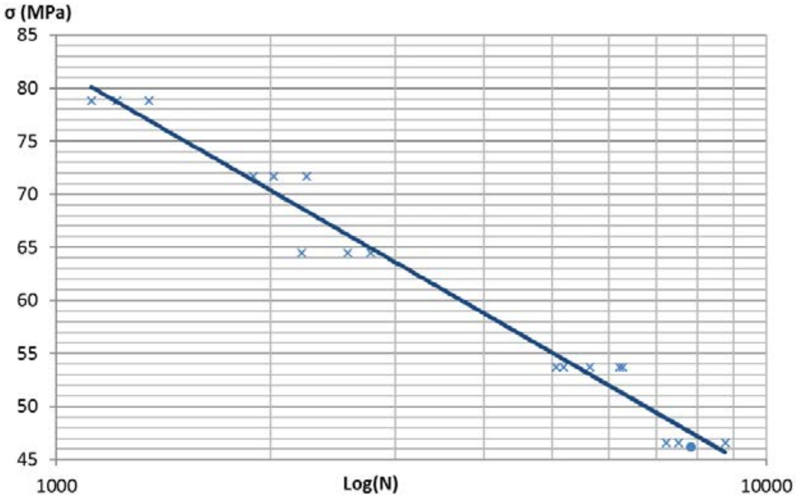

Figure 9. *S-N or Wöhler curve associated to the optimal configuration of manufacturing parameters*

4. Conclusions

The analysis of the experiments carried out leads to the following conclusions:

1. The fill density, the layer height and the nozzle diameter are, from highest to lowest, the parameters that considerably affect the fatigue behavior of the parts manufactured in PLA.
2. The parameters and their levels that generate extruded threads of greater dimensions are beneficial for the life to fatigue of the piece. In fact, a too high discordance between layer height and nozzle diameter derives in a detrimental effect on fatigue life.
3. An approximation to the fatigue limit for PLA parts manufactured using a honeycomb infill with 75% density, 0.5 mm of nozzle diameter, and 0.3 mm of layer height has been detected at around 45 MPa.

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