Infill pattern optimization of Fused Filament Fabrication samples for enhanced mechanical properties

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***Abstract**. In recent years, 3D printing has become a manufacturing process used more often in making various parts with functional or non-functional applications. One of the significant factors that influence the manufacturing time and the mechanical properties of printed parts is infill density and their pattern, both factors influencing the manufacturing cost. Printing parts with high filling densities is the most common solution for obtaining high strength parts. In order to reduce the printing time and material usage and maintain the part's strength, this paper proposes an accessible solution of locally reinforcing the samples by using mesh modifiers to change the inner fill pattern. The research was systematized through a half fractioned factorial setup with five factors controlling the mesh modifier via shape, cross-section, infill grade, infill pattern and extrusion width. The results show that mesh modifiers can significantly increase the tensile properties of regular samples, especially regarding the strain.*

***Keywords:** Fused Filament Fabrication, mesh modifier, local reinforcement, filling pattern, tensile strength.*

1. INTRODUCTION

1.1 Literature review

Fused Filament Fabrication-FFF 3D Printing is an Additive Manufacturing-AM process part of the Material Extrusion family. The process uses molten thermoplastic material (supplied by a spool of filament) to form a part (figure 1) gradually additively. The mechanical properties of FFF made parts is influenced by many factors, which can be categorized into two main groups: materials (e.g., polymer type, filament blend, moisture degree) and process parameters (e.g., nozzle diameter, layer height, line width) [1].

Aiming to improve the mechanical properties of FFF products, many researchers studied various materials and process parameters to understand their effects and interactions.

The study of Es Said et al. [2] shows that raster angle determines polymer chains' alignment along the deposition direction during printing influences the tensile, flexural, and impact strength.

In the study of Hutmacher et al., [3], the forming structures of FFF parts were analyzed from the micro perspective. It was found that the pores volumes, structure, and porosity degree of the scaffolds were mainly defined by the levels of the computer-controlled FFF machine parameters, and the honeycomb infill pattern resulted in better mechanical properties.

Although FFF offers good quality products, there are limitations regarding the load capacity, which depends on its direction. Consequently, their anisotropic character limits the practical application of components produced through FFF. Nowadays, there is a trend regarding direct manufacturing and ready to use concepts through which the stakeholders can use the parts directly. A good example is given by the medical field, where patients' prosthetic limbs can rapidly be manufactured based on their profiles.

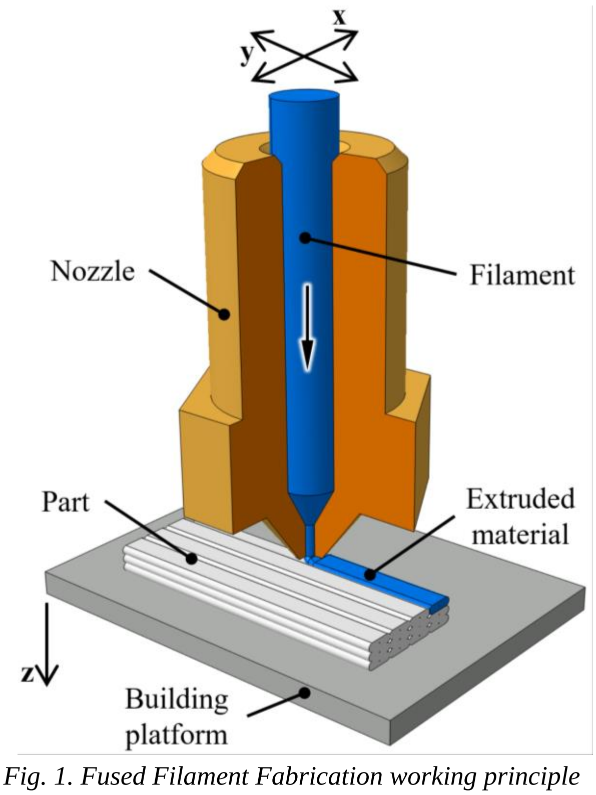


Fig. 1. Fused Filament Fabrication working principle

Although, the final mechanical properties of parts obtained using the FFF process are influenced by a considerable number of process parameters and are difficult to consider in a single printing process. For this reason, it is important to study the influence of various process parameters over the mechanical properties of

FFF products and improve the parts by optimizing the printing process by selecting the best setting [4].

Torres et al. [5] studied the effects of layer height, filling percentage, and heat treatment time at 100°C, on the shear strength of the printed PLA specimens. Improvement in shear strength was resulted from reducing the layer height, increasing the filling percentage, and the heat treatment time.

Baich et al. [6] studied the effects of filling patterns on the strength and cost of the printed parts. They investigated the effects of filling patterns with low, high, double line, and full densities. The best results in therm of tensile, compressive, and flexural strengths resulted for the 100% density samples.

Fernandez-Vicente et al. [7] studied the effects of filling patterns and the filling percentage on the tensile strength of printed ABS specimens. The maximum tensile strength of 36.6 Mpa was obtained at 100% filling percentage for the rectilinear pattern.

1.2 Fused Filament Fabrication working principle and part structure

In the FFF process, the thermoplastic materials are heated up to a temperature comprised in a melting range (e.g., for PLA between 190 and 220°C), and it is set depending on printing speed and line width (a constant material flow must be maintained to prevent inconsistent extrusion). Then the material is extruded and reshaped in as lines (figure 1). Those are printed next to each in defined patterns in other to create a layer. Depending on their position across parts' grow direction, each layer is composed of walls and solid on inner fill. The final product is made of multiple layers stacked on top of each other (as shown in figure 2a, b). Depending on the requirements, fill patterns can be considered, such as grid, honeycomb, gyroid, and others (see Figure 2c).

The most common process parameters in the FFF process include extrusion temperature, layer height, nozzle diameter, extrusion width, air gap, build orientation, raster angle, filling pattern, and filling percentage. These parameters can significantly influence the tensile properties of the specimens [1].

Printing parts with high fill densities is the most common solution for obtaining high strength parts. However, large-sized products can significantly increase the manufacturing time and material use. In order to reduce the printing time and material usage without reducing the part's strength, this paper proposes a convenient solution of locally reinforcing the samples by using mesh modifiers to change the inner fill pattern.

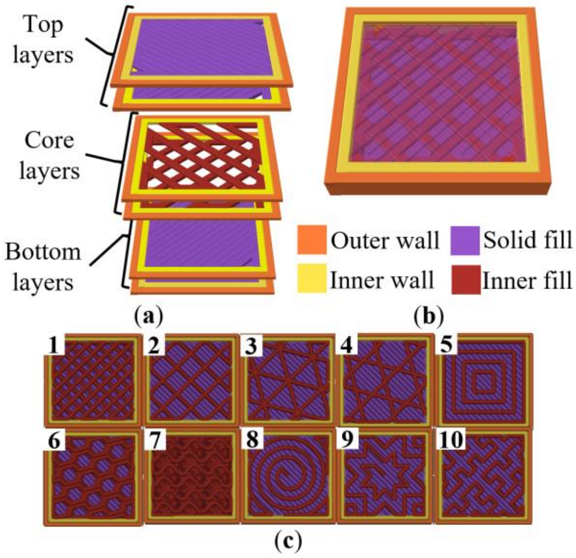


Fig. 2. FFF part's structure: (a) Exploded view of a part's layers; (b) Stacked view of the part's layers; (c) Infill patterns: 1. Rectilinear, 2. Grid, 3. Tingles, 4. Stars, 5. Concentric, 6.Honeycomb, 7. Gyroid, 8.Achemeden chord, 9. Octagram spiral, 10. Hilbert curve

2. MATERIALS AND EQUIPMENT

As printing material, the Titan X filament was considered supplied by the dutch company FormFutura. The filament is an Acrylonitrile Butadiene Styrene-ABS based material (1.75 mm diameter). According to the vendor, Titan X has improved mechanical properties and printability compared to regular ABS.

Samples were produced using a Prusa i3 Mk3S+ FFF desktop 3D printer.

All samples were printed in a closed environment with 45 % moisture. All printing sessions were started after reaching the 40°C environment temperature through passive heating (10-15 minutes with the printing bed at 110°C). Probes were removed only after slow cooling in the closed environment (after the printing bed dropped to 30°C). The 255°C extrusion temperature was used. The print bed temperature was set at 100°C for the fist layer to increase material adhesion on the glued build plate) and 90°C for the other layers.

All samples were tested using an Instron 8800 universal testing machine with a load cell of 50 kN in an environment with 55% moisture and at 23°C.

Before printing, the filament was dried according to the technical data sheet and kept in a dry storage box.

3. DESIGN OF EXPERIMENT

As the design of the experiment-DOE method, a half fractioned factorial setup was considered with five factors and two levels of variation, resulting in 16 configurations of the specimens (reference sample is 1B of ISO 527). All considered variables (Table 1) and the tensile test results were processed using the Minitab 20 statistic tool. This experimental setup was used to determine which factors have the most significant influence over the tensile properties of the locally reinforced specimens.

Table 1

Half factorial DOE variables

Factors	Parameters/Level	L1	L2
A	Modifier width (mm)	1.75	3.5
B	Modifier shape	Rectangular	Sinusoidal
C	Infill pattern	Grid	Gyroid
D	Infill grade (%)	20	90
E	Extrusion width (mm)	0.4	0.5

Table 2

Constant parameters of DOE

Nozzle diam. (mm)	0.4	Brim	Yes
Extr. temp. (°C)	255	Dist. gap (mm)	0
Bed temp. (°C)	90	Brim width (mm)	5
Raster angle (°)	45/-45	Adhesive	Yes
Walls (no.)	3	Out. wall spd. (mm/s)	30
No. top layers	5	Wall spd. (m/s)	40
No. bottom layers	5	Solid infill spd. (m/s)	40
Fan spd. (%)	0-25	Infill spd. (m/s)	50
Retract. dist. (mm)	0.8	1st layer spd. (m/s)	20
Retract. spd.(mm/s)	35	Closed env.	Yes
Abbreviations:			
- diam. – diameter;		- spd. – speed;	
- extr. – extrusion;		- dist. – distance;	
- temp. – temperature;		- retract. – retrection;	
- no. – number;		- env. – nvironment.	

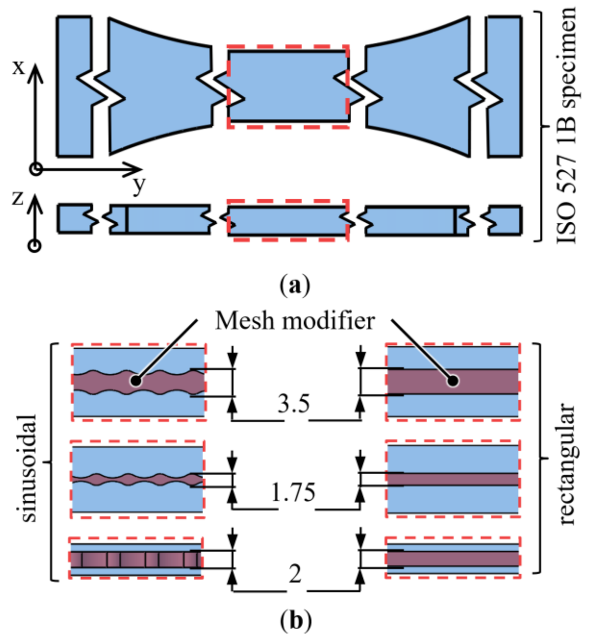


Fig. 3. Mesh modifier definition: (a) Broken views of specimen 1B; (b) Inside view of mesh modifier shape, width, height and relative position to specimen's body.

The mesh modifiers were placed on the entire length of the 1B specimens in a centred position. (figure 3). The first variable defines the mesh modifier width, and the second control its shape. The chosen shapes are rectangular, respectively, sinusoidal. Those parameters allow local adjustment of the extrusion paths by respecting the modifier shape (figure 4). It was assumed that the sinusoidal modifier would behave like a spring during the tensile test and improve the strain of the specimens. The following factors control the filling pattern inside the mesh modifier. Two patterns were chosen, rectangular and gyroid at 20 respectively 90% density. The last considered parameter is controlling the line width of the modifier walls. It was assumed that an increased cross-section area would result in higher strength. For example, the result can be observed in R3-R4 or R10-R11 pairs of figure 4.

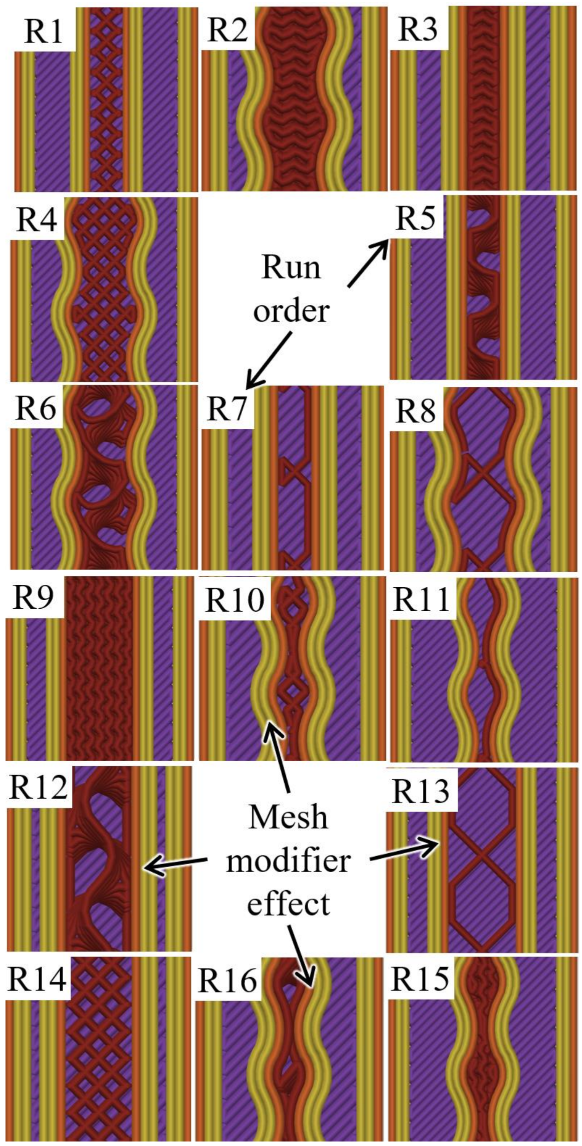


Fig. 4. The internal structure of the experimental runs

As a benchmark for the DOE resulting specimens, two regular specimens were printed with a rectangular pattern of 20, respectively 90% density. Other parameters considered for the printing process were kept at constant values during the entire study. Their levels are displayed in Table 2.

All specimens were printed in the randomized order provided by the Minitab in four blocks with one replicate for each run and printed one by one.

4. RESULTS AND DISCUSSION

All specimens were tested in the same laboratory conditions and failed in the same region, on the breaking length of 60 mm. A view of the Titan X 3D printed samples before and after the tensile test is presented in Figure 5.

(a)

(b)

Fig. 5. Test sample: (a) after printing; (b) after failing

Regarding the tensile strength, referred to the 90% infill benchmark sample (with a response of 56 MPa), the best result were obtained for the R3 sample (with R coming from Run). The specimen is characterized by a rectangular mesh modifier at 1.75 mm having 90% gyroid infill and 0.5 mm line width. Regarding strain, referred to the same benchmark, the most significant improvement was obtained for the R12 having a 101.3% increase but a decrease in load capacity of 2.7%. The R12 sample was printed with a 3.5 mm width mesh modifier with a 20% gyroid infill and a line width of 0.5 mm.

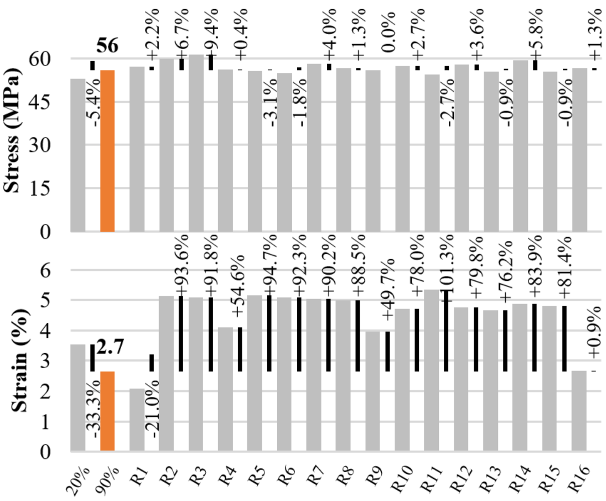
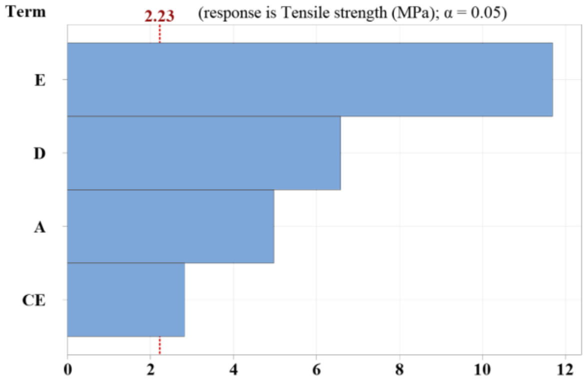
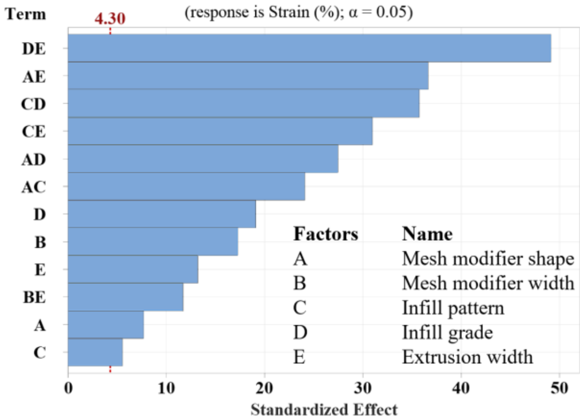


Fig. 5. Tensile stress and strain at the peak of the experimental run specimens referred to 90% grid infill benchmark sample

Overall, considering both stress and strain, the best results over the tensile properties were obtained for the R3 configuration (having a 91.8% increase in strain), as presented in figure 6.

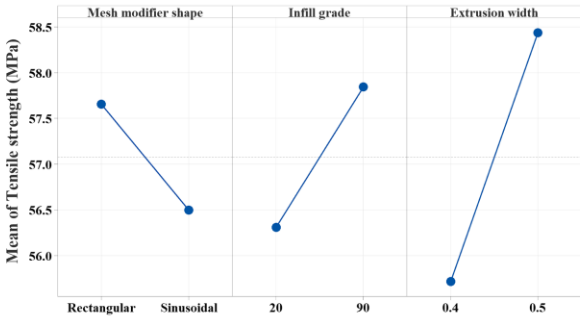


(a)

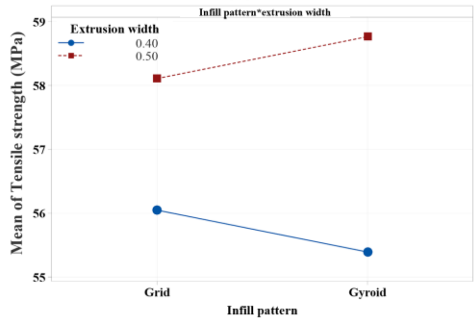


(b)

Fig. 7. The Pareto chart of the standardized effect; (a) The response is tensile strength (MPa); (b) The response is strain (%)



(a)



(b)

Fig. 8. Statistically significant factors for tensile strength; (a) Main effects plot; (b) Interaction plot

Overall, for both responses, stress and strain, the main effect plots showed that the *Mesh modifies shape*, *Infill grade*, and *Extrusion width* had the most significant influence over the tensile properties of the specimens (figure 8a and figure 9a).

The responses obtained from the experiments were analyzed using a graphical representation of the main effects and interactions and an analysis of the variance of average tensile properties. Some of the interactions between controlled variables were ignored as they were minimal. The response analysis helped identify the variables that had the most significant influence over the tensile strength of the specimens

The regression analysis was performed using the Minitab tool with a confidence level of 95% for both responses with the forward selection method to exclude the insignificant factors. The main factors' variance and interactions were graphically analyzed using Pareto charts (figure 7).

For the stress response, the most significant factors are the *Mesh modifier shape*, *Infill grade* and *Extrusion width* (figure 7a). In the case of strain, the result shows that all five considered variables are statistically significant, along with seven interactions. In addition, it was shown that interaction *Infill grade*Extrusion width* had the most significant influence over this response.

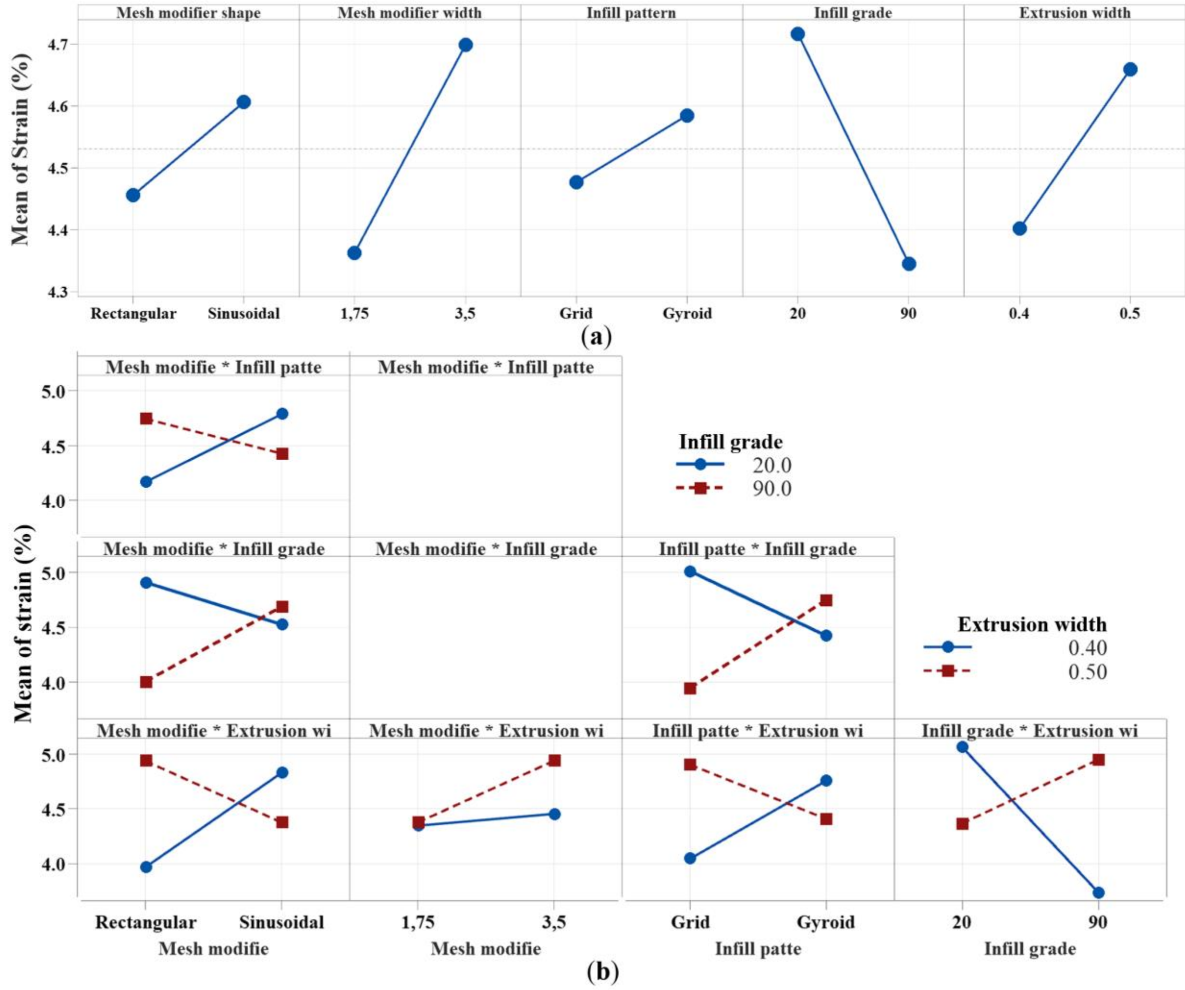


Fig. 9. Statistically significant factors for strain; (a) Main effects plot; (b) Interaction plot

5. CONCLUSIONS

The research results presented in this paper have highlighted the advantages of using mesh modifiers to locally adjust samples internal geometry via infill pattern, infill grade or extrusion width.

The use of mesh modifies helps in increasing the load capacity of samples. However, the most significant improvement is over the strain. Overall, the best results were obtained for the R3 configuration with a rectangular mesh modifier at 1.75 mm with a 90% gyroid infill and 0.5 mm wxtrusion width. The tensile test result show an increase of 9.4% in strenght and an improvemnt of 91.8% in strain compared to bechmark sample, printed with 90 fill density.

From the considered variables the most significant factors for both responses are the *Mesh modifies shape*, *Infill grade*, and *Extrusion width*, along with the interaction *Infill pattern*Extrusion width.*

Further research must be done to evaluate the influence of the mesh modifiers over the impact, and bending strength of FFF 3D Printed samples. Another

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