INFLUENCE OF PARAMETERS ON MECHANICAL PROPERTIES OF THERMOPLASTIC POLYMERS OBTAINED BY FUSED FILAMENT FABRICATION (FFF)

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ABSTRACT

Fused filament Fabrication (FFF) is one of the typical Rapid Prototyping (RP) process that can fabricate prototypes from various model materials. To predict the mechanical behaviour of FFF parts, it is necessary to understand their material properties, and the effect that the FFF build parameters have on this later. In this study, two thermoplastic polymers (ABS and PLA), obtained by two open-source 3D printers are studied. The key printing parameters that we looked into were: layer height, pattern geometry and % of infill density, by keeping constant the fabrication orientation, perimeter overlap, velocity of deposit and model temperature. In the main body of this study, we provided a detailed description of the influence of these parameters on rigidity (Young Modulus) and yield stress (0.2 % of strain). For this purpose, Taguchi's statistical experimental design technique was applied and compared to full design's one. The results obtained from Taguchi's method show that layer height and pattern geometry has no effect on the Young Modulus, as well as pattern geometry on $Re_{0.2}$ response in the studied range of infill density, whereas true infill density potentially affects the considered responses. In addition, the layer height may also affect slightly the yield stress response. Moreover, a good concordance of Young Modulus evolution versus infill density has been observed for both ABS and PLA materials, as well as two experimental design methods.

1 INTRODUCTION

Many times across history a new technology has transformed our lives (ex. Steam engines, assembly lines, personal computers…etc). Today, the latest revolution of the internet is just about over. Yet even as this is occurring, a new revolution is waiting in the wing. This time the technology that is going to change things is called 'additive manufacturing' or '3D printing'. These terms both refer to a widening range of technologies that can turn digital computer-generated geometry into physical objects using a variety of materials through a layer-by-layer building process. Because of many recent developments, this amazing process of making things has become a mainstream means of production and is now being utilized by companies large and small, startups, schools, hobbyists, designers, and artists in a wide range of industries. Today, the majority of 3D printers create objects by extruding a semi-liquid material from a computer-controlled print head nozzle. This technology is commonly known as Fused Deposition Modeling (FDM), Fused Filament Fabrication (FFF) or Fused Filament Deposition (FFD). It is widely spread nowadays in variety of industries such as automobile or food companies, model concept and prototyping and even in manufacturing development. Another word, Fused Filament Fabrication (FFF) is one of the typical Rapid Prototyping (RP) process that can produce prototypes from various model materials.

However, to predict the mechanical behavior of FFF parts, it is necessary to understand the influence of FFF build parameters on the material properties. Nowadays, the literature, talking about that, is largely oriented towards study on the mechanical properties of polymeric materials (Young modulus, ultimate tensile strength (UTS), strain at break…) or dimensional accuracy [1-2]. Lanzotti et al. studied the influence of layer thickness, infill orientations, and the number of shell perimeters on mechanical characteristics of polylactic acid (PLA) [3]. He is also interested to analyze the effects of layer thickness, deposition speed, and flow rate on the dimensional accuracy where the optimum combination of these parameters was found [4]. Rankouhi et al. analyzed the influence of layer thickness and infill orientation on mechanical properties of ABS, and performed a fractography of failure modes. They observed that smaller layer thickness increases the strength and that the large air gap causes interlayer fusion bonds to fail [5]. Akande et al. studied the significance of layer thickness, fill density, and speed of deposition on the mechanical properties. Furthermore, they developed a low-cost test jig and compared it with conventional testing machine, by obtaining a valid method for quality testing [6]. Thank to Open-Source of 3D printers including FFF technology, the lightness of parts could be reached by designing an internal structure which combines the porosity and a given filling strategy. Thus, a good ratio between the strength and this later is required for product and process design optimization.

Nonetheless, there is yet luck of studies that evaluate the different patterns that could be selected in the infill, or the influence of their density on mechanical strength. These parameters are controlled only by the Open-Source technology and not by FDM’s one. For this reason, we have studied the mechanical behaviour of two thermoplastic polymers (ABS and PLA), obtained by two open-source 3D printers (Ultimaker 2 and SpiderBot V1). The key printing parameters that we looked into were: layer height varied from 0.1 to 0.45 mm, pattern geometry (grid ±45°, Honeycombe or Octogonal and Rounded) and % of infill density (or % of voids) changed from 20 % to 100 % for PLA and 33% to 100% for ABS, by keeping constant the fabrication orientation, perimeter overlap, velocity of deposit and model temperature. In the main body of this study, we provide a detailed description of the influence of these parameters on rigidity (Young Modulus) and yield stress (corresponded to 0.2 % of strain). In addition, to predict the mechanical behavior, Taguchi’s statistical experimental design technique is applied and compared to full design’s one.

2 MATERIALS AND METHODS

To determine the mechanical properties of 3-D printed parts and the variability in these properties when different user-controlled printing and slicing parameters are used, this investigation looked at the relationship between deposition pattern geometry, layer height and infill density to yield tensile strength and Young modulus of an acrylonitrile butadiene styrene (ABS) and Polyactic Acid (PLA) polymers. For this purpose, optimisation techniques, such as Taguchi’s method [7] is utilized in the case of ABS polymer as effective method due to its cost and time efficiency. Then, this method is compared to full experimental one, applied to PLA.

Taguchi’s method uses a unique set of arrays called orthogonal arrays, which specifies the way of conducting the minimum number of experiments, which would give the full information of all factors that affect the performance parameters. In this study, a factor experiment orthogonal array design of L9 (three levels-four factors) has been selected initially according to the number of FFF variable parameters and number of settings or levels (Tables 1 and 2).

Factor N°	Name	Level 1	Level 2	Level 3
1	Layer height (mm)	0.1	0.25	0.45
2	Pattern geometry	Octo	Rounded	Grid (±45°)
3	Theoretical Infill (%)	33	50	100
3	True Infill (%)	47	71	100

Table 1: Parameters and their levels

A .STL File (as shown in Fig.1a) of a tensile test specimen conforming to the ISO 527-2 was created from CATIA V5R20 for a Spiderbot V1 and Ultimaker 2 printers. A complete set of six specimens of each of the combination of variables shown in Table 1 was printed on two considered open-source printers including the softwares Repetier Host and Cura V15.04 for Spiderbot V1 and Ultimaker 2 respectively. These later were used for slicing the .STL files into machine readable g-code which included KISSlicer (Spiderbot V1) and Simplify3D (Ultimaker 2). As ABS and PLA polymers were used for printing tensile specimens, the extrusion nozzle and bed were heated to 235 °C and 110 °C respectively for ABS parts, and to 215 °C and 60 °C respectively for PLA ones. Their density corresponds to 1.05 g/cm^3 and 1.17 g/cm^3 respectively.

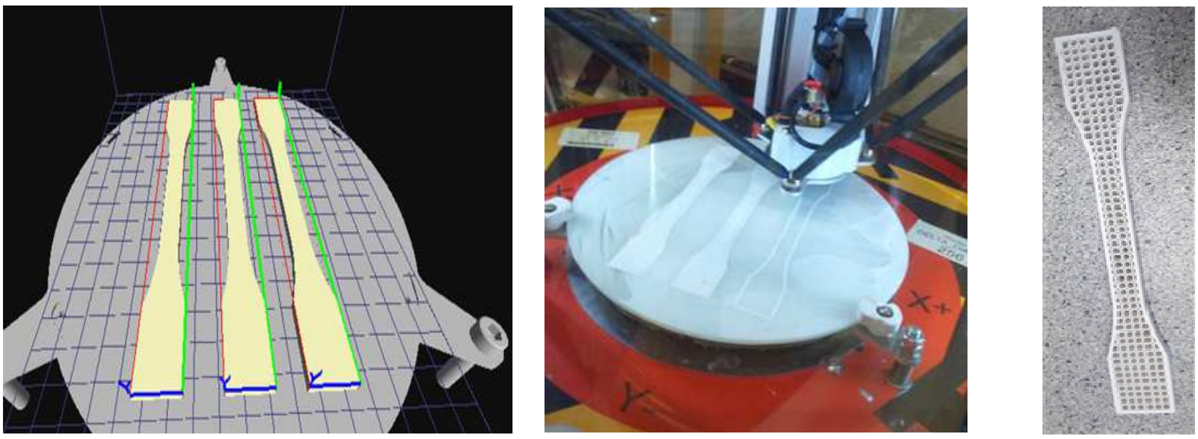
Test N°	Factors			
	1	2	3	4
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 2: Table of Taguchi L_9 orthogonal array

In order to study only the influence of slicing variables shown in Table 1 on the mechanical properties, the following parameters were invariables for all printed specimens:

- Skin thickness = 0 mm ;
- Number of Loops = 2 ;
- Extrusion Width = 0.5 mm ;
- Infill Extrusion Width = 0.48 mm ;
- Inset Surface = 0 mm ;
- Jitter = 0°.

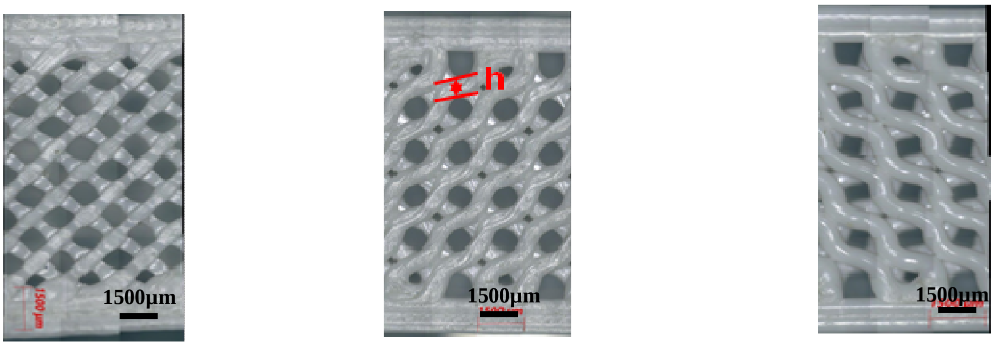
In addition, all specimens were printed in the x-y plane. An example of printing process on Spiderbot 3-D V1 printer and view of printed specimen is shown in Fig. 1 b and c.



(a) (b) (c)

Figure 1: (a) Rendering of the shared .STL filed of the tensile standard ISO 527-2; (b) printing process on Spiderbot 3-D V1 printer; (c) digital photograph of a printed specimen (example of rounded geometry, 33%, 0.25 mm of layer height).

The Figure 2 shows the micrographs of three chosen pattern geometry surfaces of 0.1, 0.25 and 0.45 mm of printed layer heights corresponded to 50% of theoretical infill density.



(a) (b) (c)

Figure 2: Surface micrographs of printed pattern geometry at 50% of infill density: (a) 0.1 mm of layer height and octagonal geometry; (b) 0.25 mm of layer height (designed as h) and rounded geometry; (c) 0.45 mm of layer height and grid of ±45°.

Tensile testing of printed specimens was performed on a Zwick load frame. The principal strain ε_I, using for calculation of Young Modulus, is measured by a 2in gage length extensometer (Fig.3). Each test was conducted using a cross-head rate of 2 mm/min.

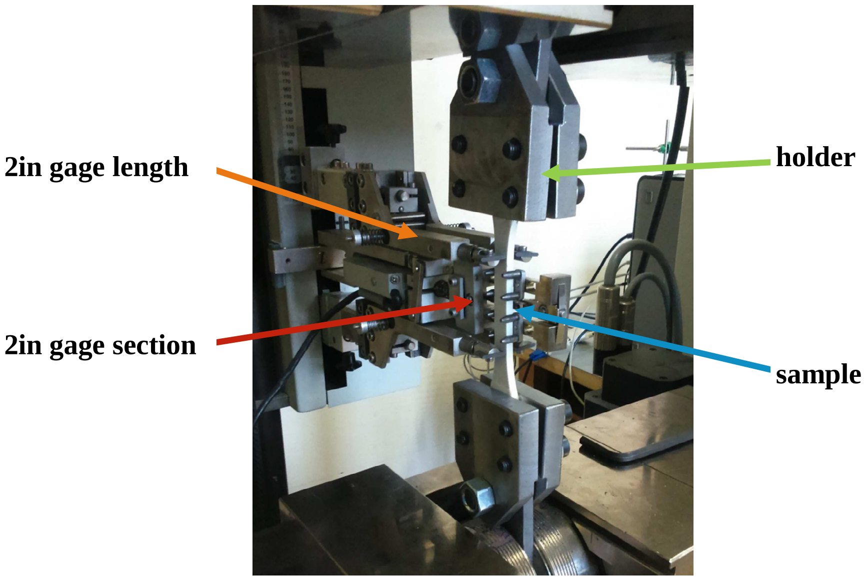


Figure 3: Tensile Zwick set-up

To determine a true area of cross-section specimen, taking into account a true infill density after printing, the density measurements of studied fills and mass measurements of printed parts have been realized using a balance AS. Knowing the density of the material filament and the volume of full printed sample, it is possible to determine the mass of this later and compare it to mass one of different unfilled density. The ratio of two mass gives the true infill density (in %). These mean values are corrected and presented on Table 1. The relative error of printing infill is about 42 %.

3 RESULTS AND DISCASSION

Averaged true stress evolution, taking into account a true area of cross-section specimen (S_0* *infill %)* according to Eq.1, versus true strain (Eq. 2) for some characteristic Taguchi's factors of ABS material is presented on Figure 4.

$$\sigma_{true} = F/\,(S_0 * \, infill\,\%)*(1+\varepsilon) \qquad (1)$$

$$\varepsilon_{true} = ln(1+\varepsilon) \qquad (2)$$

The pattern geometry plays an important role on the tensile behaviour of unfilled specimens. A brittle behaviour is more observed for the octagonal geometry, whereas two others (rounded and the grid at ± 45°) tend to plastic perfect flow. In addition, a full printed specimen develops a characteristic for thermoplastic polymers tensile behaviour with well-distinguished high threshold flow or yield stress (~ 33 MPa).

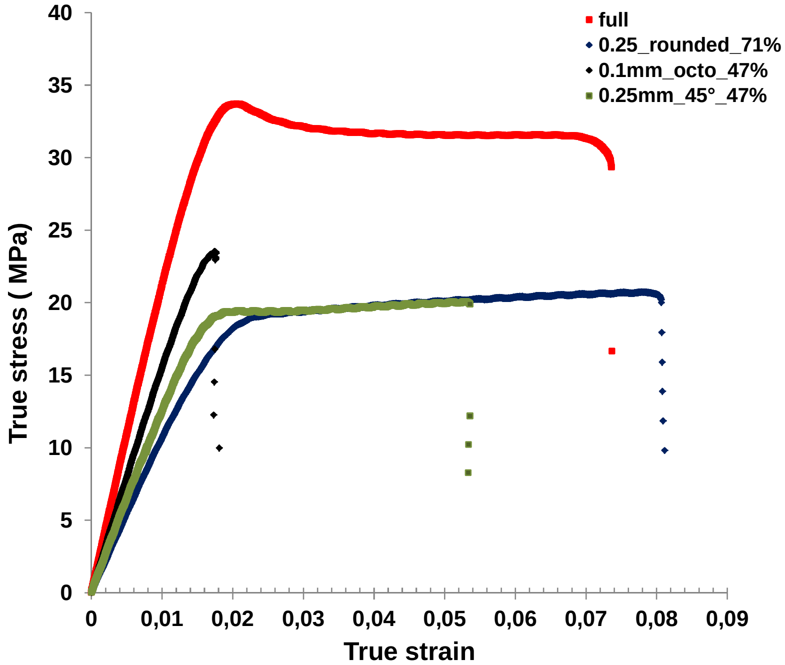


Figure 4: Averaged true stress evolution versus true strain for different Taguchi's levels of ABS material

The mean values of yield stress and Young Modulus of all studied Taguchi's factors of ABS material are summarized on Table 4.

Test N°	Mean values E (MPa)	Mean values $R_{e0.2}$, MPa
1	1536.5 ±61	22.14 ±1.61
2	1099.7 ±61	18.7 ±0.62
3	2120 ±17	32.33 ±0.17
4	2103 ±18	32.5 ±0.17
5	1267.4 ±73	19.13 ±0.52
6	1225 ±35	16.11 ±0.4
7	1345 ±47	17.95 ±0.35
8	2085 ±18	32.67 ±0.18
9	1252 ±38	18.12 ±0.85

Table 4: Mean values of Young Modulus and yield stress of realized Taguchi's factors.

The Figures 5 and 6 show the main effects plot for means. This plot is used to identify the most FFF parameters that affect the Young Modulus (Fig.5) and Yield stress (Fig.6) response according to the response means, which is attained by each parameter level. Therefore, when the mean line is parallel to x-axis then it can be concluded that the parameter has no effect on elastic and yield stress responses and when the line is inclined then the parameter affects the response. Thus, layer height and pattern geometry has no effect on the Young Modulus, as well as pattern geometry on $Re_{0.2}$ response since the mean line is parallel to x-axis. However, true infill density potentially affects the considered responses, since the mean line is tendency to increase to high values. In addition, the layer height may affect slightly the yield stress response (Fig. 6a).

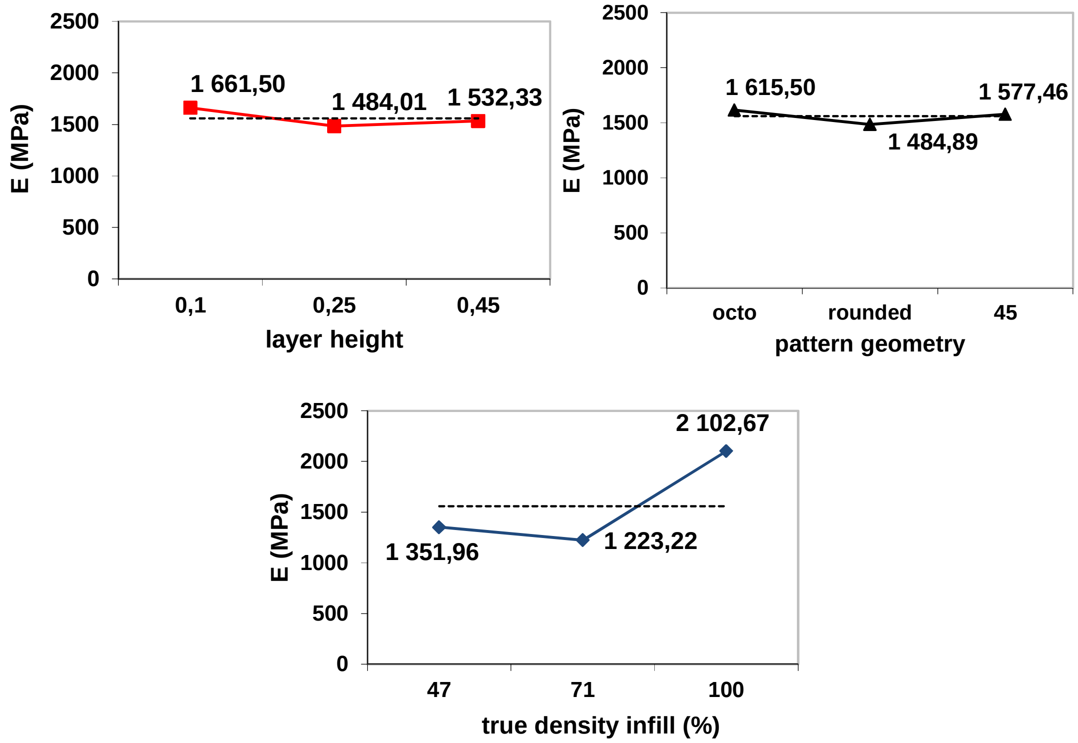


Figure 5: Main Effects Plot for Means for Young Modulus of ABS material.

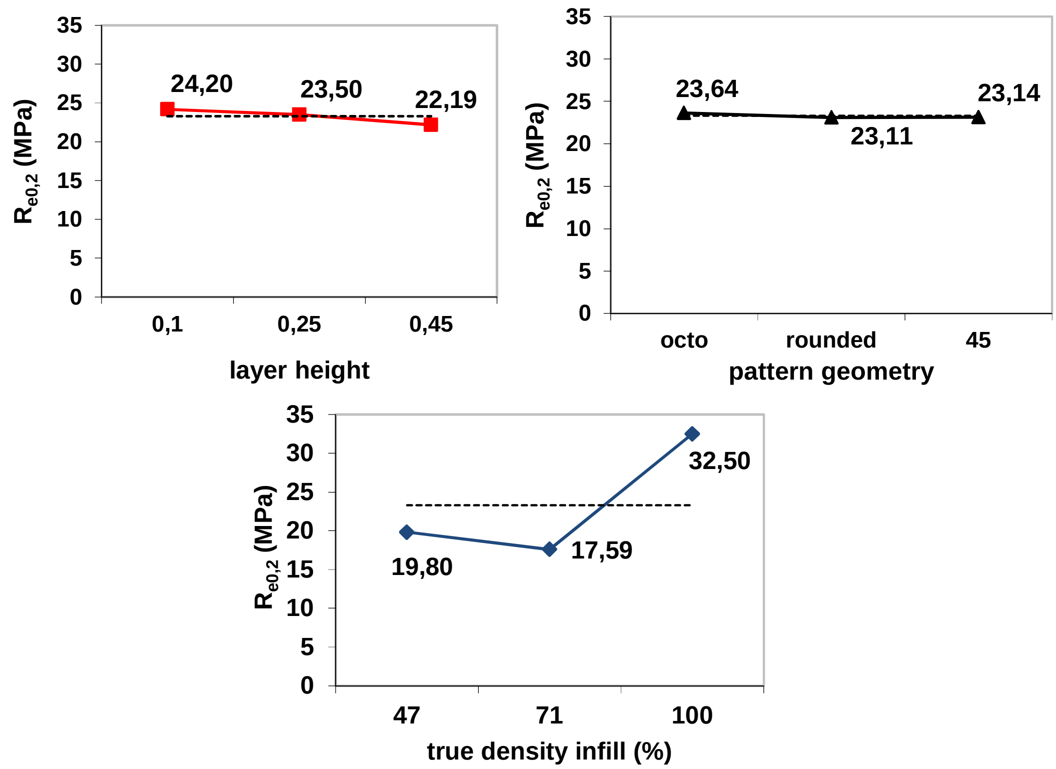
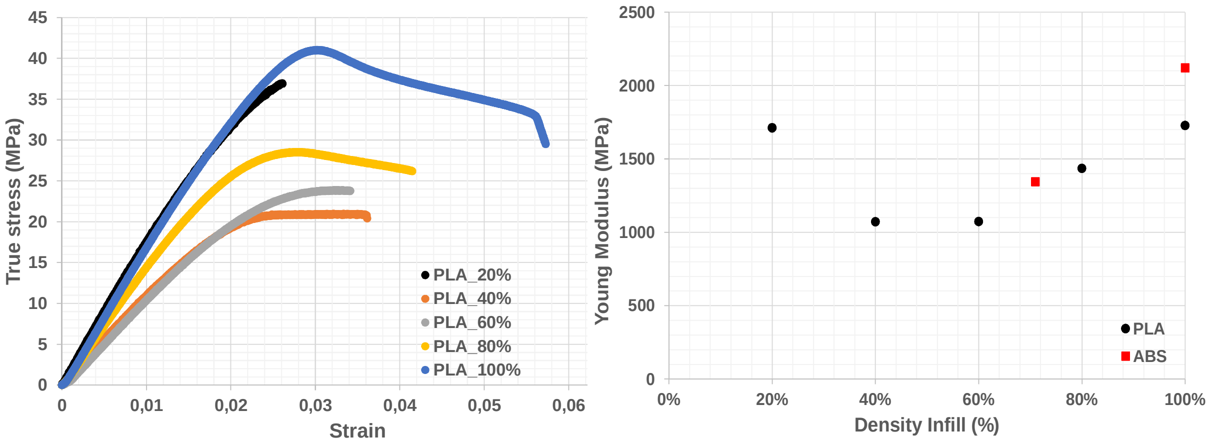


Figure 6: Main Effects Plot for Means for Yield stress of ABS material.

To confirm the results obtained by Taguchi's method concerning the effect of density infill on elastic and yield stress responses, the full experiment design was conducted on PLA material. An example of averaged true stress evolution versus strain for different % of infill density, keeping constant the layer height of 0.1 mm and pattern geometry (grid at ± 45°), is presented on Figure 7. The same tensile behaviour is observed, as it was in the case of ABS: the well-distinguished flow threshold or yield stress of full printed specimen decreases until the range of 40 – 60 % of infill density and tends to perfect plastic flow. However, the specimen seems to become brittle and stiffer at 20% of infill density than at the 40 - 60% ones. The Young modulus is attained the value of full printed sample. This could be explained by the fact that its tensile resistance is principally governed by filaments of perimeter shells oriented at 0° to loading axis, since rarely filaments at ±45° situated in the cross-section have no really significant effect on the bulk stiffness. A good concordance of Young Modulus versus infill density is observed for ABS and PLA materials, as also of two experimental design methods (Fig.7b). The full experimental method gives more complete information than the Taguchi's one.



a) b)

Figure 7: Averaged true stress evolution versus strain for different % of infill density of polyactic acid (PLA), keeping constant the layer height of 0.1 mm and pattern geometry (grid at ± 45°).

4 CONCLUSION

In this research, three FFF parameters: layer height, pattern geometry and infill density were examined at three variable settings for building test parts. The Taguchi's method and Full factor design were used separately in the case of ABS and PLA respectively and then compared to determine the optimum parameters settings that affect the output characteristic responses i.e., Young Modulus and yield stress. It has been found that not all FFF parameters (layer height and pattern geometry) have impact on the Young Modulus. Only true infill density influences on this later in the range of layer height and pattern geometry applied. The same FFF parameter tendency has been observed for yield stress. However, it is recommended to use the specimens printed close to 100% of infill density, combined with 0.1 mm of layer height and any chosen in this study pattern geometry for improving the yield stress.

In addition, a good concordance of Young Modulus evolution versus infill density has been observed for both ABS and PLA materials, as well as two experimental design methods.

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