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Mechanical properties of 3D printed polymer specimens

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Abstract

The procedure of manufacturing objects by sequentially depositing layers of material, based on 3D digital models, is called Additive Manufacturing (AM) or 3D-printing. Fused Deposition Modeling (FDM) technology along with the ABS (Acrylonitrile Butadiene Styrene) material are widely used in additive manufacturing. Until today, the mechanical properties of the AM parts cannot be determined nor even approximated before it is manufactured and tested. In this work a novel approach is presented on how the printing factors influence the mechanical properties of the printed part in order to obtain how parts can be manufactured (printed) to achieve improved mechanical properties. The methodology is based on an experimental procedure through which the optimum combination of manufacturing parameters and their values can be determined, in order to achieve the goal. The Taguchi methodology was selected as an optimization tool towards the goal of improving the part's mechanical properties.

Keywords: Additive manufacturing; AM; 3D printing; ABS; mechanical properties; tensile testing

1. Introduction

Additive Manufacturing (AM) evolves rapidly nowadays, as the research community continuously presents new achievements on materials (Ngo, et al., 2018), methodologies (Papacharalampopoulos et al. (2018)), mechanical properties of AM parts (Raj et al. (2018); Dizon, et al. (2018)) or even try to analyse future perspectives (Camacho et al. (2018); Rejeski et al. (2018); Jiang et al. (2017)).

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First steps, in this revolutionary new technology, took place in 1980 in research centers and nowadays is rapidly gaining consumer acceptance. The main innovation in this technology is the ability of constructing complex structures, which cannot be manufactured by using traditional processes. Through this method the material is heated and placed on a plate, layer by layer, until the part is manufactured. The material is heated slightly above the melting point and solidifies as soon as it comes out of the nozzle. Additive Manufacturing is, along with Subtractive and Formative Manufacturing, the third supporting pillar of the entire manufacturing technology (Gebhardt (2011)) with dynamically changing execution technologies which alter the range of use leading to the need of constantly comparing these classic methods with AM (Watson and Taminger (2018); Lesage et al. (2018)). The term of AM covers any process of adding material in order to create a 3D physical part, but nowadays the layer-based approach is most commonly used. Every 3D model that is manufactured through the AM process follows a six-step path (Gibson et al. (2015)). First is the CAD model creation with the translation to STL format following. Then the 3D printed model is created by setting the manufacturing parameters. The final step is to remove any unnecessary material from the part in order to use it.

Fused Deposition Modeling (FDM) technology along with the ABS material are widely used in additive manufacturing as an affordable solution. Through this method the material is heated and placed on a plate, layer by layer, until the part is manufactured. The material is heated slightly above the melting point and solidifies as soon as it comes out of the nozzle. The heated material is placed on to a plate by a nozzle that is moved by a numerical controller (NC).

1.1. Fused deposition modeling

Fused Deposition Modeling is a method that has been patented by Stratasys, USA in 1992. In this method, the area is heated to 80°C and the material is injected through a nozzle. The plastic (usually ABS or PLA) is heated slightly above the melting point and as soon as it comes out of the nozzle it solidifies. Characteristic of the components they produce is their high strength, relatively good precision, the fact that they do not need cleaning and finishing afterwards but also the saving of raw materials, as there is no residual (Srivatsan and Sudarshan (2016)). The affordable cost of the machinery as well as the material are the main factors that such machines increase rapidly their market share. Through this method the material is heated and placed on a plate, layer by layer, until the part is manufactured.

1.2. ABS material

In general, thermoplastics such as ABS (Acrylonitrile Butadiene Styrene), are ideal materials for 3D printing, based on their relatively low melting temperatures and low thermal conductivity (Gibson et al. (2015)). ABS is the material of the Lego bricks and is mainly used in household consumer goods. It consists of 15% -35% acrylonitrile, 5% -30% butadiene and 40% -60% styrene.

1.3. The Taguchi approach

The main goal of the Taguchi's robust design method is to improve quality of manufactured goods by using design of experiments (DOE), that is based on a loss function. Through this method the importance of each experimental parameter, or else factor, is revealed and at the same time the number of experiments is reduced. As an optimization method, aims on minimizing a loss function. According to Taguchi, the goal is to minimize the variability in the product's performance in response to noise factors, while maximizing the variability in response to signal factors. Noise factors are those that are not under the control of the operator of a product, while signal factors are set or controlled by the operator. Thus, the factors in the experiment represent control factors. Concluding, the quality can be quantified based on noise and signal factors and efforts must be made to maximize the signal-to-noise ratio. (Taguchi et al. (2005)). The methodology uses specific arrays, Taguchi's orthogonal arrays (OA), based on the selected factors in accordance with their levels.

2. The experimental protocol

In this work, a novel approach is presented, as a first step, towards how parts can be manufactured (printed) to achieve improved mechanical properties, by using affordable 3D printers. The methodology is based on an experimental procedure through which the optimum combination of manufacturing parameters and their values can be obtained, in order to achieve the goal. Importantly, a prediction of the optimum solution can be achieved. The Taguchi methodology was selected as an optimization tool, towards the goal of improving the part's mechanical properties.

2.1. CAD model

For all experiments a square cross section part (8 mm x 8 mm) was created within the boundaries of 3D solid CAD modeler. The length of each specimen was set to 12 mm based on the used tensile machine.

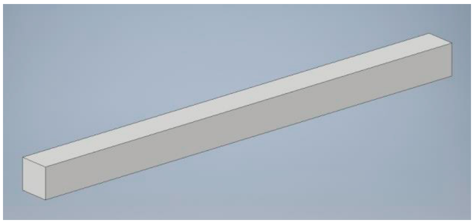

Fig. 1. CAD model of specimen.

2.2. The manufacturing parameters

Before creating the physical models, the manufacturing parameters (factors) of the AM process must be set. The layer thickness that can be achieved by the 3D printer, is the first factor, defining the dimension between every two consecutive layers of printed material. Next, is the infill printing pattern that defines the path of the nozzle. Thus, how the material will be placed within the shell that describe the manufactured part. The amount of the infill material used to build the pattern is the next factor. Finally, the placement of the produced physical part on the plate of the printer completes the selection of the manufacturing parameters, hence the factors. The levels of each factor are presented in Table 1.

Table 1. Manufacturing parameters.

Parameter	Level 1	Level 2	Level 3
Layer thickness (μm) – Factor 1	70	200	300
Printing pattern – Factor 2	Cross	Diamond	Honeycomb
Print strength – Factor 3	Hollow	Strong	Solid
Placement – Factor 4	Horizontally	Perpendicular	45°

2.3. Design of experiments

According to Taguchi's approach based on the selected parameters (Factors) the appropriate orthogonal array is L9. The selected factors are four with three levels each. Thus, the proposed experiments by the methodology are described in Table 2.

2.4. Experiments

After producing the 3D printed specimens, monoaxial tensile tests were carried out with the aid of a Galdabini QUASAR 100 tensile apparatus. The experiments were performed according to the ASTM D3039 (Forster (2015)), the strain rate was constant (0.1 sec^{-1}) and all specimens were prismatic with a rectangular cross section. Following the mechanical tests, the fracture surfaces of all specimens were investigated with the aid of a Siemens Stereoscope in order to find out the fracture mechanism of the 3D specimens (Fig.2). The above curves are the mean curves of three independent experiments.

Table 2. L9 orthogonal array.

Experiment	Factor 1 (*μm*)	Factor 2	Factor 3	Factor 4
1st	70	cross	hollow	horizontal
2nd	70	diamond	strong	perpendicular
3rd	70	honeycomb	solid	45°
4th	200	cross	strong	45°
5th	200	diamond	solid	horizontal
6th	200	honeycomb	hollow	perpendicular
7th	300	cross	solid	perpendicular
8th	300	diamond	hollow	45°0
9th	300	honeycomb	strong	horizontal

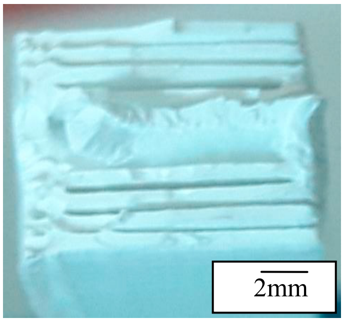

Fig. 2. Specimen 3 after tensile test.

3. Results and conclusions

As it is observed from the fracture surface of the specimen (Fig.2), the main factor that leaded to the fracture was the plastic deformation of the layer material that occurred due to the higher applied load than the ultimate tensile strength (UTS) of the layer. In addition to that there are signs of delamination between the layers. The applied load was shear on the layers' interface and leaded to the failure of the adhesion bonding of them. Fig.3 depicts the true stress-strain diagrams of all 3D printed specimens for the same strain rate $10^{-1}sec^{-1}$. All specimens showed a small amount of plasticity (8% max) and various values of UTS, depending on the printing factors combination. Specimen 1 exhibits the greatest value of plasticity among all the specimens. According to the Signal-to-Noise and Means diagrams (Fig.4, Fig.5) of the conducted study, the factors' significance according to their influence on the mechanical properties of the specimens is ordered as follows: Layer thickness > Print strength > Print pattern > Placement. Instead of eighty-one (81) experiments that were assumed to be required, only nine (9) experiments needed to be conducted, due to the Taguchi methodology implementation. A Larger-is-better strategy of Signal-to-Noise ratio was selected to maximize the response of tensile strength as the goal. The optimum combination of the manufacturing parameters resulting to the specimen with the highest UTS was the following:

- Layer thickness: 70μm
- Print strength: Solid
- Print pattern: Honeycomb
- Placement of specimen on table: 45°

Regarding the mechanical behavior of the 3D printed specimens, due to the various printing parameters it was found that the maximum UTS was about 18 MPa (Experiment 3) in addition to the fact that all specimens were plastically deformed before their fracture.

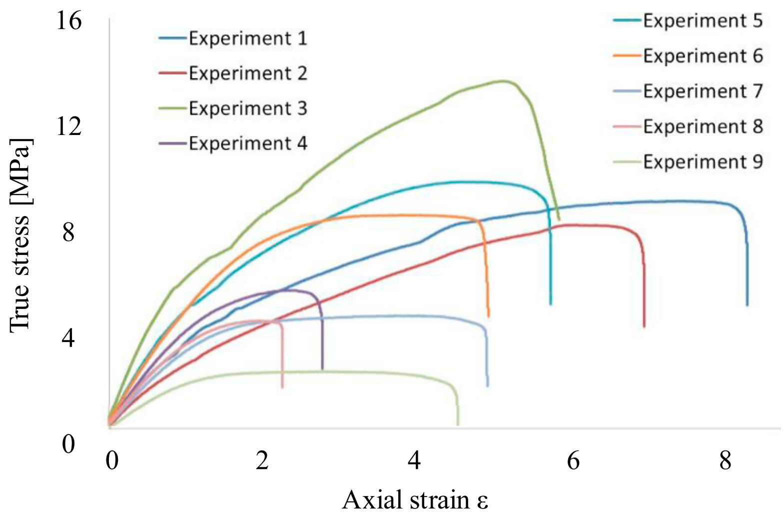

Fig. 3. Stress-Strain diagrams.

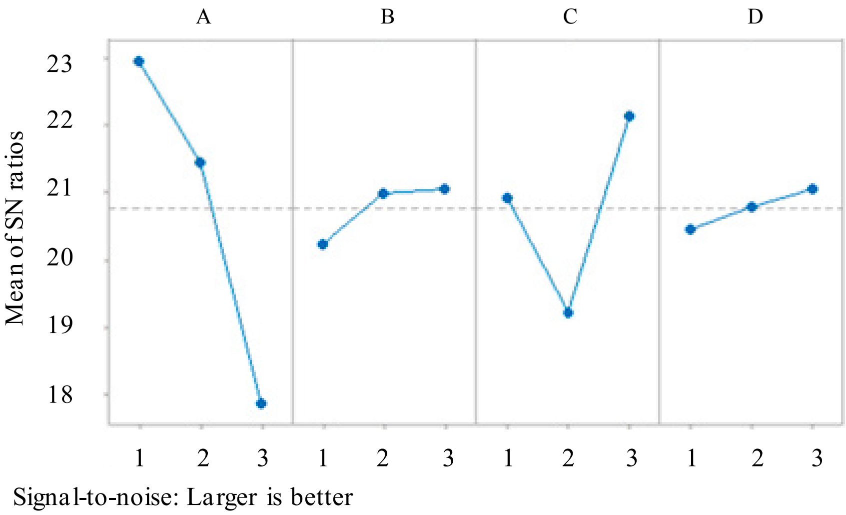

Fig. 4. Signal to noise ratio diagrams.

A first look on the methodology, reveals an expected behavior, based on the results. But a deeper view on it, could start revealing the complexity of the relation among the printing parameters, set before the manufacturing process, and the mechanical properties of the printed part. *Layer thickness* and *print strength* are the two most important factors that influence the maximum UTS.

There are many factors that influence the behavior of AM parts, for example nozzle speed and temperature or humidity while manufacturing or storing the material. In this work these factors were limited to four, aiming at investigating the possibility of creating parts with similar mechanical properties by using different AM parameters. Based on the findings, it is clear that the printing parameters have a great effect on the mechanical properties of the produced specimens. All UTS values are between 7 and 18 MPa and the elongation starts from approximately 2% and raise little above 8%. Specimens in experiment 3 along with the 1^{st} and 2^{nd}, produce 18 MPa, 13 MPa and 12 MPa respectively as the maximum UTS, even though the value of factor 1 (Layer thickness) is the same, 70μm. On the other hand, the print strength (factor 3) is set to solid on experiments 5 and 7, giving the maximum UTS 13.7 MPa and 8.6 MPa respectively. Thus, on one hand and based on the most important factors (one and three), there is not a straight forward choice and relation in calculating the mechanical properties. However through the proposed metho-

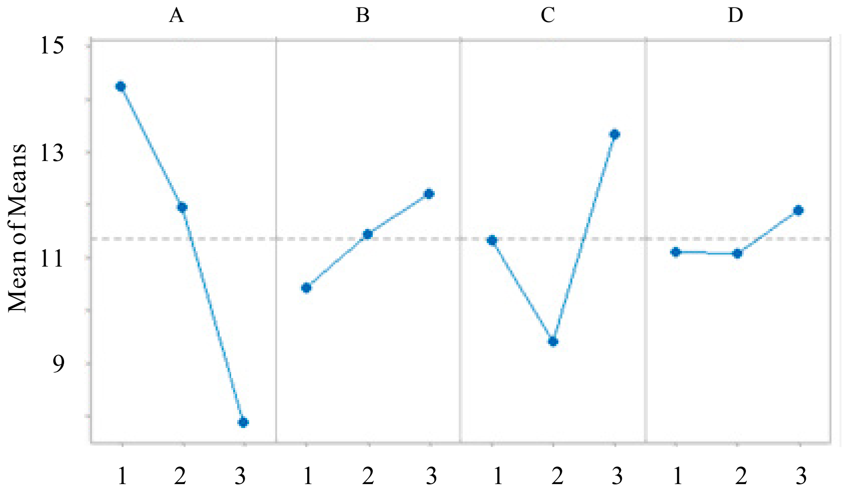

Fig. 5. Means diagrams.

dology the results can be tuned to control the UTS value. On another point of view and by comparing sets of experiments 1 and 5, or 1 and 2 we can see the similar UTS each time. The UTS are very close, although the printing parameters are very different. Subsequently a goal can be set on the UTS value and by following different set of parameters, the printing time or even the weight of the produced part, can be optimized according to part's usage limitations.

Hence, the presented methodology can be used as a pre-processing approach tool, aiming to optimize any part's mechanical properties according to its use.

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