Optimization of process variables to improve the mechanical properties of FDM structures

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Abstract. This paper presents, the experimental methodology to optimize the process variable for Fused deposition modeling (FDM) fabricated parts. Process variable plays an important role to influence the mechanical and physical properties of a component. In this study, 3 important process variables, i.e., layer thickness, infill percentage, and print speed were considered to carry out their effect on Tensile and compressive strength of ABS (Acrylonitrile Butadiene Styrene) fabricated specimens. The experiments process based on Design of experiment (DOE) methodology. The recent studies only focused one process variable at a time, and its effect on mechanical properties of FDM processed part. But the present study gives an insight into 3 process variable influence on the FDM manufactured components. Obtained results were analyzed by the DOE and optimization techniques. The experimental results highlighted that, out of the 3-process variable, layer thickness and infill percentage have a major impact on the mechanical properties of FDM structures. The remaining one process variable has less influencing characteristics, but it comes into effect in a certain domain. The results give the functional relationship between process variables and the mechanical properties of the component. This study shows very promising results to enhance the strength of a part fabricated by using FDM technology.

1. Introduction

Additive manufacturing is a technique through which 3D complex objects can be created by the deposition of a material layer by layer. This technology has found enormous applications in commercial aerospace, defense, automation, consumer product retails, health care, etc. Due to its advanced research in processing technology and materials. But still, there are many challenges which need to be addressed to achieve desired physical and mechanical properties. Some of these challenges are the material that can be used as there are limited material options available. Thus necessity the demand for new materials, the need for an increase in dimensional accuracy and repeatability of part production through adequate analysis. Rapid prototyping technologies [1][2] are characterized dependent on the introductory type of its material, i.e., the base material of model and part to be fabricated. The rapid prototyping technologies
are characterized into 3 classifications, i.e., Solid, liquid and powder-based Rapid prototyping. Fused deposition modeling (FDM) is one such solid-based rapid prototyping system in which a part is fabricated by deposition of a thermoplastic material layer by layer.

Many research studies have been done on FDM processed parts. Godfrey C. Onwubolu et al. [3] study revealed that to improve tensile strength the parameter should be, a minimum layer thickness, Negative air gap, minimum raster width, zero-part orientation, increased raster angle was favorable. For maximum tensile strength data obtained from experiments were part orientation zero, raster angle and raster width was maximized with a negative air gap, the part orientation of 9.05°. Farzad Rayegani et al. [4] developed a relationship between tensile strength and process parameters by using the group method. The process parameter included were air gap, raster angle, layer thickness, raster width, and orientation. The results revealed that to improve tensile strength desired parameters be a negative air gap, smaller raster widths, large raster angle. For maximum tensile strength the experimental parameter that was favorable include, a negative air gap of 0.0025", raster width of 0.2034", raster angle of 50°. Ala’aldin Alafaghani et al. [5] investigated that the more influencing parameter for dimensional accuracy was layer height, building direction and extrusion temperature rather than printing speed, infill percentage and infill pattern. The mechanical properties were more prone to layer height, extrusion temperature, and building direction and less prone to printing speed infill percentage specimens and infill pattern. To increase the mechanical properties, more considerable layer height and higher extrusion temperature were fixed. The larger specimens should be made with lower infill percentages to impart more room for the infill patterns. C.A. Griffiths et al. [6] used the Design of experiments approach to analyze the effects of different build parameters. The authors concluded that to increase the tensile property number of shells and infill level needs to be maximized. For optimizing the efficiency outputs, lowest levels of infill, a smaller number of shells and maximum layer height should be used. J.M. Chacón et al. [7] in their study found that for minimum printing time high feed rate and high layer thickness were recommended. Their parameter selection leads to a situation of reducing in stiffness and strength and more brittle behavior. Michael Montero et al. [8] analyzed ABS parts fabricated by the FDM for tensile loading. They concluded that for build part load was carried axially along the fibers in order to reduce the stress concentration along radius area. To increase the stiffness and strength, a negative air gap should be used. Further study concluded that the temperature and bead width do not contribute to influence strength. J. Santhakumar et al. [9] conducted for polycarbonate material using Taguchi’s method. Their study revealed that for FDM build parts to change the control in length, significant of layer thickness is more, similarly to change the control in width significant of build orientation is more. Mohammad Shojib Hossain et al. [10] performed a study for improvement of tensile mechanical properties of FDM manufactured parts by using visual feedback method, Insight revision method, Default method. These results were compared with default build parameters, and it pointed out that visual feedback method exhibited up to 19% increase in ultimate tensile strength.

In literature, the lack of experimental data, as well as the study of potential variables such as build material, infill, extruder temperature, and layer thickness, emphasize to study further the mechanical behavior and optimization of 3D printed components. This study aims to find out the functional relationship between different process variables and the mechanical properties of FDM processed ABS (Acrylonitrile Butadiene Styrene) specimen. This research also includes the Taguchi method of analysis and ANOVA test to carry out the experimental process.

2. Experimental methodology
2.1. 3D printers, specimen preparation, and materials
This research aims to analyze the mechanical properties of ABS samples. In this study, the commercial ABS filament of diameter 1.75 mm is used. The FDM printer used in this work is Flash forge 3D Dreamer. The FDM printer is compatible to print both ABS & PLA material. This FDM printer has a build volume measuring 9.1” x 5.9” x 5.5” and nozzle diameter of 0.4mm. Components are printed in
the XYZ orientation at the center of the build platform. The ABS samples were designed as per the ASTM standards. The parameters to be analyzed in this investigation were identified, based on the testing parameters available in ASTM standards, and suitable design of experiment method is adopted. The components are printed according to the experimental plan; measurement results are analyzed. The printing conditions which optimizes tensile strength and compressive strength of the printed component are also found based on the results obtained.

2.2. Process parameters
To start the experiment, the operation control parameter was selected from the literature review that was expected to affect the properties of the FDM part. The parameters were build orientation, the location of the part on the platform, layer thickness, deposition speed, support structure, raster gap, air gap, raster width, raster angle, fill pattern and infill percentage. From these parameters, we selected three parameters using literature, i.e. layer thickness, infill percentage, and print speed.

The design of experiment (DOE) is known for its through strategy towards process advancement. DOE is a statistical method that plans to give a prescient consequence of a complex multivariable activity with a couple of preliminaries. Under the DOE Taguchi strategy has been utilized. At a point when a substantial number of a parameter associated with an investigation, its end up complicated and laborious. For this Taguchi proposed a specially designed technique to lead a lesser number of trials for whole parameter space.

Table 1. Process parameters for sample preparation

| Layer thickness (mm) | 0.1 | 0.2 | 0.3 |
|----------------------|-----|-----|-----|
| Infill percentage    | 20  | 30  | 40  |
| Print speed (mm/sec) | 60  | 70  | 80  |

All nine benchmark parts were printed based on the design of experiment as shown in Table 2.

Table 2. Specification of the sample processing parameter

| Sample | Layer thickness | Infill % | Print Speed (mm/sec) |
|--------|-----------------|----------|----------------------|
| 1      | 0.1             | 20       | 60                   |
| 2      | 0.1             | 30       | 70                   |
| 3      | 0.1             | 40       | 80                   |
| 4      | 0.2             | 20       | 70                   |
| 5      | 0.2             | 30       | 80                   |
| 6      | 0.2             | 40       | 60                   |
| 7      | 0.3             | 20       | 80                   |
| 8      | 0.3             | 30       | 60                   |
| 9      | 0.3             | 40       | 70                   |

2.3. Experimental set-up
To start the experiment, samples are built on the FDM machine as per DOE data (Table 2).

2.3.1. Tensile Strength Test. The tensile test was executed as per the ASTM D638 standards. ‘FIE’ Universal Testing Machine series Unitek 9400 was utilized for the testing. The loading rate was fixed at 5 mm/min. The test samples were fabricated as per the ASTM D638, type 4 standard. The Figure 1,2 & 3 shows the tensile test specimen and experimental setup.
The test for tensile strength was followed as per ASTM standards. The material used for fabrication is ABS. The Universal testing machine was compatible with polymer materials. The results obtained were compared and analysed with standard polymer data sheet.

Figure 1. ASTM D638 type 4 (unit-mm)

Figure 2. Specimen for tensile test
2.3.2. Compressive Strength Test. The compression test [11] was executed as per ASTM D695 standards. 'FIE' Universal Testing Machine series Unitek 9400, a loading rate of 1.3 mm/min was utilized for the testing. The standard test specimen was in the form of a prism whose length was twice its principal width. Preferred specimen sizes were 12.7 x 12.7 x 25.4 mm.

3. Results & Discussion-

The results obtained through the experimental process were analyzed with the help of ANOVA test. The Tensile and compressive strength values for the specimen based on the Taguchi experimental layout is shown in Table 3.
Table 3. Results obtained through the experimental procedure

| Sample | Layer thickness | Infill % | Print Speed | Compressive Strength (Mpa) | Tensile Strength (Mpa) |
|--------|----------------|----------|-------------|---------------------------|------------------------|
| 1      | 0.1            | 20       | 60          | 33                        | 26                     |
| 2      | 0.1            | 30       | 70          | 34                        | 28                     |
| 3      | 0.1            | 40       | 80          | 39                        | 30                     |
| 4      | 0.2            | 20       | 70          | 34                        | 23                     |
| 5      | 0.2            | 30       | 80          | 37                        | 24                     |
| 6      | 0.2            | 40       | 60          | 40                        | 27                     |
| 7      | 0.3            | 20       | 80          | 36                        | 18                     |
| 8      | 0.3            | 30       | 60          | 40                        | 20                     |
| 9      | 0.3            | 40       | 70          | 42                        | 23                     |

Figure 7. Tensile strength plot for ABS sample

Figure 8. Compressive strength plot for ABS sample
3.1. Effect of layer thickness

As we see from Figure 6, the highest Tensile strength, i.e., 30 MPa occurs for the minimum layer thickness, i.e., 0.1mm. And lowest Tensile strength, i.e., 18 MPa occurs for the maximum layer thickness, i.e., 0.3 mm. Primarily reason for tensile test failure is principal stress. Since a low value of layer thickness imparts more compact specimen. Layers are closely deposited over each other. This help in better bonding between the layers. It results in an increase of tensile strength. In the same way, a higher value of layer thickness, affect the compactness of the specimen. Now the layers are not closely overlapped over each other. This leads to a loss in tensile strength.

![Main Effects Plot for Tensile Strength(Mpa)](image)

**Figure 9.** Main effects plot for tensile strength

From the Figure 8, It is clearly visible that the optimum values for maximum tensile strength are layer thickness (0.1mm), infill % (40%) and print speed (70 mm/sec).

As we see from the graph, the highest compressive strength, i.e., 42 MPa occurs for the maximum layer thickness, i.e., 0.3mm. And lowest compressive strength, i.e., 33 MPa occurs for the minimum layer thickness, i.e., 0.1 mm. Primarily reason for compressive test failure is shear stress. Shear stress causes the layers to slide over each other until the specimen finally fails. A reduction in thickness of layer gives more number of layers in a specimen. This increase in the number of layers is more prone to sliding of layers due to shear stress and ultimately compressive strength decreases. A higher thickness decreases the number of the layer in a specimen. It leads the specimen less sensitive towards shear failure. This finally helps in increased compressive strength.

Figure 9 below shows that the optimum values for maximum compressive strength are layer thickness (0.3mm), infill % (40%) and print speed (60 mm/sec).
Figure 10. Main effects plot for compressive strength

3.2. Effect of Infill percentage

As the infill percentage increases, the specimen becomes more solid in structure. It increases the tensile and compressive strength of the specimen. From Figure 8 & Figure 9, it is visible that maximum Tensile strength occurs at 40% infill.

3.3. Effect of Print speed

In this experiment, print speed is not directly affecting the tensile strength and compressive strength of the specimen as compared to layer thickness and infill percentage. But it plays a significant role when it is out of the certain limit. More increase in print speed cause vibration on a machine which prompts relocation of layers and finally fabrication of the non-uniform specimen.

As the print speed decreases beyond a specific limit, it gives more time to solidify a layer. Now the newly formed layer deposited on a previously formed layer doesn't have much bonding between them. It results in less tensile and compressive strength of the specimen.

4. Conclusion

In this Research, optimization of process variables on mechanical properties, i.e., tensile strength and compressive strength of FDM processed ABS specimen has been done using Taguchi's method of analysis. The process variables included in this study affect the tensile and compressive strength of the specimen.

Following conclusion were obtained from this research

1. Tensile strength has an inverse relationship with layer thickness, i.e., as the layer thickness increase tensile strength decreases.
2. Compressive strength has a direct relationship with layer thickness, i.e., as the layer thickness increase compressive strength increases.
3. Increase in Infill percentage gives the significant result to improve both tensile and compressive strength. Although it is more expensive as the consumption of material is high.

4. Experimental study shows that print speed is less significant as compared to the other two process variable. But its role comes into existence for very high and low-speed value. It affects the vibration produced in the machine during fabrication and time for solidification of material through the nozzle. This finally influences the strength of FDM processed part.

5. The optimized parameters found from the study has 0.2 mm layer thickness, 30 percentage infill & 80 mm/sec print speed. The fabricated specimen from these optimized parameters shows great improvement in mechanical behaviour for both tensile and compressive strength. It also shows a significant reduce in time and material used for fabrication.

Applying the above outcomes, the strength and reliability of FDM processed components can be enhanced. This study also helps in to give insight on the significant level of above-mentioned process variables.

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