**Effect of Process Parameters on Mechanical Property of 3D Printed TPU Parts**

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**ABSTRACT**

In this new era weight reduction is the primary concern of almost all manufacturing industries. In Addition to the weight reduction the mechanical strength will not be comprised leads to the evolution of optimisation of existing parts. For designing the complex parts 3D-printing is used as the manufacturing technique. In this study, the mechanical properties of Thermoplastic Polyurethane (TPU) polymer are tested for different printing parameters such as temperature for printing, Infill pattern, Layer thickness and Infill density. The Taguchi Design of Experiment is used to optimize the mechanical properties. The maximum tensile strength is obtained at temperature for printing of 215 0C, infill density of 40%, Layer thickness of 0.2mm and LINES infill pattern which is 20.77 MPa. Also, the maximum compressive strength is obtained at temperature for printing of 205 0C, infill density of 60%, Layer thickness of 0.2mm and CROSS infill pattern which is 1.249 MPa. The train, testing and validation of data is done by using ANFIS (Adaptive Neuro-Fuzzy Inference System). ANFIS model is successfully able to predict the Output based on new input parameters with error of 2.70% for Tensile test and less than 1% for Compression test.

**Keywords:** 3D-printing, Fused Deposition Modelling, Process parameter, Optimization, Taguchi method, TPU filament, ANFIS.

**1. INTRODUCTION**

In today’s world engineering has played a crucial role, various manufacturing techniques have evolved recently which has transformed the way of designing the complex geometries. One kind is Fused Deposition Modelling (FDM) under 3D-printing. FDM technique is a material extrusion process which deposit material layer by layer. 3D-printing technique allows to print complex geometries which will not be manufactured by other traditional techniques. FDM is a widely used technique in such cases because it is economical and does not generate waste.

3D-printing has wide applications in aerospace, automobile and medical industries.

Optimization is a technique to designing optimized structures in such a way by minimizing the weight or volume of the material and therefore, maximizing its strength and durability. Optimization has various applications including automobile and aerospace. It has the potential to create light weight structures leading to increase in the efficiency and performance of the product.

The application of 3D-printed material in medical field [1-2] and 3D-printed organs as well as improving surgical implants are new area of research [3]. The major drawback of 3D-printed parts includes wear and tear after long use [4]. The footwear application of 3D printed parts is also emerging in this new era [5-6]. Automotive industry has also researched on alternative material for vehicle parts [7].

Compression testing is a new method which can be a new area of research. In compression testing a 3-D printed specimen is subjected to axial compressive loads to measure how much load the specimen can withstand. The result generated is very valuable for understanding the behaviour of the material with different lattice designs subjected to compression. In research paper [8] the structures used are honeycomb and gyroid. It was concluded that honeycomb structures have advanced mechanical properties and energy absorption than gyroid structures.

In research paper [9] it was concluded that TPU strength is directly proportional to its density of the infill. It was observed that, with increase in the infill it was seen that the absorption energy will improve.

In research paper [10] TPU cores in sandwich results higher energy absorption and greater ultimate elongation and impact strength with lower flexural and tensile strength then PLA cores.

In research paper [11] higher temperature for printing shows formation of micro voids and foam also increase in temperature can lead to lower compressive deformation and higher compressive strength in 3D-printed 3-pointed star shape using TPU.

In research paper [12-14] the ANFIS model was created to determine that tensile strength was influenced more by temperature of extrusion as compared to the consecutive distance between the layers/layer thickness. The more the temperature of extrusion the more will be the tensile strength.

**2. MATERIALS AND METHODS**

## **2.1 Material**

The material used in this study was the lightweight (LW) thermoplastic polyurethane (TPU) Company Name eSUN Flexible filament 95A Manufactured by: Shenzhen eSUN Industrial Co., Ltd, as shown in Fig 1.



**Fig. 1:** Printing Spool

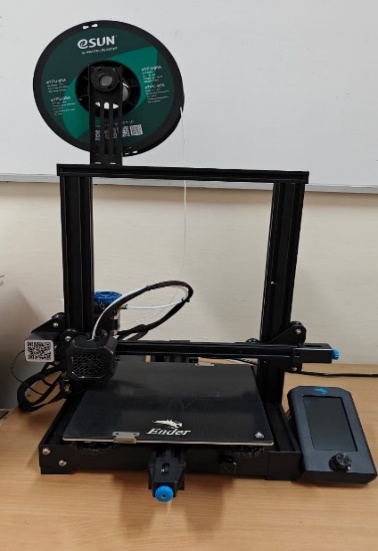
The diameter of material is 1.75 mm and the mechanical properties given by the manufacture are detailed in Table 1.

**Table 1:** Properties of TPU material

|  |  |  |
| --- | --- | --- |
| **Performance** | **Parameters** | **Unit** |
| Temperature for printing | 205- 240 | 0C |
| Temperature of Bed | 45-60 | 0C |
| Speed of Printing | 20- 50 | mm/s |
| Fan speed | 100 | % |
| Density | 1.21 | g/cm3 |
| Elasticity | 26 | MPa |
| Melt Flow index | 1.2(190 C/2.16 kg) | g/10 min |
| Tensile strength | 35 | MPa |
| Elongation at break | 800 | % |

## **2.2 3D-Printing Machine**

The Printer used in this study was the Ender 3 V2 of Creality 3D. The printing machine based on FDM (Fused Deposition Modelling) in as shown in Fig. 2. The printer consists of 3 stepper motors to get motion along X, Y and Z axes.



**Fig. 2:** 3D printing machine

## **2.3 3D-printing parameters and printer settings**

There are different parameters which are to be set before printing the parts on the printer. In this study the parameters which were used mainly involve temperature for printing, infill density, layer thickness and infill pattern. These various parameters are being selected based on the previously conducted studies and researches as shown in the Table-2.

In this study the first parameter is infill density which was varied from 20 to 60 percent. Infill density can be varied from 0% to 100%. At 0% infill density the part will be a hollow shape with top and bottom faces only while at 100 % the part will be entirely a solid.

The second parameter is the temperature for printing. The temperature for printing is recommended by the manufacturer which involves the temperature range of the TPU material which is to be used to print the material. Therefore, the temperature was in the given range of 205 0C - 225 0C. The temperature for printing is that temperature of the material at which it will get melted and gets extruded from the extruder to create the part.

The third parameter is the layer thickness. The thickness of layer was set from 0.1 - 0.15 mm as it is mentioned in the data collected by literature review. Layer thickness refers to the vertical distance between the two consecutive layers of the printed object using FDM.

The fourth parameter which is the infill pattern. There are different kinds of infill patterns available but we mainly used the LINES, GRID and the CROSS structure. The slicing is done using the UltiMaker Cura software. Infill pattern is the structure inside the object we want to print.

**Table-2:** Printing Parameters

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameters** | **Levels** | | |
| **1** | **2** | **3** |
| Temperature for printing (oC) | 205 | 215 | 225 |
| Infill density (%) | 20 | 40 | 60 |
| Layer thickness (mm) | 0.10 | 0.15 | 0.20 |
| Infill pattern type | LINES | GRID | CROSS |

## **2.4** **Design of Experiment (DOE)**

Design of Experiments (DOE) serves as a systematic approach to understand the correlation between input factors and output responses. Taguchi's method, specifically, prioritizes enhancing product efficiency and minimizing process expenses. Its versatility allows for effective application in both processes’ future endeavours. In this project, we leverage the Taguchi technique to uncover the relationships between variables which are and corresponding outputs, aiming to improve understanding and optimize outcomes. L9 is used to optimize the input parameter.

**Table-3:** Design of Experiment

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Exp. No.** | **Printing Temperature**  **( 0C )** | **Infill Density**  **(%)** | **Layer Thickness** **(mm)** | **Infill Pattern** **Type** |
| 1 | 205 | 20 | 0.1 | Lines |
| 2 | 205 | 40 | 0.15 | Grid |
| 3 | 205 | 60 | 0.2 | Cross |
| 4 | 215 | 20 | 0.1 | Cross |
| 5 | 215 | 40 | 0.15 | Lines |
| 6 | 215 | 60 | 0.2 | Grid |
| 7 | 225 | 20 | 0.1 | Grid |
| 8 | 225 | 40 | 0.15 | Cross |
| 9 | 225 | 60 | 0.2 | Lines |

## **2.5 Sample Preparation**

Tensile test samples are meticulously crafted in accordance with the ASTM D638 standard, as illustrated at Figure 3.

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| **Fig. 3:** ASTM 638 type IV specimen drawing |

# **3 RESULTS AND DISCUSSIONS**

## **3.1 Tensile Testing**

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| **Fig. 4:** Universal Testing Machine (UTM) | **Fig. 5:** Tensiletest specimen |

From the tensile testing as shown in Table-4, the maximum value of tensile strength is 20.77MPa at temperature for printing of 215 0C, Density of structural geometry 40%, consecutive distance between adjacent layers of 0.2 mm and infill pattern as LINES. The tensile strength value increases as the temperature for printing increases from 205 0C-225 0C. The infill pattern LINES depicts the maximum value of tensile strength in almost all specimens. The consecutive distance between adjacent layers and density of structural geometry does not depict any trends and further requires more investigation.

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| --- | --- | --- | --- | --- | --- | --- |
| **Exp. No.** | **Printing Temperature**  **( 0C )** | **Infill Density**  **(%)** | **Layer Thickness**  **(mm)** | **Infill Pattern** **Type** | **Tensile Strength**  **(MPa)** | **Normalised Value**  **(KN/mm2)** |
| 1 | 205 | 20 | 0.1 | Lines | 14.375 | 0.37 |
| 2 | 205 | 40 | 0.15 | Grid | 18.0375 | 0.73 |
| 3 | 205 | 60 | 0.2 | Cross | 10.5875 | 0.00 |
| 4 | 215 | 20 | 0.15 | Cross | 14.9375 | 0.43 |
| 5 | 215 | 40 | 0.2 | Lines | 20.77 | 1.00 |
| 6 | 215 | 60 | 0.1 | Grid | 12.4875 | 0.19 |
| 7 | 225 | 20 | 0.2 | Grid | 11.6 | 0.10 |
| 8 | 225 | 40 | 0.1 | Cross | 10.9541 | 0.04 |
| 9 | 225 | 60 | 0.15 | Lines | 20.6875 | 0.99 |

**Table-4:** Tensile Test Data

## **3.2 Compression Testing**

From the Compression testing as shown in Table-5, it is seen that the Compressive strength is dependent on infill density. The maximum value of compressive strength obtained is 1.249 MPa at temperature for printing 205 0C, infill density 60%, consecutive distance between adjacent layer 0.2mm and infill pattern CROSS. Similarly on increasing the infill density from 20% to 60% the compressive strength increases.

**Table-5:** Compressive Test Data

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| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Exp. No.** | **Printing Temperature**  **( 0C )** | **Infill Density**  **(%)** | **Layer Thickness**  **(mm)** | **Infill Pattern** **Type** | **Peak Force**  **(N)** | **Displacement**  **(mm)** | **Compressive Strength**  **(MPa)** | **Normalised data**  **(KN/mm2)** |
| 1 | 205 | 20 | 0.1 | LINES | 9.24 | 1.3 | 0.057 | 0.00 |
| 2 | 205 | 40 | 0.15 | GRID | 25.02 | 2.5 | 0.155 | 0.08 |
| 3 | 205 | 60 | 0.2 | CROSS | 201.52 | 9.1 | 1.249 | 1.00 |
| 4 | 215 | 20 | 0.15 | CROSS | 11.44 | 1.8 | 0.071 | 0.01 |
| 5 | 215 | 40 | 0.2 | LINES | 25.36 | 2 | 0.157 | 0.08 |
| 6 | 215 | 60 | 0.1 | GRID | 200.56 | 8.5 | 1.243 | 0.99 |
| 7 | 225 | 20 | 0.2 | GRID | 11.8 | 2.1 | 0.073 | 0.01 |
| 8 | 225 | 40 | 0.1 | CROSS | 14.9 | 1.9 | 0.092 | 0.03 |
| 9 | 225 | 60 | 0.15 | LINES | 49.32 | 3.6 | 0.306 | 0.21 |

**3.3 ANFIS network interpretation**

For designing the ANFIS model, the data obtained from testing are used for training, testing, validation. Sugeno-type fuzzy inference system having one linear output function and four input parameters are used. The tensile/compressive strength are used as output whereas temperature for printing, infill density, layer thickness and infill pattern.

**3.4 Training and testing in ANFIS**

Grid partitioning Fuzzy inference system is generated. In the ANFIS Training we have used Normalised data for the training of model. This algorithm combines both least square and back propagation mechanism. The data set inform of table is loaded and output is obtained at 10 epochs is depicted in figure 6 for tensile and figure 18 for compression. The ANFIS layout is represented in figure 7 for tensile and figure 19 for compression. The output model is shown in figures figure 8 for tensile and figure 20 below and different rules used for model is shown in figure 9 and figure 21. The error obtained in Testing for generated FIS is 2.70% for tensile and less than 1% for compression.

**3.5** **Validation in ANFIS**

Grid partitioning Fuzzy inference system is generated. In the ANFIS Training we have used Normalised data for the training of model. This algorithm combines both least square and back propagation mechanism. The data set inform of table is loaded and output is obtained at 10 epochs is depicted in figures. The ANFIS layout is represented in figure. The output model is shown in figures below and different rules used for model is shown in figure. The error obtained in Testing for generated FIS is 2.70% for tensile and less than 1% for compression and shown in figures. Also, the surface plot between the output and input is depicted in figures.

## **3.6 Algorithm for tensile and compression Testing**

This algorithm provides the optimized values of the parameters which have been taken as an input, i.e. temperature for printing, density of structural geometry, layer thickness, infill pattern, tensile and compression strength.

Tensile and compressive strength values were provided by the UTM machine. The data for training, testing and checking are provided as an input for the ANFIS software. The training error is 70% of the total data while the testing error is 30% of the total data and the checking data is only one data set. Changes are made in the membership functions using the fuzzy logic toolbox.

**3.7 ANFIS network implementation**

ANFIS is a tool in MATLAB in which the training data is loaded and it is tested. The membership functions are set between the input and the output values. Then the testing and checking data is loaded and tested. Error is measured as the difference between the squared output and input. ANFIS uses least squared method along with back propagation for the evaluation of membership function.

**3.8 ANFIS involves five layers for the authentication of model:**

1st layer: It is the layer which contains the inputs and estimates the values of membership functions. Therefore, this layer is called as fuzzification layer.

2nd layer: This layer is the Rule Layer which develops the firing strength of each rule using the various operator.

3rd layer: This layer involves the normalization of the firing strength.

4th layer: These normalized values are taken as the input for the fourth layer and the defuzzification of these values are given as an output for the next layer.

5th layer: The final layer is the output layer.

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| **Fig. 6:** Training of tensile data | **Fig. 7:** Fuzzy logic designer layout for tensile | |
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| **Fig. 8:** ANFIS model structure for tensile testing. | | **Fig. 9:** Rules for tensile testing. |

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| **Fig. 10:** Testing of tensile data | **Fig. 11:** Checking of tensile data. |

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| **Fig. 12:** 3-D contour between temperature, layer thickness and tensile strength. | **Fig. 13:** 3-D contour between temperature, infill pattern and tensile strength. |

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| **Fig. 14:** 3-D contour between layer thickness, infill density and tensile strength. | | | **Fig. 15:** 3-D contour between infill pattern, infill density and tensile strength |
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| **Fig. 16:** 3-D contour between layer thickness, infill pattern and tensile strength. | | **Fig. 17:** 3-D contour between layer thickness, infill pattern and tensile strength. | |
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| **Fig. 18:** Training of compression data. | **Fig. 19:** Fuzzy logic designer layout for compression. | | |

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| **Fig. 20:** ANFIS model structure for compression testing. | **Fig. 21:** Rules for compression testing. |

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| **Fig. 22:** Testing for compression data. | **Fig. 23:** Checking data for compression testing. |

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| **Fig. 24:** 3-D contour between temperature, infill density and compressive strength. | **Fig. 25:** 3-D contour between temperature, infill pattern and tensile strength. |

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| **Fig. 26:** 3-D contour between layer thickness, infill density and compressive strength. | **Fig. 27:** 3-D contour between layer thickness, infill pattern and compressive strength. |

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| **Fig. 29:** 3-D contour between infill density, infill pattern and compressive strength. |

# **CONCLUSION**

This research paper investigated the influence of process parameters (temperature for printing, infill density, layer thickness and infill pattern) on the mechanical behaviour of 3D-printed TPU (Thermoplastic polyurethane).

* From the Tensile Testing it has been observed that on increasing temperature from 2050C - 2250C higher value of displacement is obtained. The temperature has more influence on the tensile strength of the printed parts.
* Infill density greatly influence the structural strength of the printed parts.
* The maximum value of tensile strength is obtained at 20.77MPa.
* Similarly, from Compression testing opposite results are obtained that on increasing temperature from 205 0C to 225 0C Lower value of compressive strength.
* On increasing Infill density from 20% to 60% higher value of compressive strength is obtained.
* The maximum value of compressive strength is obtained at 1.249MPa.
* The ANFIS used to generate the prediction model for the tensile and compressive strength specimens.

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