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Process Parameters Effect on the Tensile Strength of A Carbon Fiber PLA Part with FDM Printing

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ABSTRACT:

The most common method for swiftly creating complex parts using polymer additive manufacturing is fusion deposition modelling (FDM), which is gaining popularity in a variety of technical applications. Well selected process settings have a major impact on the mechanical properties of 3D printed objects. The process known as additive manufacturing (AM) was initially developed as a quick prototyping tool for design visualization and validation. FDM has encountered difficulties with making parts that end users can use. In this study, we examine the impact of layer thickness, filler density, and printing speed on the tensile properties of polylactic acid (PLA) samples. Taguchi's technique for experiment design is applied to decrease the number of experiments and identify the perfect conditions for the best mechanical properties, low weight, and rapid stress. The ideal process parameters for tear strength and modulus of elasticity were determined based on testing findings.

1. Introduction:

AM or 3D printing uses layers of materials and digital information to build structures. Because to growing global competition and changing consumer expectations, including a higher demand for customised items and shorter production times, AM has emerged in many technical and industrial industries as a feasible option to satisfy the aforementioned criteria. Environmental effects, material qualities, quality, energy usage, and recyclable content are among the selection criteria for each AM application. Each AM application has its own functionality indices and weights that represent various design goals. By generating parts in a single cycle, additive manufacturing (AM) technology has the potential to drastically reduce the waste of raw materials. Despite the fact that AM is an effective process, issues with material and printing equipment compatibility have made it challenging to implement on a large scale. The input process parameters have a big impact on the quality of the AM components. FDM is one of the most widely used and promising technologies because of its connection to desktop 3D printers, even though there are many commercially available AM processes for the production of parts, including Inkjet modelling, fused deposition modelling (FDM), stereo lithography (SLA), sheet lamination (LOM), etc. The FDM technology, which expedites machining, allows for the creation of complex forms out of lightweight materials. FDM, unlike many other AM techniques, uses a die to extrude a thermoplastic material that is semi-solid and uses a range of lasers, powders, and resins. A variety of thermoplastic polymer materials are melted using the FDM technique, as shown in Figure 1, and are then deposited using a die onto a build platform. Acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) are materials used to construct three-dimensional constructions (section). Layers of molten filament are placed to the build platform in accordance with the part's design after being delivered by feed rollers shaped like the required material. Recycling is made possible by FDM technology, which also helps to reduce waste and improve the environment. Figure 1 depicts a schematic of the manufacturing procedure for FDM parts. According to several authors, the build orientation significantly affects how durable FDM components are. AM recommended using an optimisation procedure to figure out the elastic modulus of the PLA model. Furthermore shown is a numerical relationship between the input variables layer thickness, filling rate, deposition rate, tensile strength, and interfacial bond strength controlled by heat transfer.

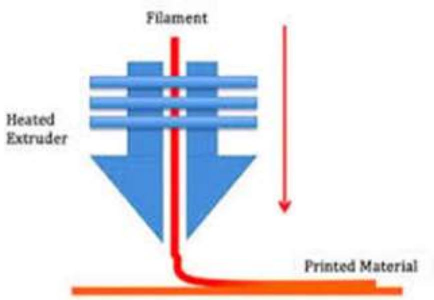

Figure 1: Fused Deposition Modelling Technique

The FDM technique is used to assess the mechanical characteristics of the manufactured items in order to assess how processing parameters impact experiment design. (DOE). The Taguchi process has shown to be the most effective technique for identifying the ideal processing parameters for producing high-quality and stable components. The literature has looked at Taguchi's method, central composite design (CCD), factorial design (FD), and other methodologies as potential tools to boost processing parameters for the FDM process. To guarantee that components made via 3D printing have appropriate functional qualities, it is essential to choose and optimise FDM production parameters.

2. Literature Review

[1] Using a Design of Experiment (DOE) methodology, The characteristics of ABS components made with Stratasys Fused Deposition Modeling are described in this paper. (FDM). The straightened samples' tensile and compressive strengths were assessed and contrasted with those of injection-molded FDM ABS P400. Several building principles were created based on the experiment findings. [2] in order to ascertain how extruded filament size and chemical composition impact the mechanical behaviour of fused deposition modelling (FDM)-based items made of acrylonitrile butadiene styrene. (ABS). CLT and the Tsai-Hill yield criterion can be used to evaluate in-plane stiffness and strength. Mechanical models may be calibrated using experimental data. [3] To dynamically estimate plating height (coating thickness) as a function of laser pulse strength, laser pulse frequency, and traverse speed, a neuro-fuzzy model is provided. The results are encouraging with a mere 0.07% absolute error. [4] Graphene oxide (GO) was hydrothermally reduced in a one-pot N-methyl-2-pyrrolidone (NMP) solution to create graphene-based epoxy composites with increased performance. Due to improved compatibility and interfacial contact between the epoxy matrix and NMPG, the tensile strength, Young's modulus, and storage modulus all showed improvements. The corresponding improvements are 28, 19, and 51%. The thermal stability of neat epoxy and its blends were assessed at weight losses of 5, 10, and 50%, temperature increases of 30, 27.5, and 29°C, and NMPG loading of 0.2% by weight. [5] When printing complicated designs utilising starting filaments from both commercial and non-commercial sources, FFF is a low-cost additive manufacturing (AM) technique. It has been demonstrated that filaments formed from nanocomposites have an advantage over microcomposites in terms of thermomechanical characteristics. [6] Fused deposition modelling is a tried-and-true method for making beautiful and useful objects, but its predictability and attainable roughness are constrained. Recently, a brand-new characterisation technique that can capture every aspect of roughness was created. It is founded on a geometric roughness profile theoretical prediction. [7] The maximum tensile and flexural strengths are maintained while the optimal design factor levels are determined through GRA optimisation. For each combination, the grey relational grade (GRG) was determined using ANOVA. According to the confirmatory experiments, the regression analysis' findings concur with the test results. [8] FFF is a potential additive manufacturing (AM) method for producing thermoplastic components because of its effectiveness. Its benefits include design flexibility, recyclability, and minimum material waste. This study examined the effects of adding graphene nanosheets on the structural integrity, dimensional stability, and surface texture of desktop 3D-printed polylactic acid (PLA) designs. The outcomes demonstrated that the PLA-graphene composite samples performed well in terms of flexural and tensile stress, interlinear shear strength, impact strength, and surface roughness. [9] The mechanical characteristics of 3D additive printing materials such PETG, PLA, ABS, ABS+, PLA ESD, ASA, and PC/ABS are examined in this article. It discovered precise parameters for every additive model and created samples for testing with the original Prusa MK3 3D printer. The PLA filament Plasti Mladic additive material produced the best outcomes. [10] The purpose of this research is to characterise the mechanical behaviour of FDM components using conventional laminate theory. (KLT). The elastic, Poisson, and shear modulus values are measured.

3. Materials and Methodology:

3.1 Materials:

Polylactic acid (PLA), which was bought from 3D Systems as 1.67 mm-diameter filament, was the polymer substance employed in this investigation. Given its non-harmful, non-toxic, and environmentally beneficial characteristics, it is one of the thermoplastics that is frequently utilised in the FDM process. PLA may be utilised to create biomedical implants for tissue engineering and orthopaedic purposes since it is biocompatible.

Particles with at least one dimension in the nanometre range, known as nanomaterials, exhibit unique and exceptional capabilities. High surface-to-volume ratios, simple derivatization techniques, and special thermal, mechanical, or electrical properties are these materials' key features. Since their discovery, carbon-based nanomaterials have captured the attention of scientists. Numerous carbon-based nanoparticles, including Nano diamonds, fullerenes, carbon nanotubes, Graphene, carbon nanofibers, and carbon Nano cones-disks, as well as their functionalized forms, have been studied as sorbent materials in sample preparation in recent years.

3.2 Selection of FDM process parameters

Three significant process factors, listed below, are taken into account by the decision to have all samples in this investigation have horizontal structural orientation.

- Temperature of Nozzle : The heat at which material from the build plate's nozzle starts to melt. The kind of material used and printing speed are a couple of variables that affect this. The interfacial bond strength between the layers is changed by the nozzle temperature, which also changes the printed component's strength.

- Infill Density: A polymeric substance is one that has a significant volumetric thickness. When using FDM, bulk density affects an object's weight or strength.
- Print Speed: As material is extruded, the nozzle moves in the XY plane of the build platform. Print speed also affects print quality and the build time as each layer is placed.

3.3 Design of Experiments:

By employing an appropriate optimisation approach, you may discover how particular FDM process parameters impact the tensile characteristics of printed samples. To find the ideal set of processing parameters, it is crucial to produce many of samples for testing at different combinations of different processing settings. This is where Design of trials (DOE) excels, since it decreases production time and cost, optimises process variables, and reduces the overall number of trials. The simplest and most useful method for producing trustworthy design solutions is Taguchi DOE. At the same time, fewer tests are required to modify the number of components and more quantitative findings may be produced. The outcome of the Taguchi method is displayed below.

I. Calculates ideal processing conditions

II. Considers the effects of each element.

III. Assesses the outcomes in ideal circumstances.

To get the required findings, the Taguchi technique frequently employs ANOVA or the signal-to-noise ratio (SN) approach. The total impact of each product property on material properties is calculated using the ANOVA approach, which analyses the correlation between several groups.

Table 1. List of FDM processing parameters and their levels considered.

Parameter	**Units**	**Level1**	**Level2**	**Level3**
Temperature of Nozzle	C	180	190	200
Infill Density	%	40	64	90
Print Speed	mm/s	70	90	110

The SN ratio method was used to calculate the deviation between the baseline and nominal at various noise levels. By changing the production parameters, depending on the outcome, the influence is assessed. When determining the independent percentage influence of each process parameter on the result, ANOVA is frequently taken into account. The SN technique, which calculates the proportion and impacts of numerous production process parameters on the result, is frequently used to target a multi-response condition. The SN technique was used in the current study to identify the best process parameters for filler density, nozzle temperature, and printing speed.

The divergence between the experimental value and the intended value, which is turned into the SN ratio to assess the link between reliability and variability, is calculated using the average value of the mechanical characteristics acquired from the test results in this approach. Taguchi divides the important qualitative aspects into three categories in order to create the ideal circumstances.

Larger the better for MRR-

$$\frac{s}{N} = -10 \times Log10\left(\frac{sum\left(\frac{1}{y^2}\right)}{n}\right) \ldots\ldots \text{Eq (1)}$$

Smaller the better for Ra-

$$\frac{s}{N} = -10 \times Log10\left(\frac{sum(y^2)}{n}\right) \ldots\ldots \text{Eq (2)}$$

The SN ratio response is greatly improved in this study, and Minitab software is utilised to analyse the data in order to better the tensile characteristics of printed samples made with the FDM technique. The nozzle temperatures, fill densities, and print rates are broken down into four stages in Table 1. Four levels of die temperatures, including 190°C, 200°C, and 210°C, were employed because the flowability of the filament material had an impact on the binding strength between the layers. Because the filament material does not melt correctly at high print speeds, build-up layer printing is unsuccessful.

Due to the fact that these speeds are frequently utilised in reality, 80, 100, and 120 mm/s were chosen as the two speed levels. Due to the fact that the filler density impacts the printed part's strength, two values of 50%, 75%, and 100% were selected. Parts having a filler density of less than 20% are eliminated because they have hollow structures and excessive porosity. It is suggested to build components with larger filling densities in light of the findings. The chosen filling concentrations were 50%, 75%, and 100%. The primary goal of the Taguchi approach is to examine how different variables impact desired results. An overall factorial design is necessary to print and test every conceivable combination. In terms of labour or materials, it is not cost-effective. Based on Taguchi analysis, which advised eight trial runs rather than 16.35, the L8 orthogonal array was chosen. Table 2 provides Taguchi's L9 orthogonal arrays for sample preparation.

Table 2. Taguchi's L9 orthogonal array for preparing a sample

S. No	Nozzle temperature	Infill density	Printing Speed
1	180	40	70
2	180	64	90
3	180	90	110
4	190	40	70
5	190	64	90
6	190	90	110
7	200	40	70
8	200	64	90
9	200	90	110

3.4 Fabrication of the test samples

Figure 3 depicts the dimensions of the specimens, which were created in accordance with ASTM D638.45. On an FDM printer that is available for purchase, the test specimens were produced. (Cube Pro, 3D Systems, USA). 0.4 mm diameter nozzles were used to print the samples. Other parameters were a linear, unsupported fill pattern, a screen angle of 45 °, a layer thickness of 0.2 mm, and a bed temperature of 60 °C. The CAD model was initially created using solid modelling software, and it was then imported into the slicing programme. (especially the CURA software). Using G-codes, the programme builds a sliced database of the model. The G-codes necessary to control the nozzle during model printing are stored in the database. Slices from imported STL files are converted by the CURA programme into G-codes. The hot-end temperature and left and right motions needed to build the model are specified in this G-code, a text file that contains instructions for the 3D printer to read and follow.

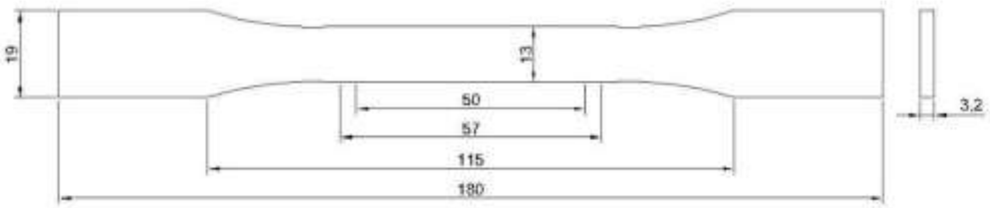

Figure 3. Dimensions of tensile test samples (in millimetres) according to ASTM D638

3.5 Tensile properties:

Using a tensometer, the tensile characteristics of PLA samples created using the FDM technique were examined. (horizontal model PC-2000). The samples were examined in a regulated lab setting in accordance with ASTMD 638. A 20N load cell was used for each trial run, and the jaw speed was 1 mm per minute.

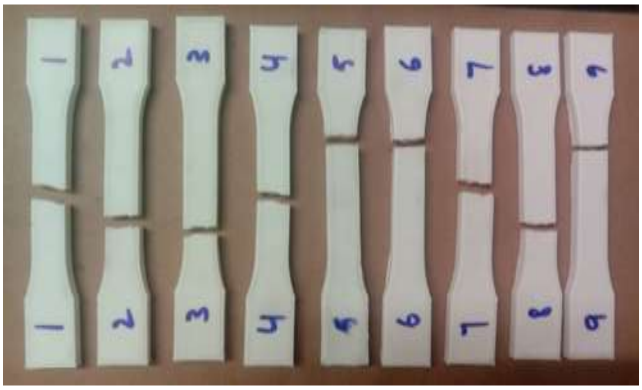

Figure 4 : Tensile Test Conducted Specimens

4. Results and Discussions:

The data produced by the S/N ratio and ANOVA tools allowed researchers to determine how input variables affected response. In table 4.1, all the responses for the various experimental situations were displayed.

Table 4.1

S. No	**Nozzle temperature**	**Infill density**	**Printing Speed**	**UTS N/ sq mm**	**S/N for UTS**
1	180	40	70	11.3	21.0616
2	180	64	90	12.5	21.9382
3	180	90	110	22.3	26.9661
4	190	40	70	11.4	21.1381
5	190	64	90	13.3	22.4770
6	190	90	110	22.3	26.9661
7	200	40	**70**	**11.2**	20.9844
8	200	64	90	13.1	22.3454
9	200	90	**110**	**22.6**	27.0822

4.1 Effect of Machine Parameters on UTS

From the S/N ratios response table of UTS shown in Table 4.2, it is observed that Infill Density is influencing more on UTS, followed by Nozzle Temperature and Printing Speed.

Table 4.2 Response Table for Signal to Noise Ratios- UTS (Larger is better)

Level	**NOZZLE TEMPERATURE**	**INFILL DENSITY**	**PRINTING SPEED**
1	23.32	21.06	23.46
2	23.53	22.25	23.39
3	23.47	27.00	23.48
Delta	0.21	5.94	0.09
Rank	2	1	3

It can be seen from the UTS major impacts graphic in fig.3.1 that UTS rises as Infill Density values are enhanced. Therefore, increasing infill density causes the tensile strength to increase. But when nozzle temperature and printing speed increase, tensile strength decreases. The ideal machining settings were identified from the major effects plot for SN ratios, and they are

Infill Density-100; Nozzle Temperature-200; Printing Speed-120

4.2 Analysis of Variance

Using the ANOVA tool, the most important factor that influences the output response was identified. Infill density and Nozzle Temperature are the two key variables that have a substantial impact on the pace of material removal. To investigate the impact of the UTS process variables, ANOVA was used. The outcomes of the ANOVA are displayed in table 4.3.

Table 4.3 Analysis of Variance for UTS

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**Contribution%**
NOZZLE TEMPERATURE	2	0.0674	0.0674	0.0337	0.69	0.592	0.11%
INFILL DENSITY	2	59.3201	59.3201	29.6601	606.71	0.002	99.69%
PRINTING SPEED	2	0.0135	0.0135	0.0067	0.14	0.879	0.16%
Residual Error	2	0.0978	0.0978	0.0489			0.16%
Total	8	59.4988					100.00%

Notes: DF, Degrees of freedom; Seq SS, Sequential sum of squares; Adj SS, adjusted sum of squares; Adj MS, Adjusted mean squares; P, Percentage of Contribution.

The residuals' normal plot is shown in Figure 4.2. The normal distribution of mistakes is tested using this graph. It will look like a straight line on this plot if the underlying error distribution is normal. The distribution depicted in figure 4.2 shows that the assumption of error normalcy is true. The residuals are plotted in the same figure according to the sequence in which the data were collected. This technique is useful for verifying the residuals' independence assumption. It is preferred that there be no visible patterns in the residual plot. Figure shows that for this experiment, the independence assumption on the residuals was satisfied. The residual values against fitted values are also plotted in this figure. The dots above and below the abscissa (fitted values) are scattered in a structure-less manner, indicating that the errors are randomly distributed and the variance is constant. As a result, it can be said that the assumption of constant residual variance was met. Now that this experiment has shown those presumptions to be true, it is safe to depend on the results of the ANOVA.

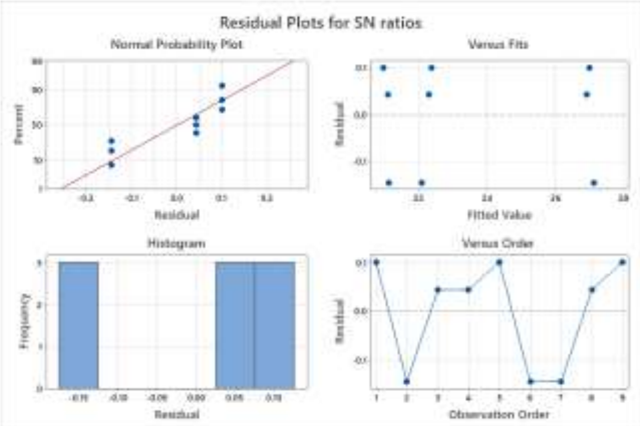

Fig. 4.2 Residual Plots for SN Ratios on Material Removal Rate

4.3 Regression Analysis

The predictive mathematical models for the dependent variables of UTS as a function of Infill Density, Nozzle Temperature and Printing Speed respectively. No transformation has been performed on each response. The predictive equations obtained from the regression analysis are shown below. The capability of developed models is checked by using a coefficient of determination R^2. The coefficient of determination value varies from zero to one. If it is close to one, it means that there is a good fit between the dependent and independent variables. Suppose if R^2 = 95 % then it means that new observations were estimated with 95 % variability. In the present study, the developed regression models for UTS are having high R^2 values as 85.85 %. The residual plot was used to check the significance of the coefficients in the predicted model. If the residual plot is straight line means that the residual errors in the model are normally distributed and coefficients in the model are significant. The residual plots obtained for UTS are shown in Fig. 4.3. From the Fig.4.3, it was observed that the residuals fall near the straight line for UTS, which implies that the developed model coefficient models are significant.

4.4 Regression Equation for UTS (R^2 = 85.85%)

UTS N/ sq mm = -3.8 + 0.013 NOZZLE TEMPERATURE + 0.2220 INFILL DENSITY + 0.0008 PRINTING SPEED

S.No.	Factor	Optimum Level	Optimum Value
1.	Infill Density	2	200
2.	Nozzle Temperature	3	100
3.	Printing Speed	3	120
Prediction			
4.	**S/N Ratio**	27.1279	
5.	**Mean**	22.5556	

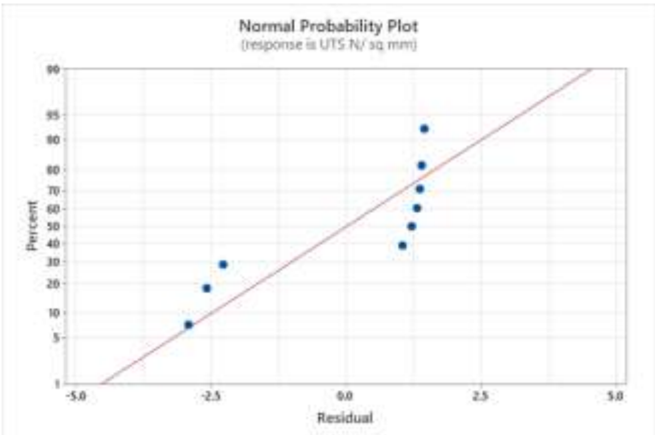

Fig. 4.3 Regression Normal Probability Plot for MRR

5. CONCLUSION

Based on the mechanical characteristics of PLA moldings, four parameters were assessed: layer thickness (Lt=0.05, 0.1, 0.2mm), build direction (flat, edgewise, upright), filling speed (Fr=20, 40, 80mm/s), and filling density (20%, 40%, process factors 80%).

The product's mechanical characteristics must be guaranteed to the 3D printing system's user while also being as efficient and affordable as feasible. This necessitates making concessions and trading off when selecting the process parameters. Because of this, employing a flat build direction, quick filling speed, and moderate filling density, it is possible to use a thicker layer while the moulded object is mostly in tension. The moulded component is primarily vulnerable to bending stresses if the filling density is low, the structure is flat, the filling speed is moderate, and the layer thickness is moderate. Use a medium layer thickness and a vertical construction direction if the generated part is mostly compressed. It is advised to fill it with a medium fill density at a medium fill speed.

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