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Effect of Process Variables on the Mechanical Characteristics of form Fabricated Materials

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Abstract

Additive manufacturing prominent rapidly advancing technologies for producing 3D-printed products. Initially developed by stratasys, FDM technology emerged during the 1980s. This additive manufacturing technique builds products by extruding semi-molten material through a nozzle onto a platform. PLA and ABS are among numerous thermoplastics that are commonly used as filaments in this procedure. Purpose of research was to observe the effect of variables such as infill percentage, bed temperature, printing speed on the output variables of ABS printed part. The variables namely tensile strength and surface topography are considered for the study. The study uses the Taguchi L27 orthogonal array and the analysis of variance (ANOVA) statistical method to evaluate the importance of the input parameters. The most important manufactured factor affecting stiffness is the infill density. Higher infill density leads to more strength due to larger material volume which causes strong internal support. Effect of printing speed and bed temperature also studied. Printing speed adversely affect on surface texture of printed part. Excessive bed temperature leads to reduction of adhesion and causing first layer to detach or warp. These findings highlight the need of optimization of 3D printing parameters, ensuring quality while reducing residual stress and warping.

Keywords: FDM, infill density, printing speed, bed temperature, PLA

INTRODUCTION

By assembling components under computer control, 3D printing develops three-dimensional objects. Initially, 3D printing referred to processes that deposit material using an extruder, but it now includes techniques like extrusion and sintering. Common filaments include thermoplastics like PLA and ABS, while modern FDM printers also use abrasives like aluminium and brass to improve strength, which can cause nozzle wear. The wear depends on various process variables. The printing process begins with a 3D model sliced into layers, which are printed using a nozzle that melts the filament and print a part [1].

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Printing parameters play a crucial role in additive manufacturing process. To improve usefulness and broaden applications produced specimens through additive manufacturing, researchers have focused on optimizing these parameters. The constant heating and cooling that happens throughout the layer-by-layer construction process is one of the factors affecting the mechanical performance of objects made via additive manufacturing techniques.

These thermal cycles can induce residual stresses, negatively affecting the part's mechanical properties and causing distortion or dimensional inaccuracies. Researchers have conducted extensive experiments to understand and internal stresses causing distortion in 3D printed parts. The industry is currently facing a significant challenge with the rejection of 3D printed parts due to quality issues, resulting in considerable losses in time and productivity. When manufacturing prototypes using FDM, process parameters often need frequent adjustments, which can impact the quality, productivity, and lead to increased machine downtime. Factors such as material variation, deposition speed, extrusion temperature, layer thickness, and standoff distance all influence the final output. Therefore, optimizing these process parameters is crucial for improving part quality. Furthermore the aim and objective of the work is to see the impact of input factors of FDM on mechanical characteristics [3].

LITERATURE REVIEW

Many researchers have explored various aspects of rapid prototyping methods, considering process parameters and their industrial applications for different purposes. They have employed different approaches to achieve their objectives, which are reviewed for further investigation. Hussein Alzyod, et al [1] studied the impact of 3D printing parameters on deformation and residual stresses of materials PEI, ABS, and PA6 using FEA. Mohammadreza Lalegani Dezaki et al [2] compared infill patterns and densities with PLA material and its impact on mechanical properties. The CAD specimens exhibited better surface texture than FDM-printed samples, while FDM-generated patterns showed higher strength and stiffness. Concentric patterns had the poor surface roughness, bent crinkled patterns had the highest at 6.27 µm. The highest tensile strength was observed in concentric and grid samples for both CAD and FDM methods. Tahseen Fadhil Abbas, et al [3] focused on the effect of infill density on the compressive strength of 3D-printed PLA specimens using FDM. Infill density (ranging from 20% to 80%), layer thickness, shell thickness, and print speed. The impact of these variables on mechanical testing and dimensional accuracy was analyzed. Derise, et al [4,9] shows the tensile characteristics of PLA 3D-printed specimens with varying infill patterns (linear, diamond, and hexagonal) and densities (25%, 50%, and 75%) were examined. For all designs, tensile strength and elastic modulus rose as infill density increased. The greatest tensile strength (42.67 MPa) and elastic modulus (1222.78 MPa) were obtained when a linear pattern and 75% infill density were combined. G Ćwikła et al. [5] concentrated on the mechanical strength characteristics of 3D-printed components composed of affordable ABS material. The effects of several parameters, including infill pattern, infill density, shell thickness, printing temperature, and material type, on the mechanical properties were examined after a set of standardized samples was printed. Md. Qamar Tanveer et al. looked at how modifying the infill density affected the tensile and impact strength of PLA specimens generated with an open-source 3D printer.[6]. Impact test specimens complied with ASTM D256 (Izod) and ASTM D6110 (Charpy) standards, whereas tensile test specimens were in accordance with DIN EN ISO 527-2. A computerized tensometer and impactometer were used to perform tensile and impact testing. The tensile strength of specimens with different infill densities was found to be higher (46.3 N/mm²) than that of specimens with a single infill density (29.9 N/mm²). Additionally, lighter specimens with varying infill densities saved raw materials. The Izod strength was 1.7 kJ/m², and the maximum Charpy strength was 4.72 kJ/m². It was discovered that impact strength and infill density were directly correlated, with decreased. Numerous researchers [7,10] looked to see if the mechanical properties of FDM-printed objects were affected by a number of process factors, such as infill density, infill patterns, extrusion humidity, layer thickness, nozzle diameter, raster angle, as well as orientation. The effects of pre-processing techniques including vacuum-assisted FDM and pre-deposition heating technologies were also examined in order to further enhance part strength. Rosli, Amirah Azwani et al. [8] examined the effect of bed temperature on ABS parts made by FDM. In order to investigate warpage, shrinkage, and density variations, the study altered the part shapes and thicknesses. Differential Scanning Calorimetry (DSC) was implemented to analyze the glass transition temperature of the printed objects.

The findings demonstrated that raising the bed temperature decreased warpage and shrinkage by raising the glass transition temperature of printed samples and lowering thermal stress. While thicker samples had less thermal contraction and were less impacted by changes in bed temperature, thinner samples showed more noticeable shrinkage. For samples with varying heights and fixed infill densities, density trends also changed with bed temperature. With an emphasis on their influence on mechanical qualities and component quality, this study examines numerous studies on the effects of process parameters in 3D printing.

Rapid Prototyping

Prototype as Direct Digital Manufacturing or End Use Part

With little assistance from humans, DDM is an industrial technique that uses computer-controlled additive and subtractive fabrication and machining processes to produce tangible items right from 3D CAD files or data. Another name for a Direct End Use product made from CAD using the RP method is Rapid Manufacturing (Figure 1). For articles that are just not possible to produce using subtractive (such as machining, grinding) or compressive (such as forging) techniques, RP is also extensively used. This includes things with intricate details, multilayer structures, and deep voids [5].

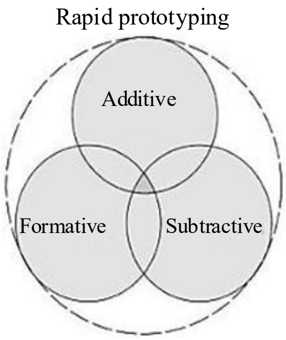

Figure 1. Overview of rapid prototyping methods [4].

METHODOLOGY AND MATERIAL

In experimentation which method and material to be used affects the performance of the printed part. The method used shall cover all the necessary fields that to be analyzed and material used is also an important factor as it is directly involved in the experimentation and the machine.

Experimental Strategy

The experimentation was carried out for the analysis of FDM process parameters. Layout was created for execution of Seamless experiment procedure. Steps of conducting experiments as follows:

Selection of Parameters

The input parameters for conducting experiments were researched. These input parameters are studied from various research papers and information available. There are some parameters which can affect significantly which are infill density, printing speed, bed temperature, etc. These variables are to be used as parameters while using DOE. This affects the strength as well as product quality.

Selection of Material

Because of its strength, endurance to heat, and longevity, Acrylonitrile Butadiene Styrene (ABS) is a material that is commonly employed in 3D printing. Prototypes, end-use components, and printed parts all benefit greatly from its durability and resistant to cracking nature. ABS usually needs a heated bed temperature of 90°C to 110°C and a printing temperature range of 220°C to 250°C for FDM 3D printing. It is also advised to keep the printing environment enclosed in order to avoid warping and guarantee continual layer adhesion.

Selection of Method

Method used in creating experimental sequence is Taguchi L 27 orthogonal array and ANOVA. In this we are implementing DOE to get the sequence of running the prints with Input parameters. By using DOE method we got 27 sets of printing the specimen. Each seat has a combination of infill density, printing speed, bed temperature as input parameters. DOE was implemented by using Minitab software.

Parameters considered as below:
Input factors: Infill percentage, Printing Speed, Bed Temp.
Output characteristics: Tensile Strength, Surface topography
Material: ABS
Machine setup: FDM 3D Printer

Specimen dimension as per ASTM standard D 638-14
Variable Input parameters as follows (Table 1):

Table 1. Process parameters with their levels

S.N.	Process parameters	Levels		
1	Infill density (%)	70	80	90
2	Printing Speed (mm/s)	30	40	50
3	Bed Temp. (°C)	90	100	110

Using this levels a Taguchi approach is used which provide minimal experimentation and analyses multiple output factors. Signal-to-Noise (S/N) Ratio performance metric used to evaluate the effect of input parameters on the output while minimizing variability. A statistical tool Analysis of Variance (ANOVA) used to find most significant parameter. It gives significant response to output characteristics.

Table 2 shows the details of Design of Experiments

Table 2. Sets of experiments by DOE and results.

S.N.	ID (%)	PS (mm/s)	BT (°C)	Ra (SR) (µm)	σ(TS) (MPa)
1	70	30	90	19	29
2	70	30	100	20	30
3	70	30	110	19	31
4	70	40	90	20	31
5	70	40	100	21	32
6	70	40	110	21	31
7	70	50	90	20	29
8	70	50	100	19	29
9	70	50	110	20	30
10	80	30	90	17	32
11	80	30	100	16	33
12	80	30	110	15	32
13	80	40	90	15	33
14	80	40	100	16	32
15	80	40	110	16	30
16	80	50	90	17	32
17	80	50	100	15	30
18	80	50	110	16	32
19	90	30	90	13	33
20	90	30	100	14	34
21	90	30	110	15	34
22	90	40	90	14	33
23	90	40	100	15	32
24	90	40	110	14	32
25	90	50	90	13	32
26	90	50	100	14	32
27	90	50	110	14	35

Experimental Setup

The experimental setup for 3D printing consists of setting up the printer, preparing the printing material, designing the model and printing the object. The steps are described below:

Printer Setup

Setting up the 3D printer according to the manufacturer's instruction. It involves assembling the printer, levelling the bed, installing the software and connecting the printer to a computer or other device. After that taking a test prints and make sure the print is Seamless. We have FABx XL 3D printer which was used for printing the specimen. Bed size of the machine is 270*270*300 mm (Figure 2).

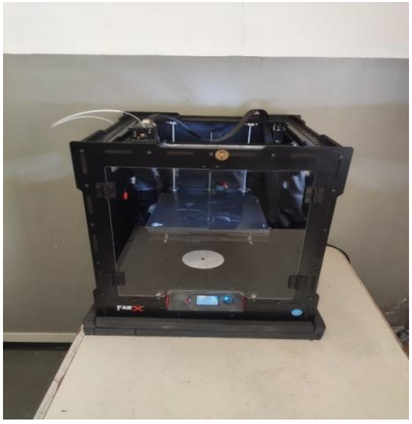

Figure 2. Experimental setup

Material Preparation

Loading the printing material or filament into the printer. This involve feeding filament into extruder after making extruder preheat according to ABS material. For ABS (Acrylonitrile Butadiene Styrene), the typical printing settings in FDM 3D printing are:

Extruder (Nozzle) Temperature: 220°C to 250°C

Bed Temperature: 80°C to 110°C

Enclosure: Recommended to prevent warping and improve layer adhesion, as ABS tends to shrink when cooling.

Model Design

By using 3D modelling software such as Solidworks Software used to design the object to be print. After making model we export the file as STL file. A standard specimen was designed and converted into STL file. Specimens standard of ASTM D638 (27 trials) are fabricated on FDM 3D printing test rig. Specimens then tested with surface roughness on surface roughness tester and tensile strength on UTM.

Experimental Analysis

Taguchi and ANOVA used to optimize process factors of FDM 3D Printer. For that L 27 orthogonal array was used.

Trials: 27 taken for the further analysis.

Columns of L27 (3^13) Array

Linear Model Analysis S/N Ratio (Table 3-5)

S/N Ratios versus Infill Density (ID), Printing Speed (PS) and Bed Temperature (BT)

Table 3. Linear model analysis S/N ratio for taguchi analysis

.	DF	Seq SS	Adj SS	Adj MS	F	P
ID	2	0.0017	0.0191	0.00137	0.028	0.000
PS	2	0.00176	0.0129	0.00193	0.23	0.04
BT	2	0.0189	0.0212	0.0326	0.799	0.031

Table 4. Analysis of variance for surface topography

Source	DF	Adj SS	Adj MS	F	P
ID	2	8.144	9.307	2.231	0.001
PS	2	9.327	8.126	4.129	0.018
BT	2	2.134	17.215	5.296	0.030

Table 5. Analysis of variance for tensile strength

Source	DF	Adj SS	AdjMS	F	P
ID	2	228.014	91.007	0.834	0.001
PS	2	191.72	108.026	1.103	0.004
BT	2	128.104	137.115	2.191	0.180

RESULTS AND DISCUSSION

The data represents (Figure 3) the Signal-to-Noise (S/N) ratio values at three levels for three different parameters: PS, BT, and ID. The Delta values show the range of the S/N ratio for each parameter across the levels, while the Rank indicates the importance or influence of each parameter based on the Delta values.

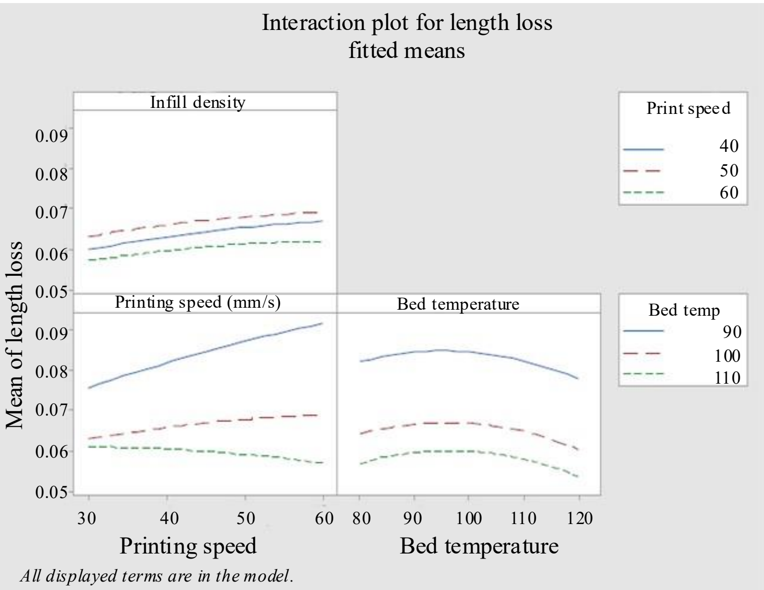

Figure 3. Effect of input factors on output properties.

Factors Impact

Level 3 has the most significant impact on the response variable since it has the highest Delta value (Δ=0.912\Delta = 0.912Δ=0.912). This shows that variations in this factor produce the greatest change in the output.

BT shows moderate influence, with a Delta value of Δ=0.056\Delta = 0.056Δ=0.056.

PS has the least influence, with a minimal Delta value of Δ=0.02\Delta = 0.02Δ=0.02. This implies that changing the levels of PS has a negligible effect on the output.

Optimization Implication

Since Level 3 is the most influential, efforts to optimize the system should prioritize this parameter. Adjusting its levels could yield the most significant improvement in performance.

BT could be considered next for optimization but with less priority compared to Level 3.

PS requires the least attention in terms of optimization, as it has a minor impact on the response.

Infill Density significantly affects Surface Roughness (p-value = 0.006). Other factors and interactions are not statistically significant. Both Infill Density (p-value = 0.038) and Printing Speed (p-value = 0.0475) significantly affect Tensile Strength.

Surface Roughness: Primarily influenced by Infill Density.

Tensile Strength: Influenced by Infill Density, Printing Speed, and their interaction.

Practical Insights

The significant variation in the S/N ratio for Level 3 could be due to its strong correlation with the process or product quality. The small Delta values for PS and BT suggest these parameters are either well-controlled or have a limited effect on the process outcome. Their optimization might not justify the resources spent.

CONCLUSIONS

Infill density of 90% shows most impact factor and which gives more tensile strength 34 MPa of than 80% or 70%. Printing speed of 50 mm/s gives moderate surface finish of Ra value as 17 μm and tensile strength of 31 MPa.

More Infill density provides best tensile strength as it holds best adhesion. More print speed gives moderate tensile strength with moderate surface finish. ANOVA analysis provides most impact factor is Infill Density on output factors as strength and surface topography.

The significant variation in the S/N ratio for Level 3 could be due to its strong correlation with the process or product quality. Investigating this parameter further through regression or ANN might uncover critical dependencies.

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