Analysis of process parameter effect on surface roughness and mechanical property during Fused Deposition Modeling on PLA

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Abstract- **Currently, Fused Deposition Modelling (FDM) is a preferred method for 3D printing in manufacturing when compared to other techniques. The FDM methodology can be seamlessly integrated by configuring a predetermined procedure and framework to the apparatus through a data transmission mechanism. There exist multiple options for modifying the input parameters in accordance with the user's requirements. In this work, the most commonly used FDM material, namely PLA and a supportive material glass fiber are used for the experiments (specimen fabrication). The experiments in this study were done to see how process parameters like layer thickness, infill%, raster angle and infill material variation PLA+5-10% glass fiber, affected their response variables which are surface roughness, tensile strength, and impact strength. Also, The Taguchi approach was utilized to optimize and determine the respective effects of the components on the response, resulting in the derivation of findings. Moreover, the ANOVA method was employed to conduct pertinent analysis and draw conclusions. Results show a uniform variation of all responses with layer thickness parameter which was found significant and the most influencing factor as well. While raster angle was found significant factor only in surface roughness response analysis. Similarly, infill% was found significant only in tensile strength response analysis. The addition of supportive material was found affirmative for mechanical property enhancement but degraded the surface quality of the fabricated specimens.**

Keywords– **3D Printing, FDM, Glass fiber, Rapid Prototyping**

1. INTRODUCTION

The concept of 3D printing in literature form for the study started in the 1970s. In 1981, 3D printing was used for the actual application and experiments performed [1]. 3D printing is a practical application and development of a rapid prototyping technique that was first used by Dr. Kodama. He also described the STL (Stereolithography) layer-by-layer approach of the 3D printing concept. Various scientists (Alain Le Mehaute, Oliver de Witte, and Jean-Claude Andre) were also interested in the same concept but failed to file the patent due to a lack of business perspective or the deadline. The first patent for SLA (Stereolithography) was filled by Charles Hull in 1986. 1st commercial product was produced in 1988 by C. Hull named SLA-1. According to Nyiranzeyimana et al. the innovation and regular experiments in the additive manufacturing technique are a new technology development i.e., SLS technology, the patent in 1988 by Carl Deckard [2]. After a few years, the FDM printing technique also gets a patent from Scott Crump and the world get three main 3D printing techniques in less than ten years. From where it can be considered the origin of 3D printing found. 3D printing has evolved in numerous forms over the previous three decades. However, in the previous five years, the manufacturing transformation has been discovered to be more cost-effective and user-friendly when compared to the old approach, which is recognized as a breakthrough point in the procedure's growth. Furthermore, the advancement of new technologies, operating software, and flexible materials allow for the creation of a diverse variety of manufactured goods utilizing 3D printing equipment. So, can a person construct or manufacture new products with the appropriate measurements? Inkjet printing was the most widely utilized quick production method in the 1980s. According to Diana Popescu et al., researcher Charles Hulls utilized the genuine 3D printing technique, Stereo Lithography, for production in 1984 [3]. Hull later created stereolithographic gear to improve SLA technology in the 1990s. The Hull device, which operates on heating optically using a laser, was initially relatively basic, and it was discovered that production could be done considerably faster than standard techniques. Stereolithography relies on a type of acrylic-based substance called a photopolymer.

Many drawbacks and loss of material make scientists innovate new manufacturing techniques. Additive manufacturing replaced subtractive manufacturing to overcome the drawbacks of it used nowadays. There is a successive pattern of adding the material layer by layer to make the final product in additive manufacturing [4]. Rapid prototyping (RP) is a computer-controlled, rapidly created, and additive manufacturing technology.

3D Systems (Charles Hull's business) built the world's first stereolithographic apparatus (SLA) machine, which permitted the layer-by-layer manufacture of complicated products in a fraction of the time [5]. Later, a 3D printer was employed to manufacture an organic body, which was generated for the first time in 1999 A.D. To adapt that component of the body, the part was covered by the patient's cells. The aforementioned concept was formulated by the Wake Forest Institute for Regenerative Medicine. In 2002, researchers achieved a significant milestone by successfully fabricating an artificial kidney through the utilisation of a 3D printing apparatus [6]. Adrian Bowyer, a researcher at the University of Bath in England, developed a 3D printer in 2005 that is capable of producing body components for a novel 3D printer known as a Rep-Rap. Finally, in 2008, the Rep-Rap project was released and dubbed Darwin. In 2008 the 3D printing industry and health industry worked simultaneously for the development of prosthetic limbs and even used for the successful implant to many patients. Similarly, Bespoke Innovations researched and invented prosthetic feet and developed in the same application till today [7]. The University of Southampton created 1st robotic-controlled aircraft using the 3D printer in 2011. Later, I. Materialise began working on printing jewelry pieces. MakerBot offers open-source DIY kits for creators to construct their 3D printers and goods. While the price of 3D printers has declined quickly and the precision of 3D printing has improved, Designers are no longer confined to printing with plastic and have begun employing metals to print. Researchers from the University of Southampton have successfully conducted a flight test of the first-ever unmanned aircraft that was produced using 3D printing technology. Additionally, KOR Ecologic has developed a prototype vehicle named Urbee, which features a 3D-printed body and is anticipated to achieve a fuel efficiency of 200 miles per gallon while driving on highways[8] . In addition to its applications in the production of ornaments and airliners, 3D printing is being increasingly employed in the creation of affordable housing for developing nations. Furthermore, innovators are utilising this technology to manufacture a diverse range of products, including robotic arms, bone replacements, and ultra-thin particles that could facilitate the development of smaller electronics and batteries. This information is sourced from references [9], [10].

From the above literature, it is understood that various developments in 3D printing are needed for further development of this process and different characteristics need to be optimized. As structural characteristics are highly influenced by the process variables, Accurate control of process parameters is essential to gain better products with less material wastage, which reduces the machining and assembly time. The present work focused on determining the optimum levels of process parameters to gain a better surface finish with mechanical property enhancement of PLA and addition of glass fibers fabricated by an FDM-type 3D printer. In this paper, Glass fiber is chosen because Glass fiber-reinforced 3D-printed parts are known for their enhanced strength and durability. The addition of glass fibers improves the structural integrity of the printed object, making it more resistant to bending, stretching, and impact.

2. EXPERIMENTAL SETUP

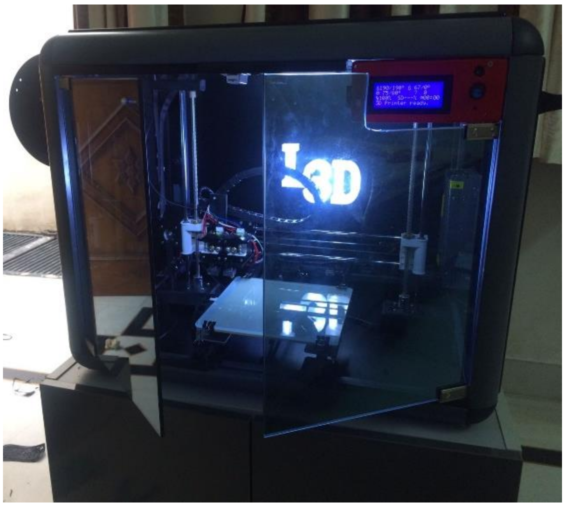

Figure 1: - L3D POLY-610 3D Printer machine

L3D POLY-610 3D Printer machine is used for the experiments (Fabrication of specimen), shown in Figure 1. The machine combines L3d unique continuous metal sheet reinforcement with workhorse reliability for the strongest. It is one of some limited machines in the industry that can produce a varied variety of specimen production or 3d printing of the material with some beautiful, strong, and end-user parts in hours. The fast mode of fabrication through this machine makes it more usable and higher in demand these days for manufacturing and industrial applications. It easily converts CAD files into fused deposition modelling technology to get metal 3D printing domestically. The top right of the printer contains a colorful HD LCD touchscreen, shown in Figure 1. The display can be used for various control or settings of machine for fabrication like bed heat, print nozzle movement, print speed, extrusion temperature, fan speed, SET, loading, and unloading of filament, and infill pattern. The bed used in the machine has improved adhesion to easily remove 3D-printed objects. The machine works on the principle of additive manufacturing. The filament was passed through the nozzle to the machine bed. Table 1 includes the technical and mechanical specifications of the 3D printer.

Table 1: - Technical specification of JGAURORA A5S 3D Printer machine

S. No.	Name	Value
1.	Technology	Fused filament Fabrication
2.	Build volume (XYZ)	610×610×610 mm
3.	Printer dimensions (XYZ)	536×480×543 mm
4.	Printing Material	ABS, PLA, PET, ASA, etc.
5.	Nozzle bore	0.2-1 mm
6.	Number of nozzles	Water cools dual head
7.	Platform for print	Heated type
9.	XY positioning precision	4.08μm
10.	Z- positioning system	Lead screw
11.	Print speed range	40~210mm/s
12.	CAD input formats	STL, OBJ, G-Code
13.	Operating Platforms	Windows7/XP/Vista/Linux/Mac-Control
14.	Electrical Voltage AC	110~220V
15.	Spool holder	Up to 5kg spool
16.	Certification	CE, RoHS, ISO 9001, MSME

3. EXPERIMENTAL CONDITIONS AND MEASUREMENT PROCEDURE

3.1 Workpiece selection

The project consists of material used for specimen fabrication as a process parameter. Long research work has been already done with pure PLA material in the last few years. New research has been trying to expand the variability in the material used for specimen fabrication. The variation found improves the build mechanical property by using supporting (filler) material like glass fibers, and other fibers. Pure PLA and ABS are popular materials used generally for specimen fabrication during FDM. But PLA has some advantages over ABS-like low melting point (requires less heat energy during heating the filament). Hence, you may print with PLA without utilising a closed chamber or a heated printing bed. PLA filament has received substantial popularity in additive manufacturing due to its mechanical characteristics and its derivation from renewable resources. It is a go-to for newcomers in the world of 3D printing due to its usability. PLA filament has a higher viscosity than ABS filament, which, if not handled properly, might clog the print head. This filament is mechanically distinct from ABS filament, which is much more durable and flexible. Because of its exceptional heat resistance, PLA is frequently utilised in the food sector. Nonetheless, if the project does not include any significant mechanical obstacles, it is typically recommended to utilise it due to its ease. For instance, PLA requires little processing after it has been manufactured. The supports may be easily peeled off, and if necessary, the surface can be sanded or treated with acetone. The initial layer of this material may be defective; thus, it is advised to apply sticky tape on the printing tray to facilitate its removal after printing.

Due to low mechanical property like poor thermal stability, ductility, and foamability, pure PLA is a less used material in various applications compared to other filament materials. This mechanical property can be improved by using some supporting material or fiber-like glass fiber. The reinforcement effect varies proportionally to the content of glass fiber in the composite material. Wang et al. found that the PLA/GF composite shows enhancement in strength and rigidity compared to the pure PLA. It was also found that the 20% GF/PLA composite shows a 2-fold enhancement in strength and rigidity and a more than 3-fold rise in toughness than pure PLA. Their thermal analysis shows the rise in heat deflection with the reduction in melt flow in the composite material in comparison with the pure PLA. The Foamability of the new composite also shows more value than the pure PLA during foaming experiments.

3.2 Experimental parameters

As per the literature review, the following parameters are selected for this study:

1. General-
   (a). No. of contours & Contour width = 3 & .4 mm
   (b). Infill pattern = Linear
2. Inputs-
   (a). Layer thickness (mm) = 0.1, 0.2, 0.3
   (b). Infill Percentage (%) = 90, 95, 100
   (c). Raster angle (º) = 0, 30, 45
   (d). Filament = PLA, PLA+5% GF, PLA+10% GF
3. Outputs- Surface roughness (SR), Tensile strength, Impact strength

3.3 Output response measurement

A portable surface roughness tester, the SURFTEST SJ-210 series, is being used to measure surface quality (Figure 4). It is a very lightweight roughness measuring tool that may show an SR waveform on an LCD color screen to the user (provided on the equipment) (given on the equipment). On the equipment, a 2.4-inch color graphic LCD with a backlight is offered for outstanding reading and easy presentation. A total of 27 values of output response were collected on all 18 fabricated specimens for the experiments (Figure 3).

Figure 3: - Fabricated specimens

Figure 4: - Surface roughness measurement using SURFTEST SJ-210

A stylus is attached to the equipment which has a sensitive 2 µm width diamond tip. Also, measuring the force and tip angle of the stylus is 0.75 mN and 60º. Figure 4.8 shows the movement of the probe on the flat surface of the fabricated specimen. The equipment has versatility in that the user can use it by a long wire connected to the display machine and the stylus probe as per comfortability. The least value of surface roughness of the equipment is 0.001 µm. The measurement for the record was performed before the mechanical impact and tensile test on the specimens.
Tensile strength was measured using universal testing machine INSTRON (Figure 5) (equipped with a 10 KN load cell) for nine ASTM Type IV specimens. The minimum cross-section area for each specimen is 6 x 3 = 18 mm². The formula used for the theoretical tensile strength calculation = ratio of maximum load during testing to the original minimum cross-sectional area of the specimen.

Figure 5: UTM machine used for tensile strength measurement

The standard fabricated specimen on ASTME23 standard was used for the impact strength analysis using the impact testing machine TINIUS OLSEN as shown in Figure 6. A total of 9 standard fabricated specimens with 63 mm length, 12.7 mm width with 3 mm depth. The section where the impact occurred on the workpiece was 63 x 3 = 189 mm^2. The notch provided for the impact test on the workpiece was 45° and 0.25 mm of radius at the center of the length.

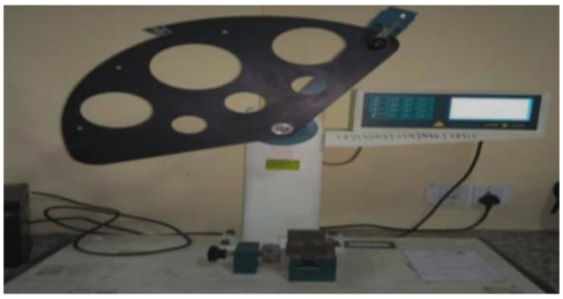

Figure 6: TINIUS OLSEN machine used for impact strength measurement

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Experimental result

All the experiments were performed as per the L9 orthogonal array for each impact and tensile test (process parameters combinations). The top surfaces of only bone shape specimens (for tensile strength) were used to observe the surface roughness value. A total of 18 specimens were fabricated and goes for 27 rounds of output responses measurement (nine for each output response) were made in this study. Table 2 represents the overall results during all specimen fabrication.

Table 2 Experimental result for specimen fabrication

Material	**Exp. No.**	**Layer thickness (mm)**	**Infill %**	**Raster angle (degrees)**	**Surface roughness Ra (μm)**	**Tensile strength (N/mm^2)**	**Impact strength (kJ/m^2)**
PLA	1.	0.1	90	0	1163	27.28	0.56
	2.	0.2	95	30	5913	32.47	3.07
	3.	0.3	100	45	9663	37.98	5.61
PLA+ 5%	4.	0.1	95	45	5517	29.64	1.46
	5.	0.2	100	0	4269	35.44	3.37
	6.	0.3	90	30	8267	33.48	4.96
PLA+ 10 %	7.	0.1	100	30	3924	32.94	1.89
	8.	0.2	90	45	7926	30.87	3.50
	9.	0.3	95	0	6682	36.13	5.41

4.2 Result analysis on surface roughness

In this section, effects, interactions of parameters, the effect of material variation on SR, and the ANOVA table are mentioned only for surface roughness response. All the analysis was done with the help of Taguchi optimization in the means form. The optimization and analysis of variance were performed using MINITAB 19.0. Figure 7 shows the main effects of the mean of each process parameter on surface roughness at all considered levels. For surface roughness, the smaller the value provides the desired surface finish or better surface of specimens. In figure 7, 0.1 of layer thickness, 90% of infill percentage, and 0º of raster angle show the lowest value can be considered as the optimum point for surface roughness. Table 3 represents the ANOVA result for surface roughness in mean value. The table 3 shows that all parameters are significant factors for surface roughness variation except infill%. Layer thickness contributes the most (61.09%) and raster angle (37.65%) compared to infill % (0.18%).

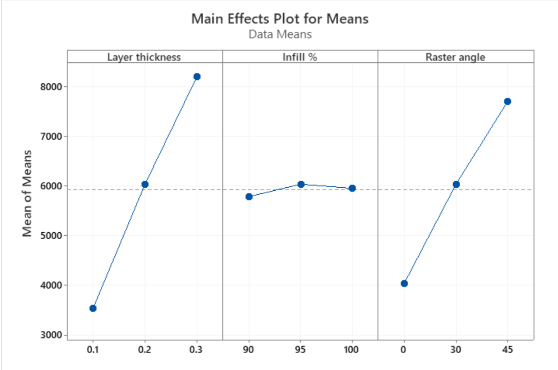

Figure 7: - Mean graph for SR

Table 3: - ANOVA (means) for surface roughness

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**Contri. (%)**
Layer thickness	2	32759566	32759566	16379783	57.02	0.017	61.09
Infill %	2	98564	98564	49282	0.17	0.854	0.18
Raster angle	2	20191574	20191574	10095787	35.14	0.028	37.65
Residual Error	2	574543	574543	287271			
Total	8	53634247					

4.3 Result analysis on tensile strength

Figure 8 shows the main effects of the mean value of each process parameter on tensile strength at all levels. For tensile strength, a larger value provides a better mechanical property of the fabricated specimen. In figure 8, 0.3mm of layer thickness, 100% of infill percentage and 0º of raster angle provide the maximum value for the tensile strength of the fabricated specimen, which can be considered as the optimal machining setting for further study in the same condition and parameters. Table 4 represents the ANOVA result for tensile strength in mean value. The table shows that all parameters are significant factors for tensile strength variation except raster angle. Layer thickness contributes the most (58.51%) and raster angle (40.53%) compared to infill % (0.04%).

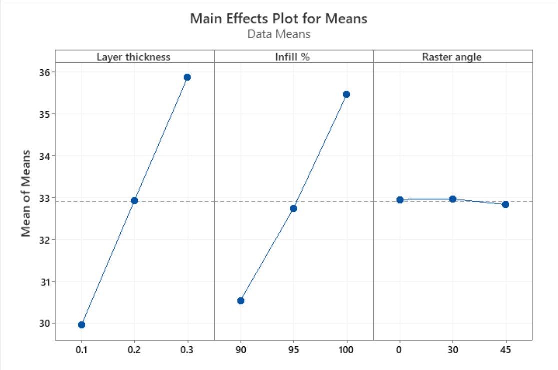

Figure 8: - Mean graph for tensile strength

Table 4: - ANOVA (means) for tensile strength

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contri. (%)
Layer thickness	2	52.39	52.39	26.19	63.06	0.016	58.51
Infill %	2	36.28	36.28	18.14	43.68	0.022	40.53
Raster angle	2	0.0324	0.0324	0.0162	0.04	0.963	0.04
Residual Error	2	0.8308	0.8308	0.4154			
Total	8	89.5448					

4.4 Result analysis on impact strength

Figure 9 shows the main effects of the mean value of each process parameter on impact strength at all levels. For impact strength, a larger value provides a better mechanical property of the fabricated specimen. In figure 9, 0.3mm of layer thickness, 100% of infill percentage and 45° of raster angle provide the maximum value for the impact strength of the fabricated specimen, which can be considered as the optimal machining setting for further study in the same condition and parameters.

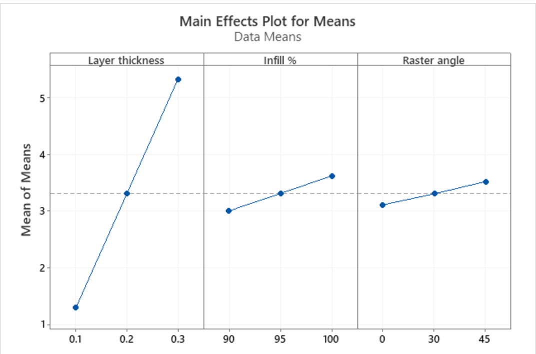

Figure 9: - Mean graph for impact strength

Table 5 represents the ANOVA result for impact strength in mean value. The table shows that all parameters are insignificant factors for impact strength variation except layer thickness. Only layer thickness is found to be the significant factor for the impact strength of the fabricated specimen. Also, Layer thickness contributes the most (95.14%) than infill% (2.24%) than raster angle (0.99%).

Table 5: - ANOVA (means) for impact strength

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contri. (%)
Layer thickness	2	24.28	24.28	12.14	58.18	0.017	95.14
Infill %	2	0.5704	0.5704	0.2852	1.37	0.423	2.24
Raster angle	2	0.2524	0.2524	0.1262	0.60	0.623	0.99
Residual Error	2	0.4174	0.4174	0.2087			
Total	8	25.5210					

5. CONCLUSIONS

Fabrication and experimental investigation of specimens fabricated under 3D printing on surface roughness and mechanical property analysis (tensile and impact strength) along with some base property variations were successfully done. After the result observation, effect analysis and significance of factors were also performed successfully. These are the conclusions made after the completion of the study:

- Among all the process parameters, layer thickness was found the most effective and significant factor for the all-output response. Where raster angle was also found to be an effective and significant factor for SR. The raster angle can significantly impact the mechanical properties of the printed object. By changing the angle, we can influence the direction of the printed layers, which can affect the part's strength, stiffness, and resistance to forces. Adjusting the raster angle can influence the amount of material used in the printing process.
- On the other side, infill% was found significant only in the case of the tensile strength of the fabricated specimen. Most of the time, layer thickness was the only parameter found to be the most contributing factor in surface roughness tensile strength and impact strength (highest). Another side the raster angle was found less contributed (mean value in all cases) factor for all responses.
- There is a scope for further investigation or correction in the minor areas under the related field for better results can be found.
- More filament material can be used under the same fabrication condition for better relative

results. Also, two or more two filament materials can be used in such an investigation for exact comparison purposes too.

- L_{27} can be used for further experiments in which infill base material can be also used as an input parameter for optimum point analysis as four factors with three levels. There are more process parameters (air gap, extrusion temperature, raster width, and print speed) that can be also used for experiments and analysis of their behavior for specimen fabrication.

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