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Influence of the FDM 3D Printing Process Parameters on In-Layer and the Inter-Layer Fracture under Tensile Failure

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Abstract: 3D Printing technology is slowly making its way into the mainstream manufacturing Processes. Fused Deposition Modelling (FDM) is one of the most popular techniques of manufacturing objects by 3D Printing. Under tension, two types of failure phenomenon occur in 3D printed specimen i.e. In-layer & Inter-layer fracture. In-layer fracture is considered to be a desirable failure type as it signifies that the layer separation is not occurring in the specimen and the fusion bond created is sufficiently strong which leads to superior tensile strength of the specimen. In this study, we have carried out experiments to study the effect process parameters like Nozzle Temperature, Printing speed & Rastor Angle has on the fusion bond between the layers by studying the angle made by the fractured surface with the layer. Poly Lactic Acid (PLA) material and FDM 3D Printing Method is used for making the testing specimens. Results showed that nozzle temperature & Rastor Angle have significant effect on tensile strength & In-layer fracture. Tensile strength was found to be increased with both increase in nozzle temperature & Rastor Angle. However, 40 mm/s is found to be the most suitable printing speed value. Using regression analysis, an equation to predict the type of failure for the given values of process parameters is given. 45^0 is found to be the critical rastor angle of separation for In-layer & Inter-layer fracture phenomenon.

Keywords: Fuse Deposition Modelling, PLA, In-layer & Inter-layer fracture

I. INTRODUCTION

3D printing technology in the last decade has seen lot of Research and progress being carried out in the field of additive manufacturing. The Cost and Time associated with the 3D printing process has reduced significantly in recent time with the emergence of new electronic technologies. With the operating cost of 3D printing reducing, it has caught the attention of lot of researchers to carry out study on the process. There are many printing technologies used in 3D printing. Fuse Deposition Modelling (FDM) has emerged as one of the most popular techniques for its ability to print objects with different polymers. Lots of studies are being carried out on the effects FDM 3D Printing Process parameters have on the mechanical properties of an object printed by FDM. Therefore it is necessary to evaluate how these mechanical properties of an object react to change in the process parameters. Different polymeric materials react differently to the change in process parameters. In this study, we have used Poly Lactic Acid (PLA) filament for the making the testing specimen. Numbers of specimen were printed using FDM Machine with varying Nozzle Temperature, Printing Speed, and Rastor angle.

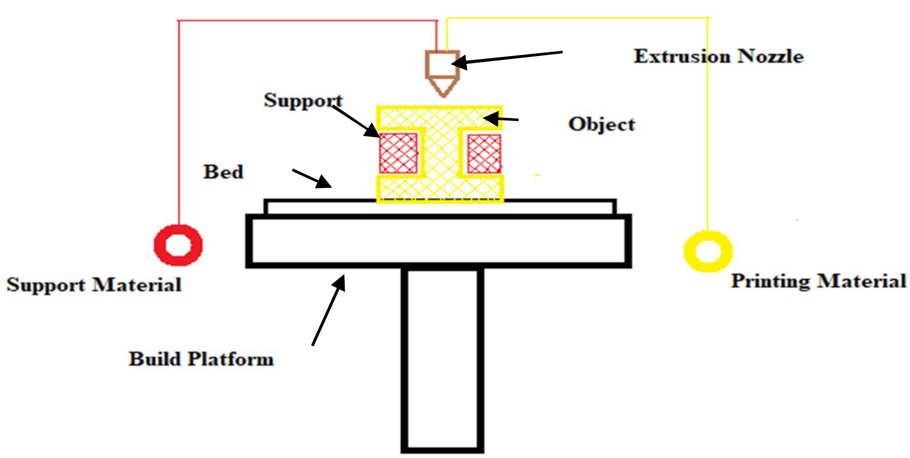

Figure 1 Schematic diagram of FDM 3D printing technology

Tianyun Yao et. al. [1] in their study talked about the In-layer & Inter-layer Fracture phenomenon that occur when the specimen are subjected to the tensile load. The below figure 2 explains the concept of In-layer & Inter-layer fracture phenomenon. In the figure Angle θ shows the Rastor angle i.e. the angle of the direction in which layers are deposited with the vertical axis. If during the tensile failure, the fracture takes place parallel to the layer, it's called Inter-layer fracture. But if the fracture takes place at some angle β, inclined to the direction of deposition of layer then it is termed to be In-layer fracture. Where, the fracture takes place across the thickness of layer. In this study, the angle β is termed as the angle of deviation. Angle β can be used to define the type of fracture. If $\beta = 0^0$, then the fracture is Inter-layer. Whereas, if $\beta > 0^0$ then the failure that has occurred is In-layer fracture. These two failure mechanisms are significant in describing the fusion bond between the layers. If the proper adhesion between the layers is not obtained, then tendency of occurring layer separation i.e. inter-layer fracture increases. Therefore, it was important to study the effect printing process parameters has on these fracture phenomenon and hence ultimately on the tensile strength of the specimen. In this paper, we studied the influence of the three process parameter of the FDM 3D Printing technique i.e. Nozzle temperature, Printing speed and Rastor angle on the tensile strength and the Angle of Deviation β i.e. the type of failure. **θ**

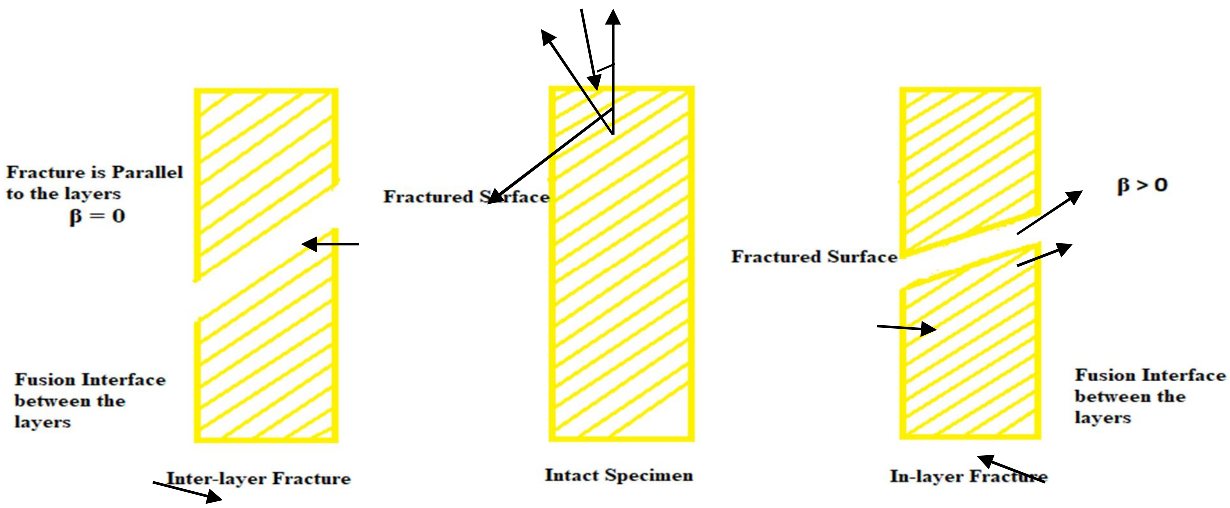

Figure 2 Concept of In-layer & Inter-layer Fracture

II. EXPERIMENTAL SETUP

For this experimental study, Poly Lactic Acid (PLA) material is used for the printing of testing specimen. Some of the important properties of PLA are given in the Table 1. These testing specimens were printed using Dual Nozzle FDM type 3D Printing machine as shown in the Figure 5. The Maximum Nozzle temperature that can be reached in this machine is 250 ^{0}C which is sufficient for the materials like Poly lactic Acid; ABS etc. the specifications of the 3D Printing machine used for the experiment are given in the Table 3.ASTM E8 standard specimen is used for the tensile test. Figure 3 & 4 shows the detailed dimensions and the actual testing specimen printed for the testing. The Specimens were tested on the UTM machine shown in the figure 5 at the testing lab facilities of the Central Institute of Plastics Engineering & Technology, Aurangabad (MH), India. It is a certified and leading organization for the testing of plastic and polymers. The specification of the UTM machine is given in the table 2.

Table 1 Properties of Poly Lactic Acid (PLA) Material

Properties	
Density	1.3 kg/m3
Tensile Strength	50 MPa
Young's Modulus	2.0 to 2.6 GPa
Heat Capacity	1800 J/kg-K
Elongation at Break	6%
Melting Onset (Solidus)	160^{0}C

Table 2 UTM Machine Specifications

Manufacturer	SHIMADZU Corporation, Japan
Voltage rating	3 Φ AC 200-230 V
Frequency	50-60 HZ
VA	1.8 K
Frame Capacity	100 KN
Frame Weight	800 kg

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Table 3 FDM 3d Printing Machine Specifications

Machine Specification:	
Manufacturer	Global 3D Printer (HYD)
Machine type	Double Nozzle FDM Type
Maximum Printable Space (Width * Breath * Height)	450 * 500 * 500 mm
Material	Poly Lactic Acid [PLA] White
Feed Filament Diameter	Φ1.75 mm
Nozzle Diameter	Φ 0.4 mm

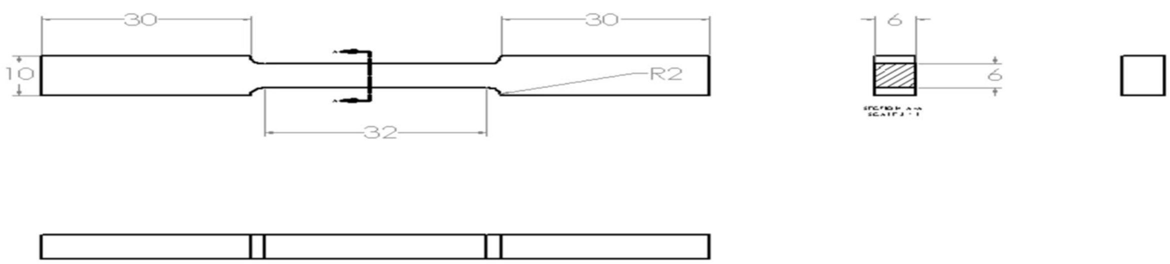

Figure 3 ASTM E8 Standards Tensile Testing Specimen

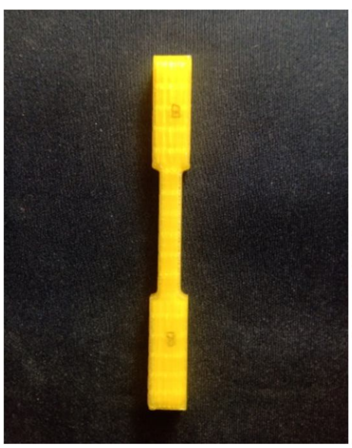

Figure 4 Actual Specimen

Figure 5 FDM 3D Printing Machine

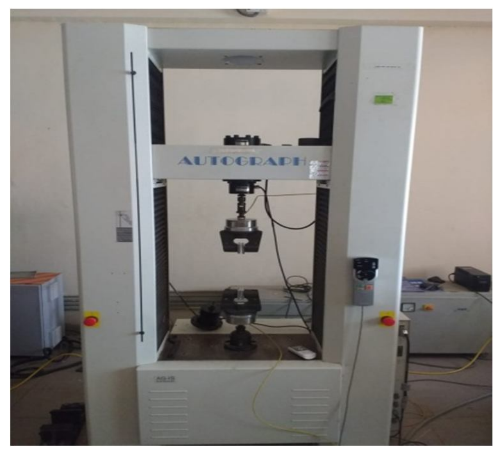

Figure 6 UTM Machine

III. DESIGN OF EXPERIMENT

In this study, tensile test was carried out on the specimen to study the type of tensile failure. In order to find critical range of the parameters for ANOVA analysis, ONE VARIABLE AT A TIME (OVAT) analysis is carried out on all the three selected parameters for optimization. The values of the process parameters for the OVAT Analysis are shown in the following table 4. The behaviors of the graphs were studied and the proper ranges of values were selected for optimization iterations.

Table 4 Process Parameters for OVAT Analysis

Parameters	Unit	1	2	3	4	5
1. Printing Speed (S)	mm/s	20	40	60	80	100
2. Nozzle Temperature (T)	^{0}Celsius	190	200	210	220	230
3. Rastor Angle (β)	Degrees	75	60	45	30	15

1) *OVAT Analysis of Printing Speed:* During the OVAT Analysis of Printing speed, Nozzle Temperature and Rastor Angle were kept constant at 210^{0}C and 75^0 respectively at the layer height thickness of 0.3 mm. For this inverted curve was obtained with increase in Tensile strength for the Printing speed from 20 mm/s to 40 mm/s and then again decreasing with further increase in printing speed.
2) *OVAT Analysis of Nozzle Temperature:* During the OVAT Analysis of Nozzle Temperature, Printing Speed and Rastor Angle were kept constant at 40 mm/s and 75^0 respectively at the layer height thickness of 0.3 mm. It was observed that tensile strength shows significant increase with increase in temperature beyond 210^{0}C. For temperature below 200^{0}C tensile strength obtained is very low. 210^{0}C-230^{0}C was found to be critical range for nozzle temperature.
3) *OVAT Analysis of Rastor Angle:* During the OVAT Analysis of Rastor Angle, Nozzle Temperature and Printing Speed were kept constant at 210^{0}C and 40 mm/s respectively at the layer height thickness of 0.3 mm. Almost linear behavior was obtained for the Rastor Angle. The tensile strength goes on decreasing with decrease in Rastor Angle. During this analysis it was found that for the build orientation of less than or equal to 45^0 inter-layer fractures were seen whereas for the orientation of greater than 45^0 In-layer fracture was observed. To study both kinds of failure, the rastor angle is to be kept 45^0 and above.

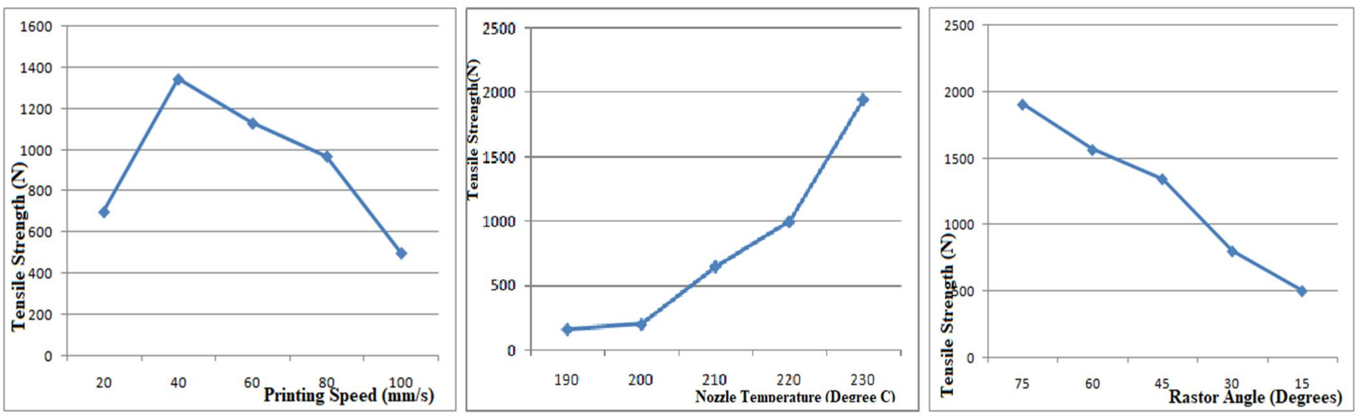

Figure 7 OVAT Analysis Graphs for the Tensile Strength vs (a) Printing Speed, (b) Nozzle Temperature and (c) Rastor Angle

Based on the O-VAT Analysis following levels of the process parameters were selected for ANOVA analysis as shown in table 5.

Table 5 Process Parameter Levels For The Variance Analysis

Parameters	1	2	3
Printing Speed	20 mm/s	40 mm/s	60 mm/s
Nozzle Temperature	210^{0}C	220^{0}C	230^{0}C
Rastor Angle	75^0	60^0	45^0

Using these levels of the parameters, 9 Specimens were prepared according to the combinations of L9 orthogonal array for the ANOVA Analysis. These specimens were then tested on above mentioned UTM machine.

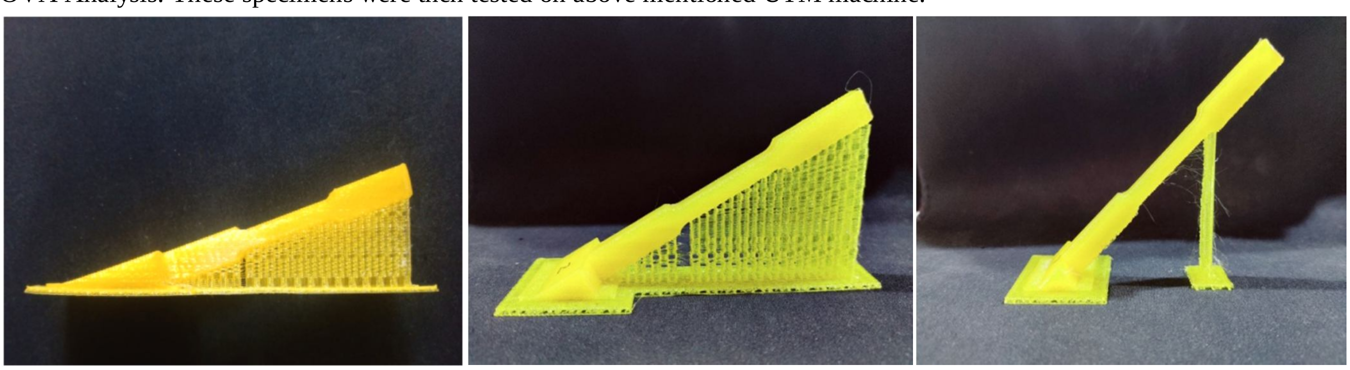
Figure 8 testing specimen with the rastor angle (a) 750, (b) 600and (c) 450

IV. RESULTS & DISCUSSION

In this experiment, effect of three independent FDM 3D printing process parameters was investigated for the type of fracture failure i.e. Angle of deviation β and the tensile strength of specimen. Experimental results for the Angle of deviation and the Tensile Strength are given in the Table 6. For the analysis of experimental results, Minitab 2020 software was used.

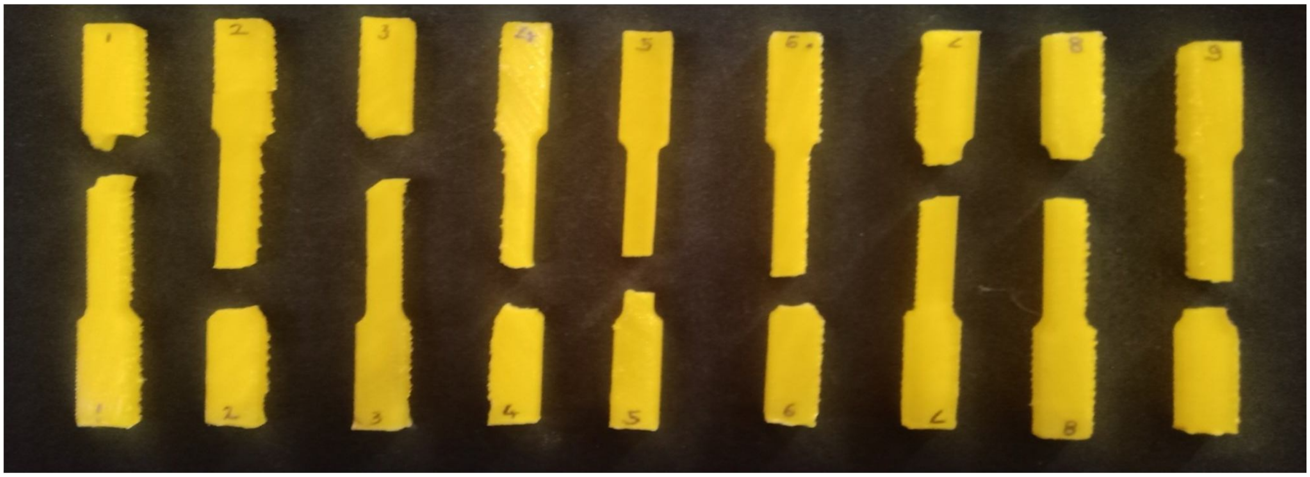

Figure 9 Broken Specimen

Table 6 Tensile Testing Results Of The Specimens

Specimen number	Printing Speed	Nozzle Temperature	Rastor Angle	Tensile Strength (N)	Angle of Deviation β (Degrees)
1	20 mm/s	210 ^{0}C	75^0	900	69
2	20mm/s	220 ^{0}C	60^0	1000	42
3	20 mm/s	230 ^{0}C	45^0	1100	0
4	40 mm/s	210 ^{0}C	60^0	1545	36
5	40 mm/s	220 ^{0}C	45^0	1735	0
6	40 mm/s	230 ^{0}C	75^0	2000	73
7	60 mm/s	210 ^{0}C	45^0	800	0
8	60 mm/s	220 ^{0}C	75^0	1480	70
9	60 mm/s	230 ^{0}C	60^0	1450	44

A. Influence of the Process Parameters

Figure 1 and 2 shows the main effects of the parameters on tensile strength of the specimen and the angle of deviation which is used to find out whether fracture was in-layer or inter-layer. It was found that the Printing speed is the most significant parameter affecting the Tensile Strength of the specimen. At 20 mm/s due to slow deposition rate, poor fusion bond is obtained resulting in lower tensile strength of the specimen. Whereas at 60 mm/s material does not get enough time to liquefy. Lower liquefaction again results in weaker fusion bond between the layers and therefore lower tensile strength was witnessed at higher speeds. It was found that 40 mm/s is most suitable Printing Speed maintaining the balance between deposition rate and liquefaction time. Effect of the Printing Speed on the angle of deviation is given in figure 2. No significant effect of the speed was noticed on the Angle of Deviation.

Nozzle Temperature has a great influence on the tensile strength of the specimen as shown in the figure 1. As we increase the temperature, more material liquefaction is obtained. Therefore, better fusion between the layers can be obtained. This results in the increase in tensile strength of specimen with increase in Nozzle Temperature. The highest tensile strength was observed with the temperature of 230^{0}C. But it was seen that, for the temperature higher than 230^{0}C, material starts to burn instead of liquefying. So it is recommended to keep the temperature up to 230^{0}C for PLA material. Similar to Printing speed, Nozzle Temperature is not much significant parameter for the angle of deviation and hence does not affect the occurrence of type of fracture much. The main effect of temperature on Angle of Deviation is given in figure 2.

Rastor Angle shows linear relationship with the tensile strength of the specimen. Main effect of the Rastor Angle as shown in figure 1 decreases linearly from 75^0 to 45^0 suggesting that the larger the Rastor Angle, greater the tensile strength of the specimen. Rastor Angle is also the most significant parameter affecting the type of the fracture failures that has occurred as shown in the figure 2. At 45^0, Angle of deviation was found to be equal to zero for all the specimen, suggesting the failure occurred was inter-layer fracture. For the higher values of Rastor Angle, positive value of angle of deviation was obtained i.e. in-layer fracture failure. Higher values of Rastor Angle increases the printing time and makes process infeasible whereas values of lower 45^0 results in inter-layer fracture and lower tensile strength. Therefore, according to the need a suitable value can be chosen in between 45^0 to 90^0 Rastor Angle. It states that the Rastor Angle selected for the process should be higher than 45^0.

Table 7 Anova Table For Means For Tensile Strength

Source	DF	Seq SS	F	P
Printing Speed	2	905459	43.02	0.023
Nozzle Temperature	2	306522	14.56	0.054
Rastor Angle	2	92049	4.37	0.186
Residual Error	2	21049		
Total	8	1325078		

Table 8 Anova Table Means For Angle Of Deviation B

Source	DF	Adj MS	F	P
Printing Speed	2	4.22	0.28	0.779
Nozzle Temperature	2	24.22	1.63	0.381
Rastor Angle	2	7547.56	506.93	0.002
Residual Error	2	14.89		
Total	8	7590.89		

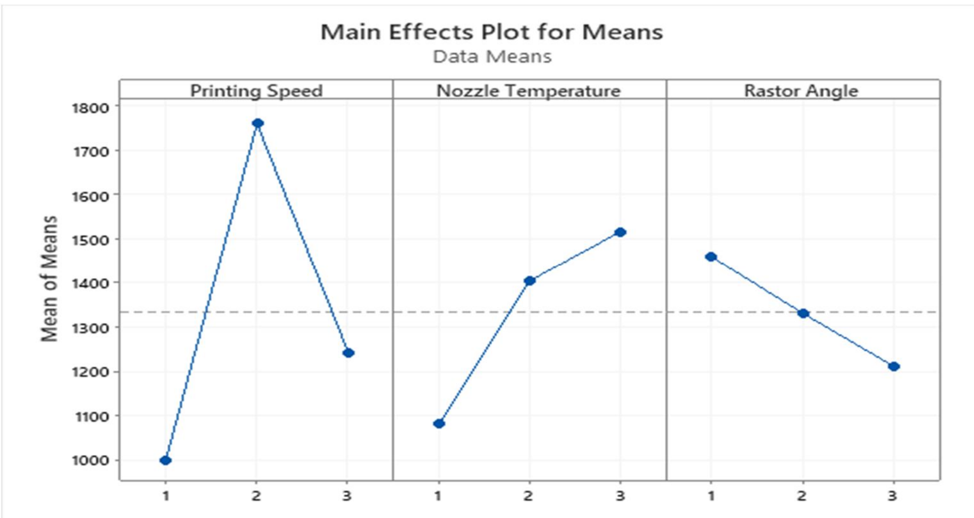

Figure 10(a) Main effects of Process parameters on tensile Strength

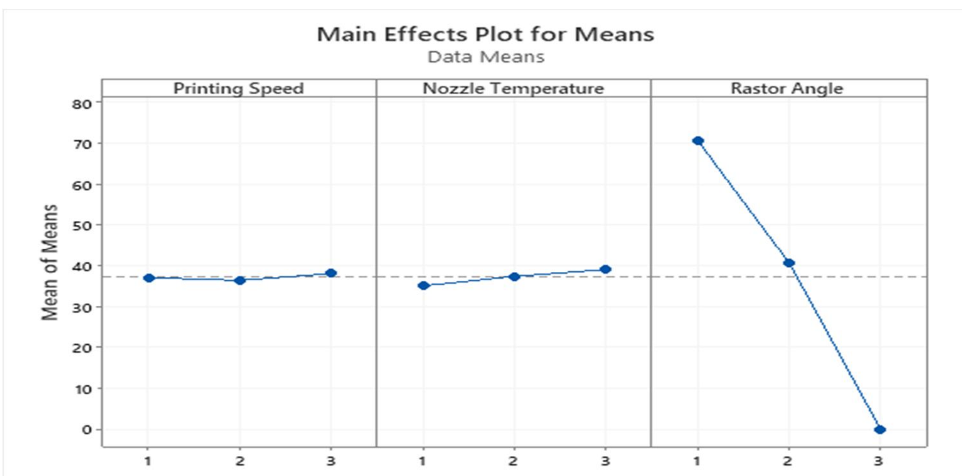

Figure 10(b) Main effects of Process parameters on Angle of Deviation β

A regression equation model given by equation 1 was proposed for the theoretically predicting the value of angle β.

$$\beta = X_0 + \sum X_1 S + \sum X_2 T + \sum X_3 \theta \quad \text{.................................. (1)}$$

Where, β is predicted response of Angle of deviation, Xs are the regression constant. S, T & θ are the Printing Speed, Nozzle Temperature and Rastor angle respectively.

Table 9 Regression Analysis Tables Of The Parameters

Intercepts	Coefficients	Standard Error	t Stat	P-value
X_0	-149.22222	35.45410875	-4.208883751	0.008417266
X_1	0.025	0.078910404	0.316815005	0.764184698
X_2	0.2	0.157820808	1.267260019	0.260877429
X_3	2.355555556	0.105213872	22.38826033	3.30342E-06

From the Regression analysis given table no.9 for Angle of deviation β, the significance of the three parameters can be noticed using the p-value given in the table. Rastor angle is the most significant parameter (p-value < 0.05) whereas the Nozzle temperature & Printing Speed can be said to be insignificant (p-value > 0.15). However considering the closeness of the p-value to 0.15, Nozzle temperature can still be considered for further iterations.

Table 10 Regression Analysis Table Excluding Insignificant Parameter Printing Speed

Intercepts	Coefficients	Standard Error	t Stat	P-value
X_0	-148.2222222	32.55846277	-4.552494486	0.003881584
X_2	0.2	0.145508898	1.374486387	0.218417877
X_3	2.355555556	0.097005932	24.28259284	3.2062E-07

From the regression model can be given by,

$$\beta = -148.2222 + 0.2T + 2.3556\theta \quad \text{.................................. (2)}$$

B. Conformity Test

For the validation of the of the regression model, three more specimen were tested with the following parameter level as shown in the table 9. The actual and predicted values of Angle of Deviation were compared. The Percentage error was found to be less than 5% is within acceptable limit.

Table 11 Results Of The Conformity Test

Specimen No.	Printing Speed (mm/s)	Nozzle Temperature (^{0}C)	Rastor Angle (Degrees)	Tensile Strength (N)	Actual Value of β	Average β	Predicted Values of β	% Error
L1	40	230	75	2020	74^0	73.66^0	74.44^0	+1.05%
L2	40	230	75	2005	74^0			
L3	40	230	75	1950	73^0			

C. Critical Rastor Angle θ_C

As the Regression model is validated with the conformity test and the results were found to be within acceptable limit. This regression model can be used to find the critical rastor angle which can be used as a separating point between the In-layer & Inter-layer fracture.

Using Equation 2, **$\beta = -148.2222 + 0.2T + 2.3556\theta$**

Taking β=0, for the nozzle temperature of 210^0C, 220^0C & 230^0C, the value of the critical rastor angle can be given by 45^0, 44^0 and 43^0 respectively.

Therefore, for rastor angle θ> θ_C, In-layer fracture is likely to occur whereas for θ< θ_C Inter-layer fracture will prominent.

V. CONCLUSION

Following conclusions were made from the results of the experiments and TAGUCHI method analysis.

1) Maximum Tensile Strength & Angle of Deviation obtained for following combination of parameters,
   1) Printing Speed- 40 mm/s, 2) Nozzle temperature – 230^0C & 3) Rastor Angle- 75^0
2) Printing speed significantly affects the Tensile Strength of the specimen. 20 mm/s and 60 mm/s both results in weak fusion bond due to slow deposition rate and less liquefaction time respectively. 40 mm/s was found to be most suitable Printing Speed maintaining the balance between deposition rate and liquefaction time. No significant effect of speed was noticed on the type of fracture phenomenon i.e. Angle of Deviation β.
3) Nozzle Temperature also plays significant role in the fusion bonding between the layers. Tensile strength of the Specimen increases with increase in temperature due to better liquefaction of material which results in stronger fusion bond. However, it is recommended to limit the temperature up to 230^0C in order to avoid the burning of PLA. Although unlike Printing Speed, Nozzle Temperature has slightly linear effect affect on the Angle of Deviation β.
4) Tensile Strength of the specimen decreases linearly with decrease in Rastor Angle. Maximum strength was observed for 75^0 whereas, for the nozzle temperature of 210^0C, 220^0C & 230^0C**,** the value of the critical rastor angle can be given by 45^0, 44^0 and 43^0 respectively. Proper Orientation can be chosen in between Critical Rastor Angle θ_C and 90^0 in order to avoid Inter-layer fracture and maintaining the balance between tensile strength and printing time.
5) Angle of Deviation β can be predicted by the regression model, $\boldsymbol{\beta = -148.2222 + 0.2T + 2.3556\theta}$

VI. ACKNOWLEDGEMENT

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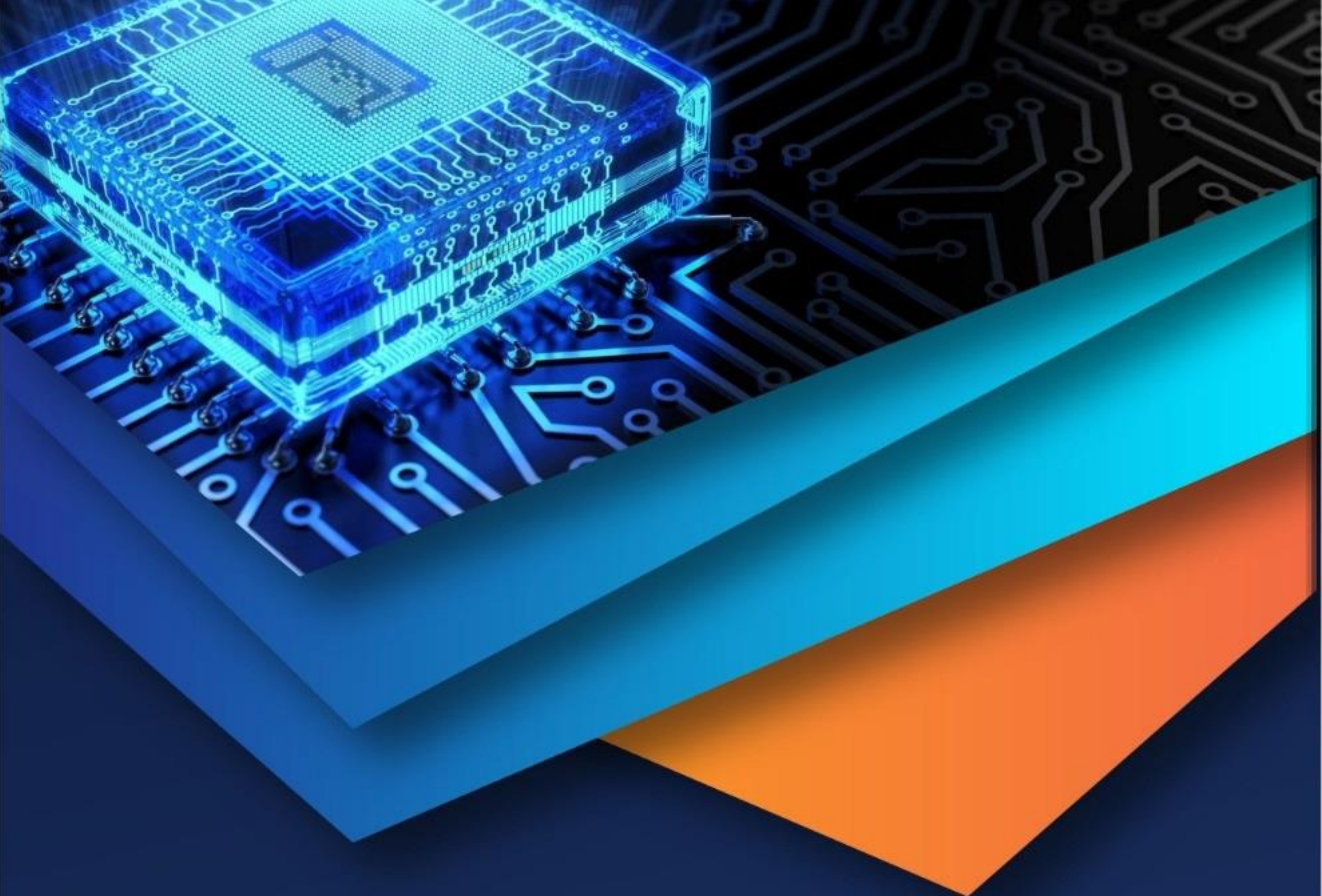

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