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Effect of process parameters on mechanical properties of carbon fiber reinforced 3D printed polymer composites

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ABSTRACT

Fused deposition modeling (FDM) is the three- dimensional technology that creates physical solid objects by depositing material in multiple layers based on a 3D model. Therefore, in this study we investigated the quality and influence of process parameters on the mechanical properties of FDM fabricated CFRP composites by Taguchi L9 orthogonal arrays. Four process parameters and three levels used in this study are layer thickness, infill density, raster angle, and nozzle temperature. After the fabrication part, impact test, tensile test, surface roughness, wear test were checked using mechanical equipment. taguchi L9 design and ANOVA analysis were used to identify relationships between process parameter values. The objective of this study is to investigate the effect of process parameters on various process factors using CFRP composite materials, which includes mechanical considerations like tensile strength, impact strength, and surface roughness test. According to ANOVA analysis of variance, layer thickness is the most efficient process parameter for impact or tensile test on CFRP printed components, while raster angle is the most efficient process parameter in surface roughness test.

Keyword: 3D printing, CFRP, FDM, SEM, Taguchi DOE, ANOVA

1 INTRODUCTION

In the recent year 3D printing manufacturing zone, additive manufacturing (AM) has proven to be a flexible process to create parts with complex geometries to adopt new technologies in rapid prototyping. One of the most common 3D printing technologies is fused deposition modeling (FDM) which is producing layer by layer technique using CAD (computer-aided design) or CAM. (Computer-aided manufacturing). In this study we used Fused deposition modeling (FDM) is an extrusion method of additive manufacturing in which the 3D printing process(R.Keshavamurthy, H.V.Ravindra, &G.V.Naveen, 2014).The FDM 3D printing process was developed by Scott Crump, and applied by Statasys Ltd. in the1980s. The FDM process is where the FDM 3D printer melts the plastic filament, the filament is input layer-by-layer through a nozzle onto the build platform, and the next layer begins as soon as the layer is complete. This process is repeated until the product is completely finished or ready Additive manufacturing is used in biomedical industries, aerospace industries, automobile industries (Dey & Yodo, 27 June 2019) Varieties of materials are available for additives manufacturing technology such as PLA, ABS, PETG. Polylactice acid (PLA) its raw materials lactice acid derived by fermentation of corn starch, sugar, wheat, maize etc (Shady, Daniel, & R., 2016).

(Mohammed, 2021) This study investigated the effect of two process parameters, raster angle and moisture, on the mechanical properties. They use PLA as the printing parts and L27 orthogonal are used to fabrication of tensile specimen.(A.E & L.Ramdani, 2017)They found that the Raster angle 90° and 10% moisture content have the most effect on mechanical properties. (Saini, 2019) examined the tensile strength of ABS materials and PETG, temperature and infill density are most significant effect for improving tensile strength.

(Auffray, Pierre-Andre, & Lamine, 2021) In this research examined the tensile test for CFRP with FDM process. L27 Taguchi orthogonal array was used to printing parts. Seven process parameters were used such as infill pattern, infill density, printing velocity, layer height, raster orientation, outline overlap etc. After Taguchi analyzing result was found the infill density, Infill pattern, printing velocity, and printing orientation were the most affecting parameters on young's modulus and yield strength.

(Dr, J, & B, 2020) In this research studied the effect of three process parameters (speed, layer thickness, Infill density; etc). On the impact test and surface roughness of FDM printed parts. ANOVA analysis and Taguchi analysis were used for the optimization process. The result obtained that the infill density was the most influential parameters for impact strength. whereas surface coarsening density was the most significant effect. (Demei & Guan, 2020) conducted on the study, FDM process parameters (bed temperature, print orientation) on impact strength. It was found that the 45º orientation printed sample showed superior mechanical impact strength that the 90° orientation sample.

(Meena, RanganathMSingari, Pawan, & Harish, 2020)studied the effect of layer thickness, build orientation, extruder temperature on the Wear performance of 3–D printed parts of PLA. and applied Taguchi design to experimental design. And statistical analysis was utilized to identify the relation between process parameters. It was found that build orientation has the most significant effect.

Inspired by all the above research studies, the effect of four process parameters such as layer thickness, raster orientation, infill density, nozzle temperature on the tensile test, surface roughness, wear performance and impact testing of FDM printed CFRP parts is investigated. Three levels are considered for each process

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parameter. A Taguchi L9 array is used. And PLA is used as a printing material. And statistical analysis is used to identify the process parameters effect, quality and optimal levels.

2 Materials/Methodology

The material is used in the study Carbon fiber reinforce polymer with PLA (Poly-Lactic-Acid) filament. The most common filament used in FDM techniques to produce durable parts and reliable prototypes is PLA, which flexible, hard. PLA filament that's synthesized from corn, starch, and sugarcane. Possessing a low melting factor is selected, which is a suitable fabric for depositing complicated items with desirable results in smooth prints.PLA is easy to print with relatively low temperature and its mechanically quite strong.

Table 1: Properties of Poly-lattice acid (PLA) materials

Melting Temperature	Density	Tensile Strength	Carbon used
180°C-220°C	1.3 g/cm3	55MPa-65MPa	20%

2.1 Specimen Preparation

In this work, we are studying four mechanical properties for testing, those properties are in Tensile Specimen, Impact Specimen, Wear Test Specimen, Surface Roughness Specimen, and we need to prepare 3D modeling of each specimen. Before the testing the study starts with 3D modeling to create a design by using Solid work modeling software we prepare all specimen dimension according ASTM-D256 standard.

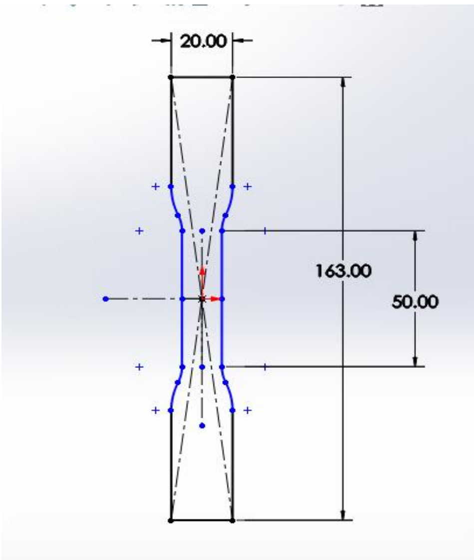

Fig-2.1: Tensile test Sample, all dimension are in mm

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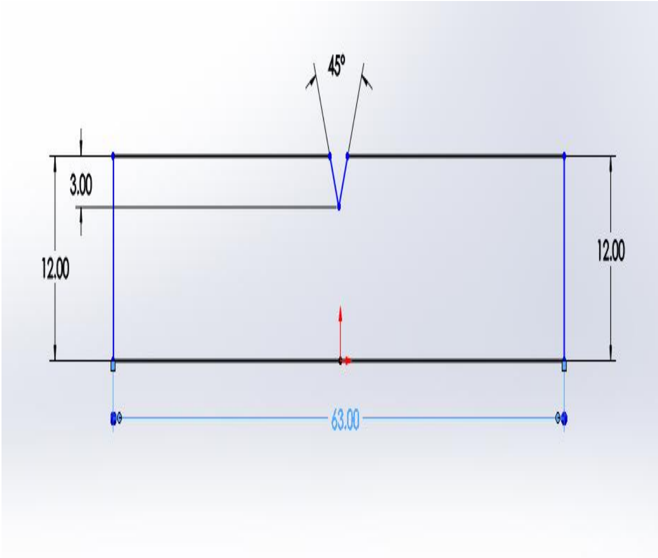

Fig- 2.2: Impact test Sample, all dim are in mm

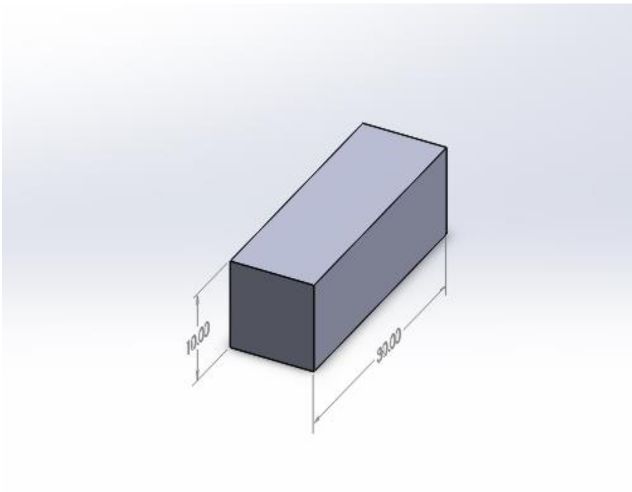

Fig-2.3: Surface Roughness sample , all dim are in mm

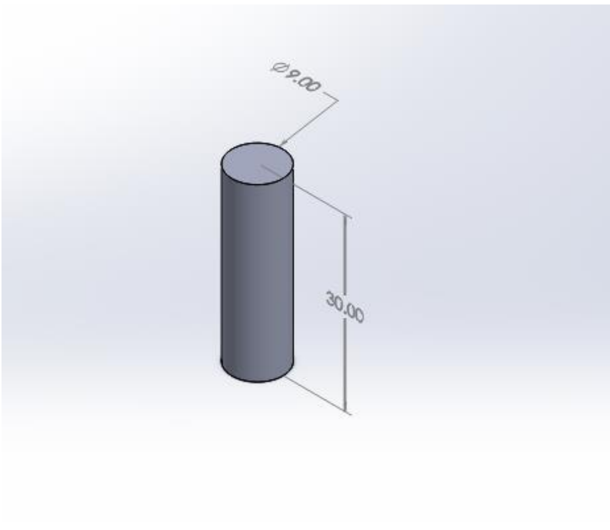

Fig-2.4: Wear Test Sample, all dim are in mm

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2.2 Selection of factors to study:

When process parameters are more than two, large number of experiment have to be conducted .To overcome this problem, Taguchi method developed a special design. After studying literature reviews, in this work, we used L9 orthogonal array. it would 9 Run experiment to optimize the parameters.

Process Parameters:

1. Layer Thickness
2. Infill Density
3. Raster Angle
4. Nozzle Temperature

Table 2: The Printing process parameters

Parameters	**Levels**		
	level1	**level2**	**level3**
Layer Thickness (LT)/A (mm)	0.1	0.2	0.3
Infill density (%)	80	90	100
Raster Angle (RA)/(°)	0	45	90
Nozzle Temperature (T) (°C)	180	200	220

Design Summary of printing samples:

Taguchi Array L9 (3^4)

Parameters 4

Experiment run 9

Table 3: The L9 all printing parameters and their levels

Experimental no	**Layer Thickness (LT)/(mm)**	**Infill density (%)**	**Raster Angle (RA)/(°)**	**Nozzle Temperature (T) (°C)**
1	0.1	80	0	180
2	0.1	90	45	200

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3	0.1	100	90	220
4	0.2	80	45	220
5	0.2	90	90	180
6	0.2	100	0	200
7	0.3	80	90	200
8	0.3	90	0	220
9	0.3	100	45	180

2.3 3D Printed Fused Deposition Modeling

All experimental samples were printed at 3D Global Laboratory in Bangalore. Samples are printed with four processing parameters and three layers using a three-dimensional 3D fused deposition modeling method. A taguchi l9 orthogonal array was used to drive 9 test samples in the FDM machine.FDM follows the process of developing models by adding materials layer by layer. One of the most popular methods for improving the quality of CFRP in 3-D manufacturing is FDM. Three-dimensional model developed by CAD software (Solid Works, Catia Creo). Any complex component can be advanced through the FDM process without difficulty.

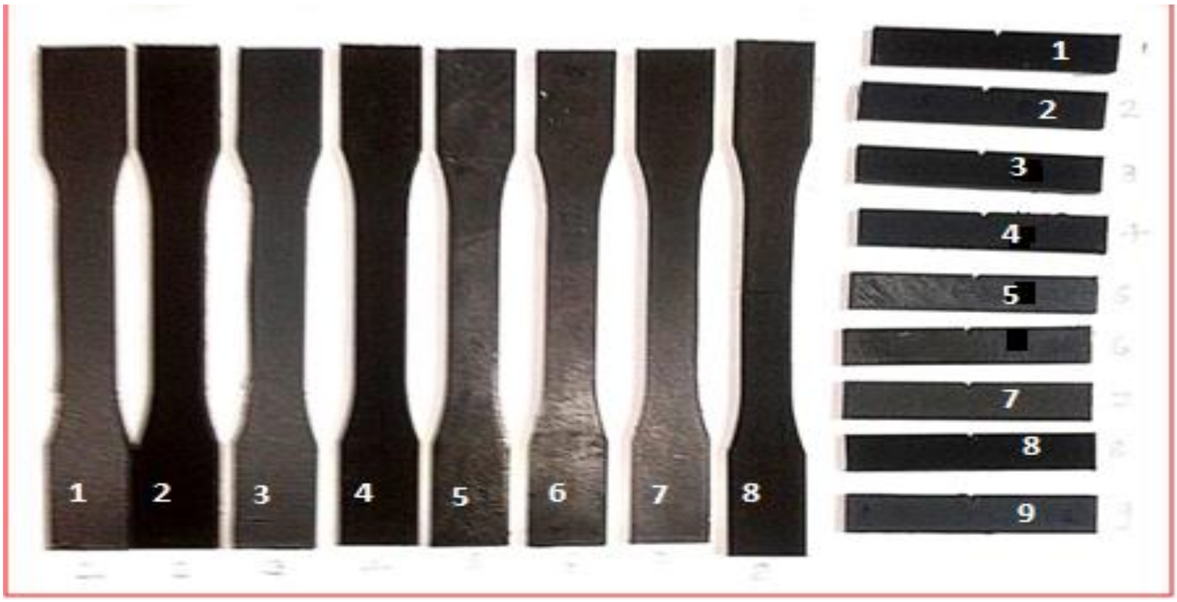

Fig-2.5: 3D Printed sample of tensile test and impact test ASTM-D256

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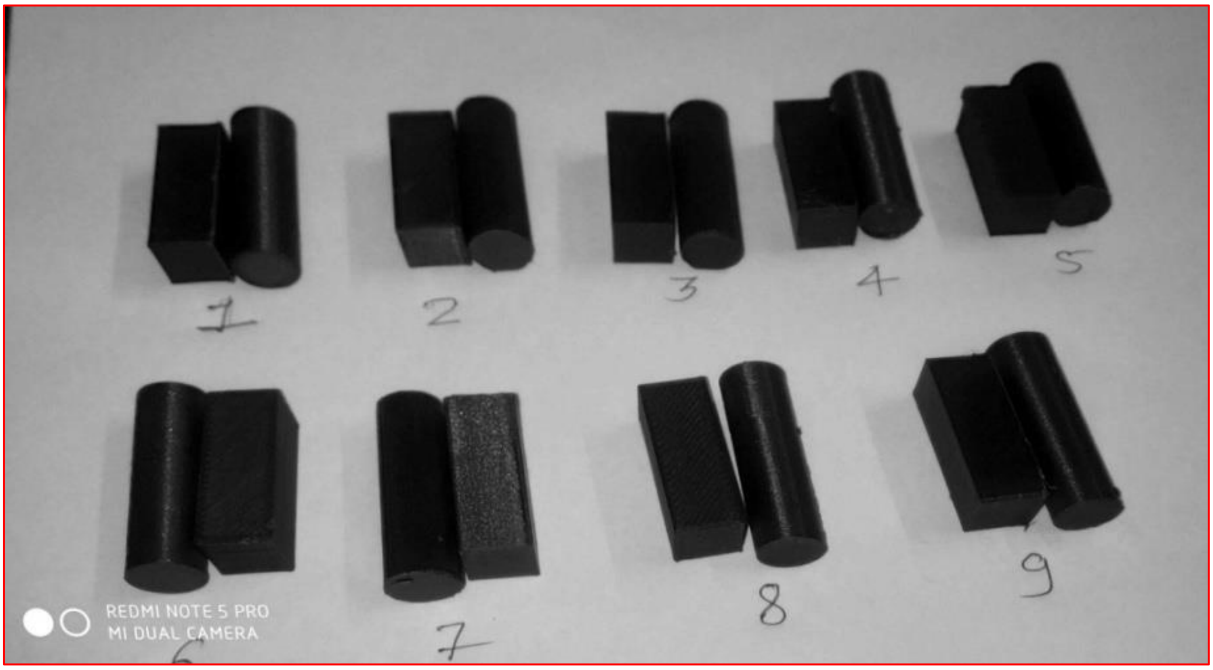

Fig-2.6: 3D Printed sample of surface roughness and wear test ASTM-D256

3 Tests conducted

3.1 SEM morphological test for fractured surface

Utilizing an optical scanning microscope (VEGA3 TESCAN), the microstructure analysis of the manufactured homogeneous CFRP composite was examined to reveal the distribution of structure inside the cracked CFRP surface. The SEM analysis of fractured samples was carried out at the BMS College of Engineering

Fig-3.1: Morphological sets

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3.2 Tensile Test:

In this study tensile strength plays a key role to test the mechanical properties of CFRP. From this testing, ultimate tensile strength, Yield Strength, % of Elongation can be obtained. The tensile test strain rate sets 5mm/min was select with ISO527 test standard and all 9 samples were carried out under equal condition with constant 25ºC of room Temperature. During the testing graph is prepare between the stress vs strain up to break point of specimen and each sample graphs record in memory.

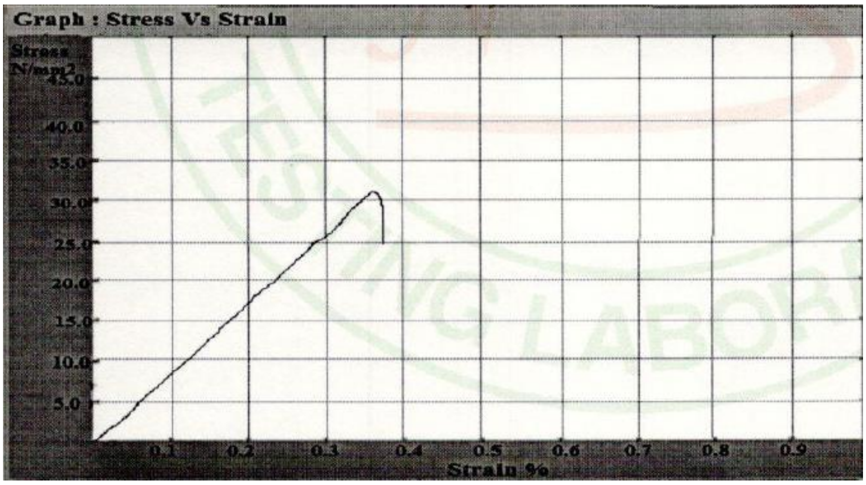

Fig-3.2: stress vs strain graph for sample 9

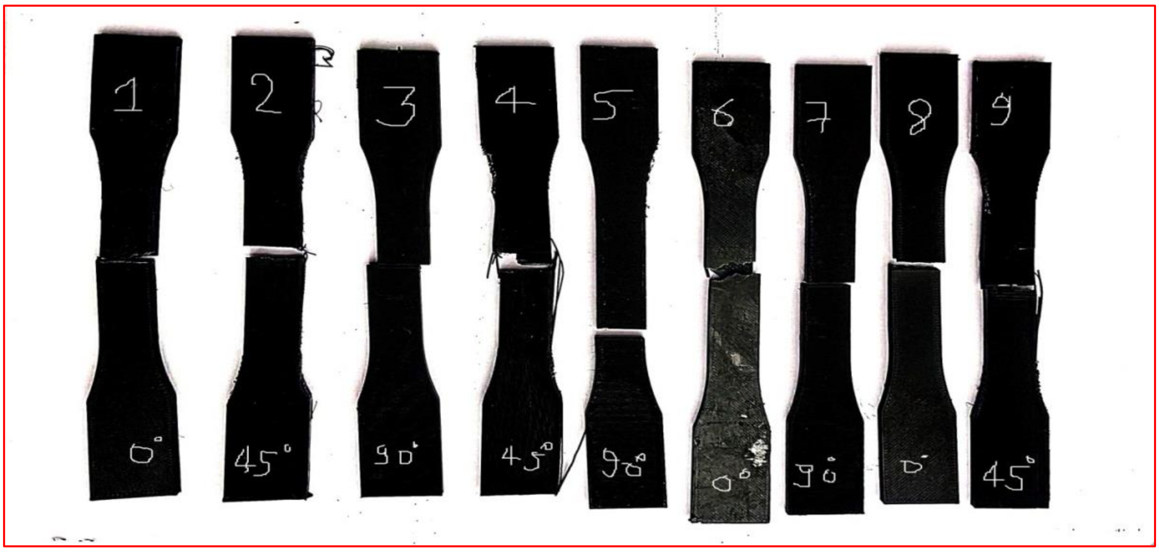

Fig-3.3: Specimen after testing

3.3 Impact test:

In this study impact test plays a vital role to test the mechanical properties of CFRP. Tests were done on CFRP material and the samples measure 63x12x4 (mm), with respect to ASTM D265.ASTM impact energy expressed in Jkg/mm^2 .This method involves carrying out an impact izod test to check how the CRPF will react to these potential problems.

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The following equation is used to calculate the impact strength.

$$I = \frac{E}{A}$$

Where I—Impact Strength, E—Recorded Impact Energy, and A—Area of the

specimen. According to(R., et al., 2021)

Fig-3.4: specimens after impact test

3.4 Surface Roughness test:

In this work, surface roughness was measured using the Mitutoyo surface roughness tester. The average surface height and depth throughout the surface is used to calculate surface roughness. The value "Ra" for "Roughness Average" is most frequently used to represent this measurement, and it is used to assess if equipment complies with different industry requirements. It also depends on how much deviation occurs before the surface becomes smooth or rough.

Fig-3.5: surface roughness tester

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4 Result and Discussion:

4.1 SEM observation test

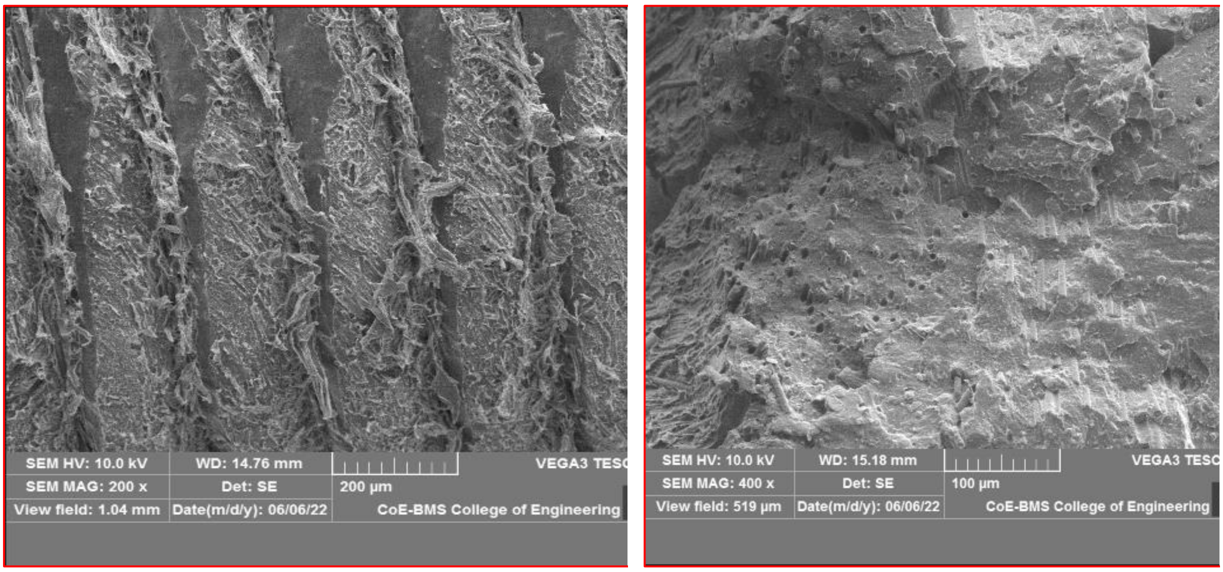

Fig-4. 1: SEM for tensile fracture sample 9

We utilized a tensile test cracked specimen no 9 for SEM examination. Because sample 9 had the greatest tensile strength value, we evaluated its structure in this investigation. We can view the inter-layer adhesion as well as the location and size of pores in micrographs using morphological testing. The 4.1 depicts that, the porosity bonding between the layers is good and it shows brittle fracture, which clearly demonstrates the presence of good strength and other properties which are not seen in the figure.

Tensile test: Ultimate strength, Yield strength, % Elongation

4.1.1 Ultimate strength analysis:

Table 4: response data of UTS

Level	**Layer Thickness(mm)**	**Infill Density (%)**	**Raster Angle (°)**	**Nozzle Temperature (°C)**
1	28.19	29.04	29.10	29.08
2	29.10	29.12	29.11	29.18
3	30.09	29.23	29.17	29.13
Delta	1.90	0.19	0.08	0.10
Rank	1	2	4	3

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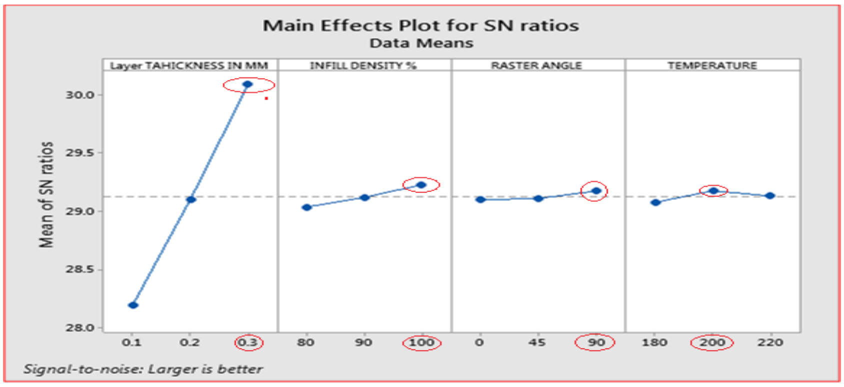

Fig-4.1: main effect plot for SN ratio, UTS

From the tensile study, UTS value is based on **Larger is best** analysis which can detects two most significant effect factors. Figure 4.3 indicates that the increase in the thickness of layer from the 0.1mm (low) to 0.3mm (high) level has a positive effect on ultimate tensile strength. The optimization process demonstrated that the layer thickness is the parameter that has the most influence on the ultimate tensile strength. Layer thickness gives rise to an increase in the UTS of 7%. The 2nd most effective parameter is the infill density. Response table delta values shows that the layer thickness 0.3mm,infill density 100%, raster angle 90º and nozzle temperature 200°C are the most effective parameters according to.(Mohamed, Najoua, Khalid, & Abderrahim, 2021).

Table 5: P value of UTS

Parameters	**D.F**	**Seq. SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	4	59.7281	99.48%	59.7281	14.9320	192.22	0.000
Layer Thickness	1	59.0948	98.43%	59.0948	59.0948	760.74	0.000
Infill Density	1	0.5340	0.89%	0.5340	0.5340	6.87	0.059
Raster Angle	1	0.0726	0.12%	0.0726	0.0726	0.93	0.388
Nozzle Tem	1	0.0267	0.04%	0.0267	0.0267	0.34	0.589
Error	4	0.3107	0.52%	0.3107	0.0777		
Total	8	60.0388	100.00%				

Regression Equation

UTS = 18.98 + 31.38 Layer Thickness + 0.0298 Infill Density + 0.00244 Raster Angle+ 0.00333 Nozzle Tem

Using MINITAB19 software, regression equation results and P values for yield strength tests were determined. With a 95% confidence level, it may be concluded that the observed factors are statistically significant or enormous. The mechanical characteristics are most significantly impacted by layer thickness. At the 95% confidence level, the layer thickness is proven because the P value is smaller than 0.05.

4.1.2 Yield strength:

Table 6: response data of yield strength

Level	**Layer Thickness(mm)**	**Infill Density (%)**	**Raster Angle (°)**	**Nozzle Temperature (°C)**
1	27.80	28.66	28.75	28.76
2	28.77	28.76	28.77	28.77
3	29.67	28.83	28.73	28.71
Delta	1.87	0.17	0.04	0.06
Rank	1	2	4	3

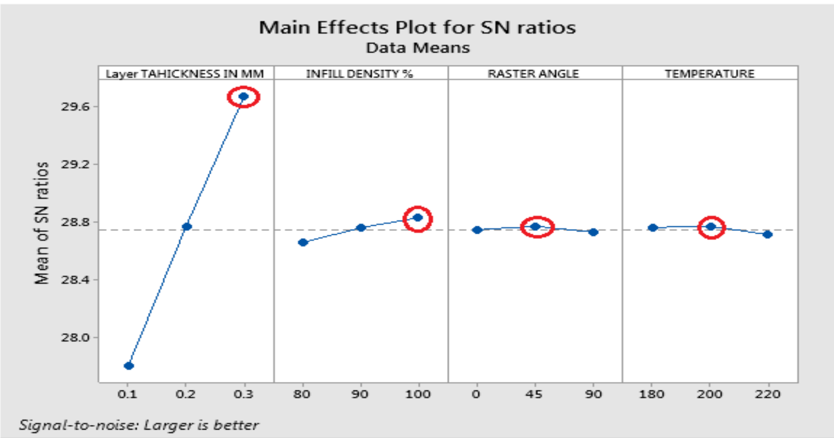

Fig- 4.2: main effect plot for SN ratio, YTS

The S/N ratio graph is shown between the four process parameters and yield strength. As shown in Fig 4.4, all process parameters have a positive effect on the yield strength value. Analyzing the experimental results shows that the layer thickness is the most significant process parameter on yield strength. As the layer thickness increased from 0.1mm (low) to 0.3mm (high) levels, this effect directly increased the impact strength value. The effect of layer thickness at the 0.3mm level is greater than that of the other three process parameters.

Table 7: ANOVA VARIANCE FOR YIELD STRENGTH

Pameters	DF	Seq SS	Contribution	Adj SS	Adj.MS	F-Value	P-Value
Regression	4	59.7281	99.48%	59.7281	14.9320	192.22	0.000
Layer Thickness	1	59.0948	98.43%	59.0948	59.0948	760.74	0.000 Significant
Infill Density	1	0.5340	0.89%	0.5340	0.5340	6.87	0.059 Significant
Raster Angle	1	0.0726	0.12%	0.0726	0.0726	0.93	0.388
Nozzle Tem	1	0.0267	0.04%	0.0267	0.0267	0.34	0.589
Error	4	0.3107	0.52%	0.3107	0.0777		
Total	8	60.0388	100.00%				

Regression Equation

Yield Strength = 20.030 + 29.533 Layer Thickness + 0.02800 Infill Density - 0.00081 Raster Angle- 0.00467 Nozzle Tem

Results of regression equations and P values for yield power tests were calculated using MINITAB19 software. This assessment is completed with a confidence level of 95%, indicating that the observed variables are statistically overwhelming or significant. The layer thickness has the most influential effect on the mechanical properties. Because the P value of layer thickness is less than 0.05, it proves at a 95% confidence level.

4.1.3 % of Elongation

Table 8: response data of elongation

Level	Layer Thickness(mm)	Infill Density (%)	Raster Angle (º)	Temperature (ºC)
1	-4.745	-6.962	-7.254	-6.685
2	-7.137	-6.783	-6.607	-6.890

3	-8.412	-6.549	-6.434	-6.719
Delta	3.667	0.414	0.820	0.205
Rank	1	3	2	4

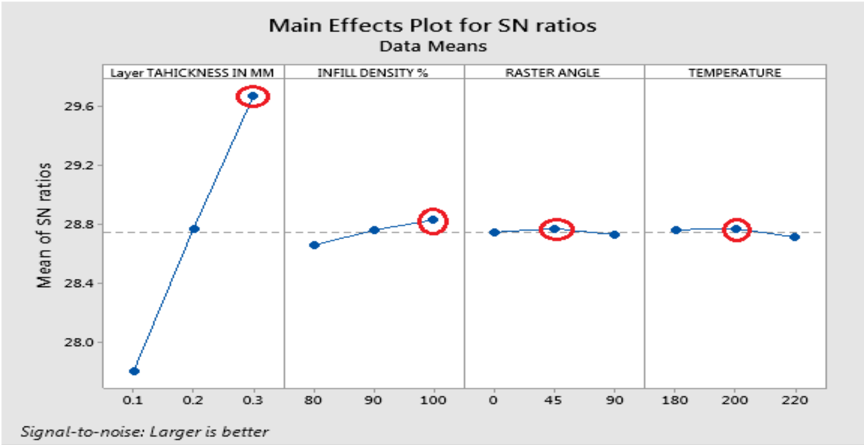

Fig-4.3: % elongation mean effect plot for Sn ratios

The Taguchi analysis's findings in the table indicate that the layer thickness has the greatest impact on the percentage of elongation. The layer thickness increases from the low level of 0.1 mm to the high level of 0.3 mm have a positive effect on elongation break, as shown in Figure 4.5. The element that had the most effect was layer thickness, which had an average increase in elongation break of 77%. The least impact is caused by the nozzle temperature.

4.1.4 Impact Test:

Table 9: response data of impact test

Levels	Layer thickness mm	Infill density %	Raster angle °	Temperature °C
1	56.17	62.34	62.65	62.65
2	64.50	62.65	62.34	62.65
3	67.59	63.27	63.27	62.96
Delta	11.42	0.93	0.93	0.31
Rank	1	2.5	2.5	4

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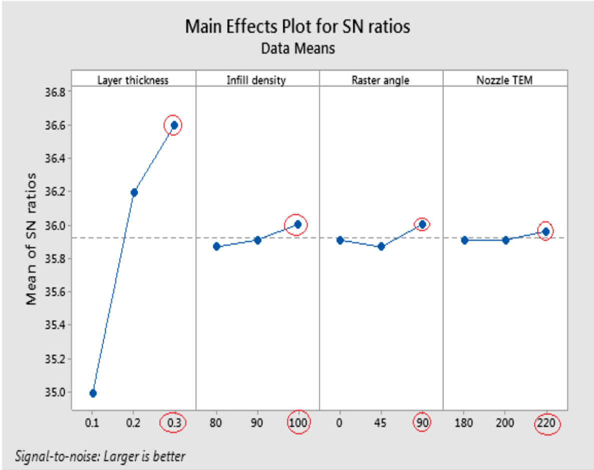

Fig- 4.4: impact test SN ratio Plot

From the analysis of the Taguchi design experiment, based on the S/N ratio results, a influential effect on the impact strength of the FDM fabricated specimens was obtained for the CFRP material where the layer thickness was 0.3 mm, the filling density was 100%, the raster angle was 90º, and the nozzle temperature was 220°C. Table 13 shows that raising the layer thickness from 0.1 mm (low) to 0.3 mm (high) has a good influence on impact strength. Similarly, increasing the nozzle temperature from low to high levels helps in reducing the impact strength. Therefore, the temperature of the nozzle is not affected much.

Table 10: F and P values of impact test

Parameters	DF	Adj SS	Adj MS	F-value	P-value
Regression	4	201.155	50.289	14.35	0.012
Layer Thickness	1	199.181	199.181	56.82	0.002
Infill Density	1	1.354	1.354	0.39	0.568
Raster Angle	1	0.400	0.400	0.11	0.752
Nozzle Tem	1	0.220	0.220	0.06	0.814
Error	4	14.022	3.505		
Total	8	215.177			

Regression Equation

Impact Strength = 44.8 + 57.62 Layer Thickness + 0.0475 Infill Density + 0.0057 Raster Angle+ 0.0096 Nozzle Temperature

To study how factors affect performance indicators, ANOVA analysis of variance is utilized. A parameter is deemed significant if its F ratio is higher than 4 & the F ratio is believed to be unimportant if it is less than 1.

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& P value less than 0.05 denote a significant finding the layer thickness has the most relevant impact on the mechanical properties, i.e., the impact strength according to (Kyrlaki, Dimitrios, & John, 2020).The 95% confidence level increases as the value of layer thickness (0.02) is less than the p (0.05) value.

Table 15: Result of optimal values confirmation of impact test

Parameters	**Level**	**Actual value**
Layer thickness mm	3	0.3
Infill density %	3	100
Raster angle °	3	90°
Nozzle Temperature °C	3	220°C

4.1.5 Surface roughness:

Table 16: response data of surface roughness

Levels	Layer thickness mm	Infill density %	Raster angle °	Nozzle Temperature °C
1	-16.53	-17.53	-10.98	-16.67
2	-20.07	-17.51	-17.05	-17.71
3	-15.92	-17.51	-24.49	-18.14
Delta	4.16	0.04	13.50	1.47
Rank	2	4	1	3

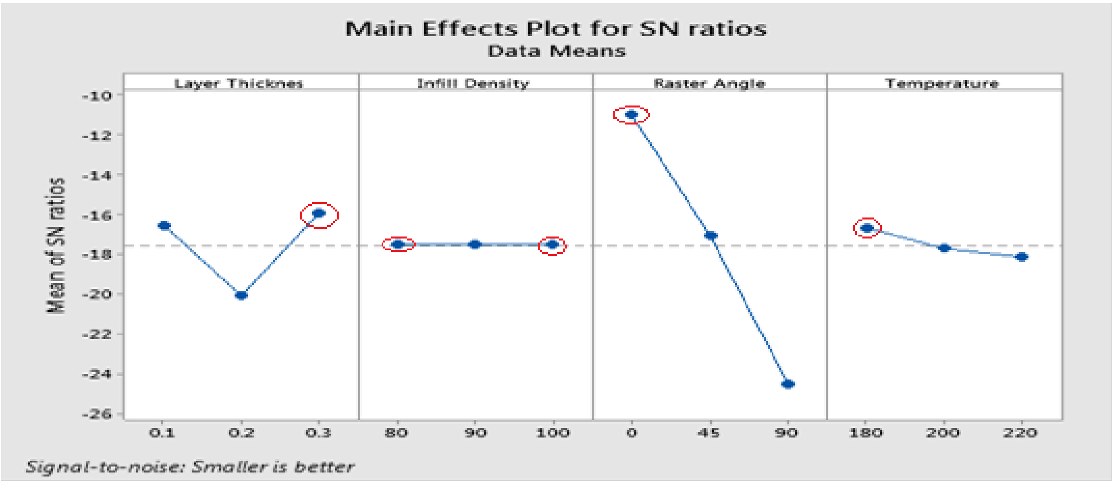

Fig- 4.5: surface roughness S/N ratios plot

The effect of process parameters on SN ratios for each parameter was analyzed as shown in figure 4.7. The result point was calculated using a ‘smaller is better’ approach because this research is targeted at reducing surface roughness value. This is the reason; the "smaller-is-better" equation was used for the evaluation of the SN ratio. The SNR ratio was displayed in response table15.The most significant effect on surface roughness was raster angle. Surface roughness was reduced by an average of 55% by increasing the raster angle from 0º to 90º, Layer thickness was the second-most important factor. In addition, filling density is the least effective parameter among these parameters.

Table 11: ANOVA analysis for Surface roughness

Source	D.F	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	4	265.273	83.87%	265.273	66.318	5.20	0.070
Layer Thickness	1	1.293	0.41%	1.293	1.293	0.10	0.766
Infill Density	1	0.163	0.05%	0.163	0.163	0.01	0.916
Raster Angle	1	263.675	83.37%	263.675	263.675	20.68	0.010
Nozzle Tem	1	0.142	0.04%	0.142	0.142	0.01	0.921
Error	4	51.005	16.13%	51.005	12.751		
Total	8	316.277	100.00%				

Regression Equation

Surface Roughness = 3.6 - 4.6 Layer Thickness - 0.016 Infill Density + 0.1473Raster Angle+ 0.0077 Nozzle Tem

The table shows that the surface roughness test determined that the P value, only the value of the raster angle is the most significant effect among the selected input parameters. This situation shows that the affect of raster angle on mechanical properties is more significant than other parameters.

Table 17: Result of optimal values confirmation of Surface roughness

Parameters	Level	Actual value
Layer thickness mm	3	0.3

Infill density %	4	80,90,100
Raster angle °	1	0°
Nozzle Temperature ºC	1	180°C

4.2 Conclusion:

In this work, we have accurately used the Taguchi technique to evaluate how different system factors affect the three-dimensional printing of CFRP specimens. Additionally, studies were conducted to determine the effect of selected 3D printing parameters—layer thickness, fill density, raster angle, and nozzle temperature on mechanical properties.

- Statistical analysis is used to evaluate the optimal choice of tensile strength values. From Taguchi's Design of Experiment (DOE) optimization analysis for response, layer thickness is the most significant process parameter on the mechanical properties (ultimate tensile strength, yield strength,& % elongation break) of CFRP printed parts. And it has been proven that as the layer thickness increases, the tensile strength also increases.
- From Statistical analysis design of experiment, it was proved that the impact strength is most significantly influenced by layer thickness and raster angle for CFRP printed parts. According to the study, the nozzle temperature has the lowest effect.
- In this study, Taguchi (DOE) and ANOVA analysis were performed to find the best parameters with the least amount of surface roughness. The outcomes demonstrate that the raster angle& surface roughness are closely connected. The roughness of the surface also reduces with increasing raster angle. Compared to other factors, raster angle provided significantly greater surface roughness. It means the minimum roughness of the surface.

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