

SELECTION OF POLYMER EXTRUSION PARAMETERS BY FACTORIAL EXPERIMENTAL DESIGN – A DECISION MAKING MODEL

Raja S¹, John Rajan A*²

¹School of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamilnadu, India-632014. Email: engineerraja@yahoo.com, Tel/Fax: +91 9976376489.

^{2*} School of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamilnadu, India-632014. Email: ajohnrajan@vit.ac.in , Tel/Fax: +91 9444119988.

Abstract

In this modern world, 3D printing technology plays a very important role in the manufacturing sector. It can be found easily in recent decades, be the increasing use of 3D printing in many fields and including FDM (Fusion Deposition Modeling) technology. This research paper is for an Indian electrical switch product-based manufacturing MSME (Micro Small and Medium Enterprises) company, to select the optimum set of printing parameters of the FDM machine for producing a high-quality final product in less time. To this end, the fifteen pieces of ASTM D638 tensile specimen were fabricated with a modified cluster of fourteen printing parameters for ensuring the mechanical property with less production time by the results of fabrication time, tensile test, and microstructure analysis. Moreover, the Design of Experiments (DoE) has been used for the analysis of the tensile strength and FESEM (Field Emission Scanning Electron Microscope) equipment has been used for the analysis of microstructures. Finally, the optimum printing/process parameters have been suggested to the MSME Company based on the experimental results.

Key words- Fusion Deposition Modeling, polymer filament, extrusion process parameters, optimization, Factorial design of experiment, Decision making model.

1. Introduction

The fusion Deposition Modelling machine is based on the type of material extrusion in additive manufacturing. The main raw materials of FDM are PLA (Polylactic Acid), ABS (Acrylonitrile Butadiene Styrene), PC (Poly Carbonate), PA (Poly Amide), medical-grade ABS, and casting wax. The product of material is also manufactured for use in many fields [1-8]. In that sense, an MSME electrical components manufacturing company newly started in India decided to produce high-quality final products in less time by printing parameter optimization of modern FDM machines. Accordingly, many previous researchers have done many kinds of research related to this field. Drummer et al [9] explored the scaffold's mechanical properties by using an FDM machine. Lee W.C et al [10] had designed a low-cost five-axis FDM machine.

Perez et al [11] found that warpage can be prevented by preheating the platform temperature of the FDM machine.

Design of Experiments (DoE) is a well-known optimization method to determine whether a factor or a collection of factors, has an effect on a production process. Mohamed et al [12] explored a review article on the optimization of FDM processes and have also found optimal process/printing parameters like temperature, printing speed, travel speed, etc through the design of the experiment. Azadeh et al [13] was used DoE to select the maintenance parameter for FDM machines. Raja et.al [14] explored the research on selection of optimum printing parameter for ABS filament with tensile behaviour. Efferdz et al [15] was used DoE to optimize spot welded aluminium alloy parameters and obtained the suitable lap shear force. Zhou et al [16] were special nozzle structure is found by DoE method and the data are taken as inlet velocity width and thickness. Then Abdul kadir et al [17] was used DoE to optimize the process parameters selection for cutting speed of the emission prediction. Bernal et al [18] recommended the topological design method for the FDM machine in thermo plastic production and 26% of these reveal Young's modulus variation. Lin et al [19] recommends versatile algorithm for printing isotropic objects and the results of this research describe the isotropic properties of the printing mould. Mustafa et.al [20] explored the research on the selection of appropriate polymer material in the pipeline application

Zekavat et al [21] x-ray computed tomographies were found that tensile strength decreases if the final product's production temperature is low. Paggi et al [22] has detected high flexural modulus starch / cellulose acetate (SCA) and produced it by FDM machine. Zaman et al [23] was selected the FDM process parameters in taguchi method and thus their research uses infill, layer thickness and infill percentage.

Baca et al [24] were compared to single nozzle production method to multi-nozzle filament extrusion process and there are two types of filament extrusion described. Composelo Negrefe [25] explored five optimized responses to find 3D printing process variables. Liu et al [26] were introduced a new rectangular circular grid filling pattern to streamline the use of raw materials in the FDM machine. Feng et al [27] was applied the DoE to select plastic injection moulding process parameters in two staged multi-objective modes. Cherif et al [28] explored compressed properties and failure behaviour by the DOE method.

Oemar and Chang [29] found nine different experimental designs and processing parameters in the DoE system. The purpose of this research is to select the suitable printing parameters of the polymer filament for the MSME electrical switch manufacturing company by using fabrication time, tensile test result and the microstructure. The first step was to modify the cluster of fourteen printing parameters in the FDM machine and fabricate the ASTM D638 polymer tensile specimen with PLA filament and determine the production time. Then the ultimate tensile strength of 5 (specimen) \times 3 (each three sample) was detected from taking into account of tensile test on the produced tensile specimen. Further results were found to be the best

tensile specimen by the DoE single factor experiment. Finally, the microstructure of the fabricated material by FESEM is identified and the appropriate printing parameters are recommended to MSME Company.

2. Experimental Design

2.1 Assumptions made in this research

To find the optimum printing parameter for polymer filament in electrical switch manufacturing, the following assumptions were made.

- Cluster of printing parameters are vital influences in the mechanical property of the final product.
- PLA filament is only used for testing purposes and based on results can find the optimum process parameter for other polymers
- The values of the printing parameters have been taken from the literature from minimum to maximum.
- The printing machine and slicing software if change then the transition of the result occurs.
- Each specimen represent the cluster of printing parameter
- DoE is used to select and compare the clustered printing parameter (specimens)
- FESEM analysis is used to evaluate the printing pattern, defects and surface smoothness of samples (cluster printing parameter formation check)
- This model is help to select the printing parameter for the polymer filament with minimum samples and tests.

2.2 Optimization parameters

For this research, the clustered fourteen process/printing parameters in the slicing software [30-40] were first modified and the tensile specimen for polymer that the ASTM D 638 type V was manufactured using a modern FDM machine. The recent slicing software of flash print 5 has been used for this research. Further, the modified printing parameters are shown in the Table 1. During manufacturing, the time taken for manufacturing and time for printing in slicing software is separately addressed in this research article. Usually, the printing time is available after slicing the production printing parameters. However, the time taken during production is final for calculation because the time available in slicing software is subject to change. Thus this study points out that these two different times were calculated and found differences.

2.3 Tensile Test

The manufactured ASTM D638 specimens are subjected to a tensile test and experiment results (Ultimate Tensile Strength (UTS)) are obtained. The modern INSTRON 5980 series tensile testing machine was used for this and tensile test results can be found in Table 2.

The best tensile specimen can be identified by DoE based on the available UTS (Ultimate Tensile Strength). The best tensile specimen here is to reflect its modified printing parameters. This is because the purpose of this research to recommend the best printing parameters for MSME Electrical Switch manufacturers. The geometrical specifications of the specimen are shown in below Figure 1.

Figure 2 shows the total experimental process of this research work. Figure 2 (A) has a 3D printer that prints the tensile samples and Figure 2 (B) was printed tensile samples of 3 pieces for each specimen. There are 15 samples made for test the tensile strength. Figure 2 (C) shows the tensile test setup and finally Figure 2 (D) shows the output of different specimen microstructures. Figure 2 (D) is also separately detailed in the result section 3. The whole process of this research can be seen in Figure 3.

2.3.1 Single Factor Experiment

Single factor experiment is defined by the previous literature that one predictor variable and one level manipulated [30-35]. Here is a general procedure for conducting a single-factor experiment:

Define the objective: Determine what specific aspect or variable want to investigate and how it relates to the dependent variable.

Select the factor: Identify the single factor (independent variable) that wants to study. It could be a process parameter, a material property, an environmental condition, or any other variable that believe could affect the outcome. The variable of this research is considered the different specimens (each specimen has clustered printing parameter).

Determine the levels: Decide on the range or levels of the factor that want to investigate. This could involve selecting specific values, ranges, or categories for the factor. Make sure the levels cover a meaningful range and are relevant to research. In this research, three trials were conducted for each specimen.

Perform the experiment: Conduct the experiment according to the predefined design. Apply the different levels of the factor to the experimental units or conditions. Ensure that all other factors are kept constant or controlled to isolate the effect of the single factor being studied.

Collect data: Measure or observe the dependent variable for each experimental unit or condition. Record the data accurately and ensure consistency in data collection methods. The Table 2 shows the results of the tensile test of each specimen and also the total for each row and the final total (y_i).

Analyze the data: Perform statistical analysis on the collected data to determine the effect of the factor on the dependent variable. Use appropriate statistical tests, such as ANOVA

or regression analysis, depending on the nature of data and research. Assess the significance of the factor and identify any patterns or trends.

Interpret the results: Interpret the statistical analysis results to draw conclusions about the impact of the factor on the dependent variable. Consider the magnitude of the effect, statistical significance, and any practical implications. If applicable, compare the levels of the factor to identify the optimal or most favorable conditions.

Validate and refine: If necessary, repeat the experiment or perform additional experiments to validate the results or further refine the understanding of the factor's impact. Iterative experimentation can help refine the conclusions and optimize the factor's settings [36-47].

The correction factor was calculated based on the calculated final total value by using formula equation 1.

$$\begin{aligned} \text{Correction factor}(C.F) &= \frac{y_i^2}{n} \dots\dots\dots (1) \\ &= \frac{738.44^2}{15} \end{aligned}$$

$$\text{Correction factor}(C.F) = 36352.9089$$

The obtained Correction factor value is 36352.9089 and here 'n' is the total number of tensile results.

Step: 1 To find the Sum of Square of Total (SST), Sum of Square of Treatment (SS Treatment) and Sum of Square of Error (SSE) by using C.F

$$\begin{aligned} \text{SST} &= [79^2 + 65.25^2 + \dots + 42^2] - \text{CF} \\ &= 38666.9052 - 36352.9089 \end{aligned}$$

$$\text{SST} = 2313.9963$$

The SST is obtained by taking the square of all 15 tensile results and subtracting with the CF.

$$\begin{aligned} \text{SS Treatment} &= \frac{1}{3} [214.07^2 + 152.04^2 + 129.54^2 + 113.79^2 + 129^2] - \text{CF} \\ &= 38437.3007 - 36352.9089 \end{aligned}$$

$$SS \text{ Treatment} = 2084.3918$$

The SS Treatment is obtained by taking the square of all tensile Specimen total results and dividing by three treatments and subtracting with the CF.

$$SSE = SST - SSTreatment$$

$$SSE = 2313.9963 - 2084.3918$$

$$SSE = 229.6045$$

The SSE is obtained by subtracting SST with the $SS_{Treatment}$.

Step: 2 To find the Degrees of Freedom (DoF)

Degrees of Freedom (DoF) were found for Sum of Square of Total (SS_T), Sum of Square of Treatment ($SS_{Treatment}$), and Sum of Square of Error (SS_E) according to the formulas given below equations 2, 3 and 4.

$$SSE = N - 1 \dots\dots (2)$$

$$= 15 - 1$$

$$SST = 14$$

$$SSE = a - 1 \dots\dots\dots (3)$$

$$= 3 - 1$$

$$SSE = 2$$

$$SSE = SST - SSTreatment \dots\dots\dots (4)$$

$$SE = 14 - 2$$

$$SSE = 12$$

Here 'N' is the total number of tensile test result and 'a' is total number of samples from each modified printing parameter.

Step: 3 Establish the ANOVA table

ANOVA table is defined based on the sum of square and degrees of freedom available data and it shown in Table 3. Further, MSE (Mean Square Error) values can be found based on

dividing by its parallel DOF value. F-calculation is obtained by dividing the lower value of the MSE and the larger value of the MSE. The F-table value is found from the standard ANOVA data book from $F_{0.05, 2, 12}$ and the value is 3.89.

The tensile results obtained are considered significant because the F - calculation value is greater than the F-table value.

Step: 4 Test on means (Yi)

Consequently test on means is found by dividing the total number of treatments and number of tensile test.

$$Y_i = \frac{214.07}{3}, \frac{152.04}{3}, \frac{129.54}{3}, \frac{113.79}{3}, \frac{129}{3}$$

$$= 71.356, 50.68, 43.18, 37.93, 43$$

The results are then written in ascending order and sorted.

IV V III II I ... (*Ascending order of specimen*)

$$Y_i = 37.93, 43, 43.18, 50.68, 71.356$$

Step: 5 To find the Sustainable Yield Index (Syi)

Sustainable Yield Index (Syi) is found by the formula given below equation 5 and is multiplied by the k value of the Studential range data. This will make the least square range (LSR) obtained [48].

$$Sy_i = \sqrt{\frac{MSE}{n}} \dots\dots\dots (5)$$

$$= \sqrt{\frac{19.13}{3}}$$

$$Sy_i = 2.52520$$

Here $k = 2, 3, 4, 5$ and ‘k’ means clustering result to evaluate the performance.

From Studential range data, $1 - \gamma = 0.05, \alpha = 12$

$$k = 2, k = 3, k = 4, k = 5$$

$$3.081, 3.773, 4.199, 4.508$$

$$[3.081 \times 2.52520], [3.773 \times 2.52520], [4.199 \times 2.52520], [4.508 \times 2.52520]$$

$$[7.780], [9.528], [10.60], [11.383]$$

Then compare all test mean values and significant combination results with LSR as defined below.

Step 5: Test on mean comparison with least square range data

IV V III II I

$$37.93, 43, 43.18, 50.68, 71.356$$

$$[7.780], [9.528], [10.60], [11.383]$$

Step 6: Comparison of specimens

Compare the terms from higher value of specimen to lower values of specimen with least square range data for significant check

$$I \text{ VS } IV = 71.356 - 37.93 = 33.426$$

$$= 33.426 > 11.383$$

$$= S(\text{Significant})$$

Comparing specimen I and the specimen IV is significant. Then the specimen I is greater than specimen IV.

$$I \text{ VS } V = 71.356 - 43 = 28.356$$

$$= 10.60 < 28.356$$

$$= S(\text{Significant})$$

Comparing specimen I and the specimen V is significant. Then the specimen I is greater than specimen V.

$$I \text{ VS } III = 71.356 - 43 = 28.356$$

$$= 28.176 > 9.528$$

$$= S(\text{Significant})$$

Comparing specimen I and the specimen III is significant. Then the specimen I is greater than specimen III.

$$\begin{aligned} \text{I VS II} &= 71.356 - 50.68 = 20.676 \\ &= 20.676 > 7.780 \\ &= \text{S (Significant)} \end{aligned}$$

Comparing specimen I and the specimen II is significant. Then the specimen I is greater than specimen IV.

$$\begin{aligned} \text{II VS IV} &= 50.68 - 37.93 = 12.75 \\ &= 12.75 > 7.780 \\ &= \text{S (Significant)} \end{aligned}$$

Comparing specimen II and the specimen IV is significant. Then the specimen II is greater than specimen IV.

$$\begin{aligned} \text{II VS V} &= 50.68 - 43 = 7.68 \\ &= 9.528 > 7.68 \\ &= \text{NS (Not Significant)} \end{aligned}$$

Comparing specimen II and the specimen V is not significant but specimen II is greater than specimen V.

$$\begin{aligned} \text{II VS III} &= 50.68 - 43.18 = 7.5 \\ &= 7.780 > 7.5 \\ &= \text{NS (Not Significant)} \end{aligned}$$

Comparing specimen II and the specimen III is not significant but specimen II is greater than specimen III.

$$\begin{aligned} \text{III VS IV} &= 43.18 - 37.93 = 5.25 \\ &= 9.528 > 5.25 \\ &= \text{NS (Not Significant)} \end{aligned}$$

Comparing specimen III and the specimen IV is not significant but specimen III is greater than specimen IV.

$$\text{III VS V} = 43.18 - 43 = 0.18$$

$$= 7.780 > 0.18$$

$$= \text{NS (Not Significant)}$$

Comparing specimen III and the specimen V is not significant but specimen III is greater than specimen V.

$$\text{V VS IV} = 43 - 37.93 = 5.25$$

$$= 7.780 > 5.25$$

$$= \text{S (Significant)}$$

Finally, comparing specimen V and the specimen IV is significant and specimen V is greater than specimen IV.

Based on this, the ultimate tensile strength of specimens I is considered to be better than other tensile specimens.

2.4 FESEM (Field Emission Scanning Electron Microscope)

Microstructures were examined by FESEM after the tensile test. This process helps to find out the microstructure defects and proximity of the product and all of these were detected by a modern Quanta TM 250 FEG machine according to 61x and 100y magnification. Figure 4 (A) illustrates the smallest flaw in the microstructure of the tensile specimen I and a very close and consistent microstructure can also be found. Figure 4 (B) shows the slight shortcomings of specimen II and the slightly random microstructures. Figure 4 (C) illustrates the microstructure with the longest spacing of specimen III. Furthermore, Figure 4 (D) illustrates the minor flaw and ambiguous microstructure of specimen V. The most important finding of this research was that if an object was produced using the 3D infill pattern method the microstructure of that object could not be explored. The main primary reason for this is considered to be the high infill exhibits high moisture or conductivity and other factors should be identified through individualized exclusive research for this. Specific FESEM results are taken into account in this study because the value of specimen I and specimen V in terms of tensile strength is more significant than other specimen. Accordingly, the specimen I has a much clearer and closer microstructure than other specimens. Therefore specimen I is considered the best in terms of FESEM analysis.

3. Results

The aim of this research is to produce a final product in less time. Therefore approximate time is available after adjusting the printing parameters of an object by FDM slicing software. However, differences were found within one or two minutes compared with after production time. The approximate fabrication times of specimen I, specimen II, specimen III, specimen IV and specimen V in Table 4 are given as 10, 19, 11, 9 and 8, respectively but the time available after production is 11, 19, 12, 10 and 9 minutes. All Specimens, slicing software times are slightly different except for specimen II. Therefore the time available after production is considered as the final time.

Accordingly, specimen V has the shortest time and Specimen II has the longest time. The typical production time of all available specimens is estimated at 12.2.

$$\text{Average time} = (11 + 19 + 12 + 10 + 9) / 5 = 12.2 \text{ minutes}$$

Thus the specimen less than 12.2 minutes is taken into account for the result.

The single factor experiment in the DoE method is used to calculate the final ultimate tensile strength. For this, the specimen I is considered significant and also specimen I is considered to be much better than other specimen. Then the UTS of specimen I has evaluated by 71.356 MPa.

The microstructure of specimen I is also considered to be better than other specimens based on FESEM results. Specimen II, specimen III, and specimen V microstructure have vague and long gaps.

It is noteworthy that microstructures could not be detected when using the 3D infill pattern as another novelty of this research and all these can be seen in figure 4. Considering the overall results of this research paper, specimen I is less than 12.2 minutes based on fabrication time, specimen I is significantly more specific than other specimens in terms of ultimate tensile strength, and finally FESEM based specimen I has a much closer microstructure and less flaws. Therefore the printing parameters of specimen I (the parameters specified in table 1) were recommended to MSME Company.

4. Conclusion

This research aims to enable an Indian MSME electrical switch manufacturing company to produce high-quality final products with modern FDM machines in less time. For this, five types of ASTM D638 type V tensile specimens were produced by modifying the clustered 14 process parameters that can be used in the FDM machine. The time produced during production is calculated and compared with the slicing software time. A slight time difference has been found in this. Thus the process/printing parameters of Specimen I are considered to be the best in terms of tensile strength and FESEM depending on the time of production. This research also reveals that if an object is produced with a very new 3D infill pattern its microstructure cannot be

detected. It would be a scope of new novelty for future researchers to discover this significant cause. Finally the process parameters in specimen I, are recommended to the MSME Company that obtaining the objective of this research.

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Captions: List of Figures and Tables

Figure 1 Specifications of tensile specimen as per ASTM D638

Figure 2 Experimental process of this research

Figure 3 Entire research flow of this paper

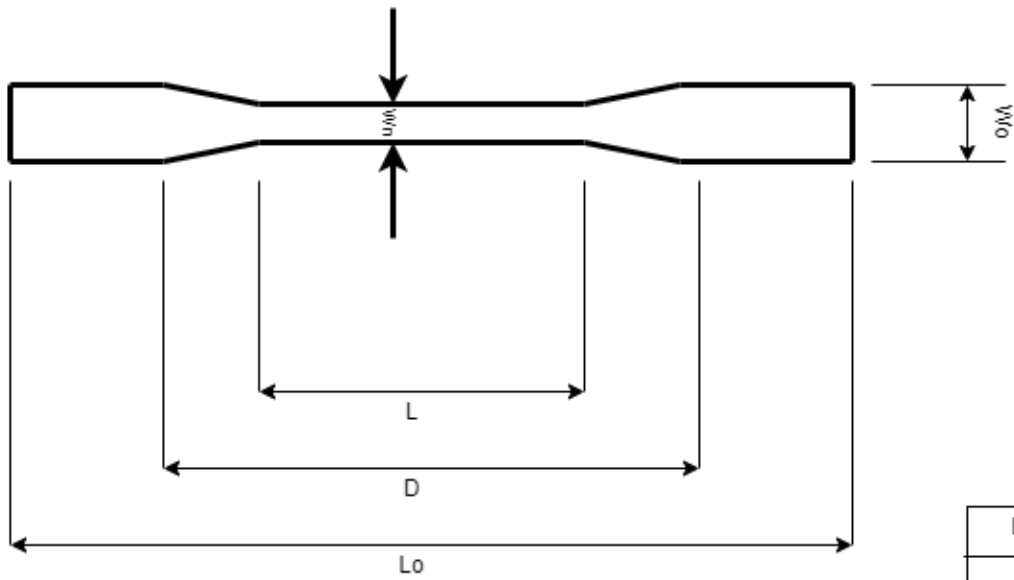
Figure 4 Microstructure of different specimens (caption: red/white color circles indicate the gaps, dents, flaws, and defect in structures)

Table 1 Printing parameters in material extrusion (Slicing Software: Flash Print 5)

Table 2 Tensile test result of specimens

Table 3 ANOVA (Analysis of Variance)

Table 4 Slicing software time VS Fabrication time



ASTM D638
TYPE-V

Lo	63.5 mm
D	25.4 mm
L	9.53 mm
Wo	19 mm
Wn	3.18 mm

Figure 1

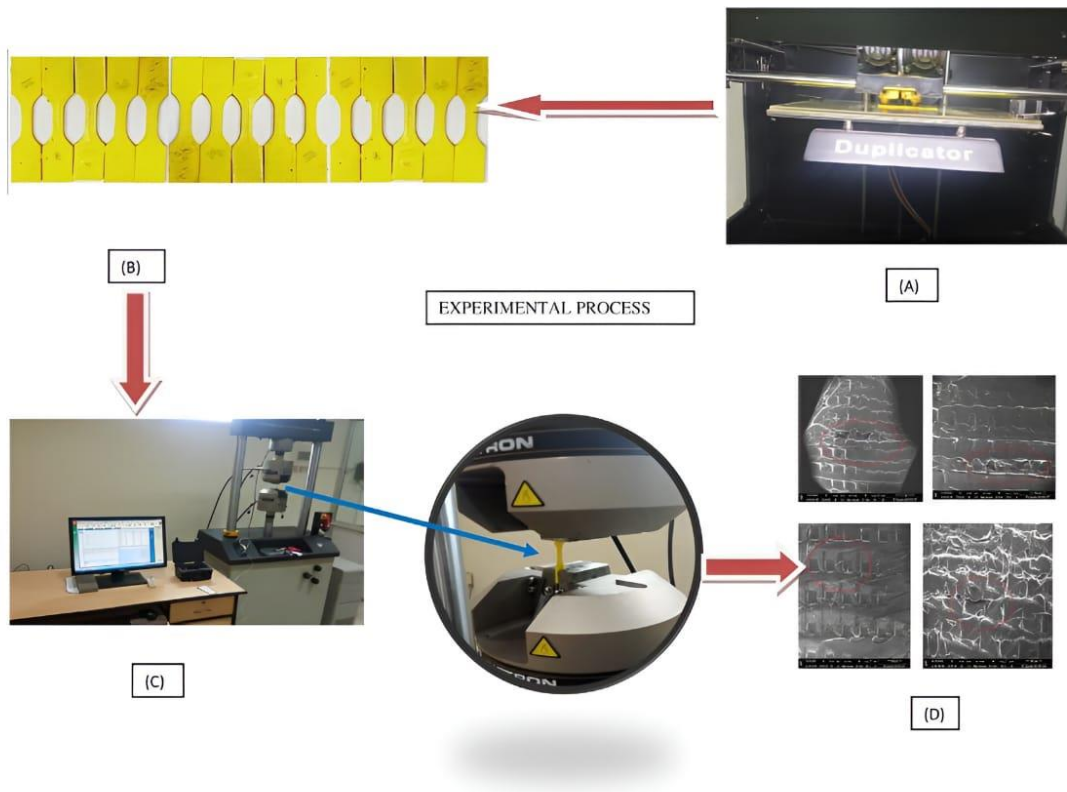


Figure 2

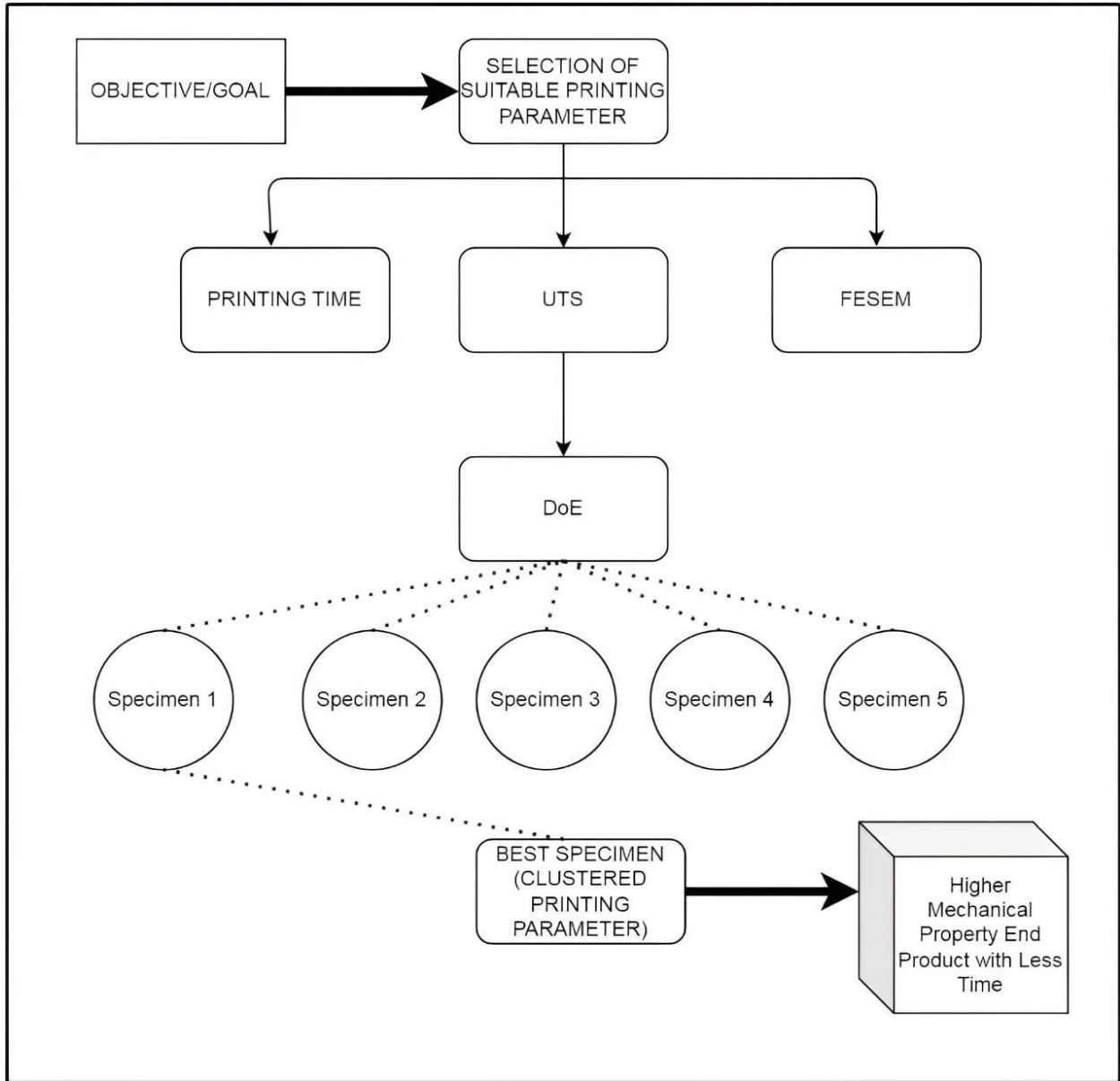


Figure 3

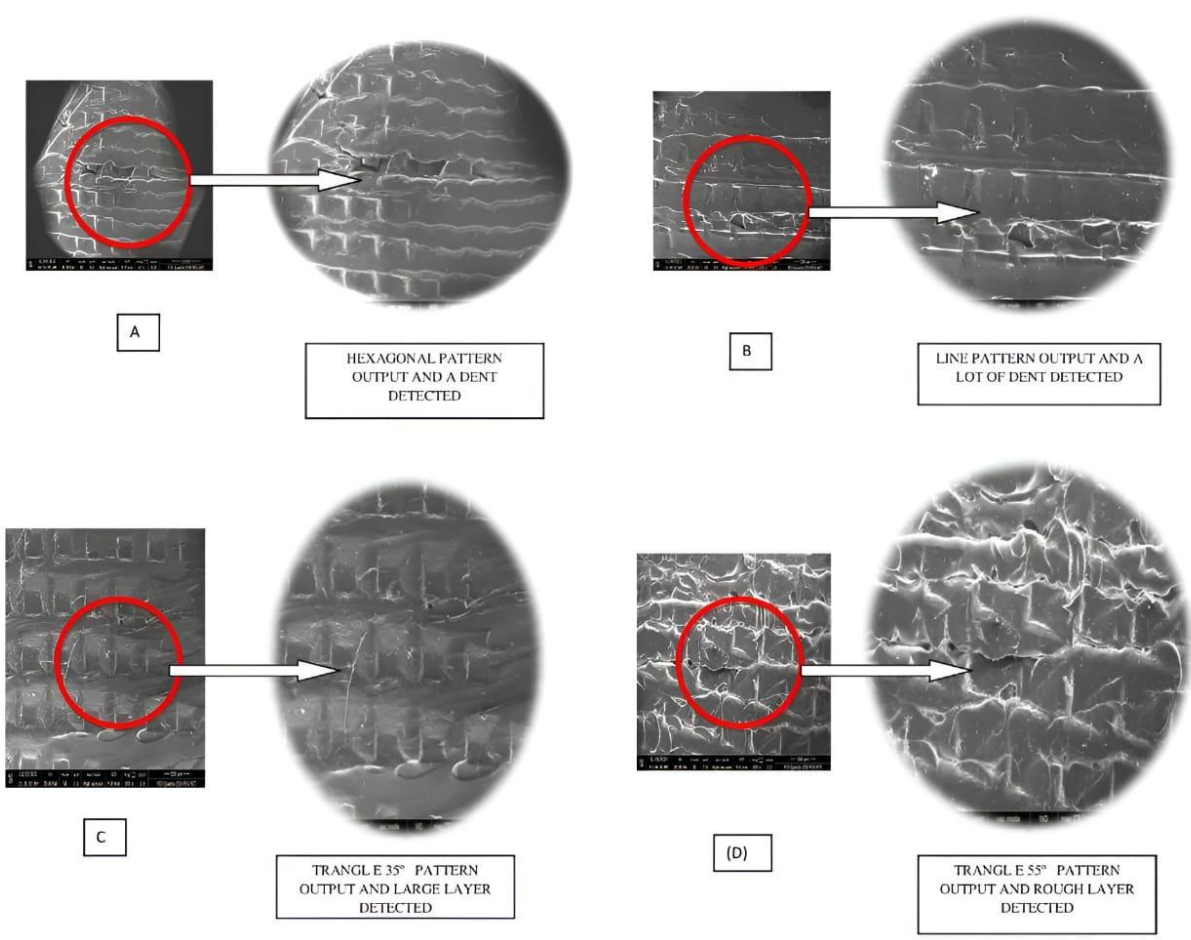


Figure 4

Table 1

Parameters	Specimen -I	Specimen-II	Specimen-III	Specimen-IV	Specimen-V
Extruder temperature [30-40]	200°C	210°C	215°C	217°C	219°C
Platform temperature [9,30-40]	50 °C	0 °C	0 °C	0 °C	0 °C
Layer height	0.18 mm	0.12 mm	0.20 mm	0.20 mm	0.23 mm
First layer height	0.27 mm	0.20 mm	0.25 mm	0.24 mm	0.21 mm
Printing speed [9,30-40]	60 mm/s	30 mm/s	70 mm/s	75 mm/s	55 mm/s
Travel speed [9,30-40]	80 mm/s	60 mm/s	90 mm/s	80 mm/s	70 mm/s
Shell count	2	3	2	2	2
First layer maximum speed	10 mm/s	10 mm/s	10 mm/s	15 mm/s	15 mm/s
Infill density [18, 9,30-40]	15%	15%	30%	20%	35%
Infill pattern [18, 9,30-40]	Hexagonal	Line	Triangle 35°	3D Infill	Triangle 55°
Shell thickness	0.80 mm	1.20 mm	0.80 mm	0.90 mm	1.10 mm
Exterior speed	0.40mm	0.40 mm	0.40 mm	0.40 mm	0.40 mm
Exterior maximum speed	40 mm/s	40 mm/s	45 mm/s	50 mm/s	40 mm/s
Top solid layer	3	4	3	4	3

Table 2

Parameters optimized specimen	Ultimate Tensile Strength (UTS) (MPa)			Total
I	79	65.25	69.82	214.07
II	49	55	48.04	152.04
III	48	39.25	42.29	129.54
IV	40	34.14	39.65	113.79
V	48	39	42	129
Final Total (y_i)				738.44

Table 3

Source	Sum of Square	DOF	Mean Square	F-CAL	F-TABLE	REMARK
Treatment	2084.3918	2	1042.1959	54.47	3.89	Significant
Error	229.6045	12	19.13			
Total	2313.9963	14				

Table 4

Specimens	Approximate time taken for fabrication by slicing software (Minute)	Actual time taken for fabrication (Minute)
I	10	11
II	19	19
III	11	12
IV	9	10
V	8	9

Authors Biography



Raja.S received his Diploma and Bachelor's in Mechanical Engineering and Master in Industrial Safety Engineering from Anna University, Tamilnadu, India. He received MBA, PGDCFS, and PGDNGOM from Annamalai University, Tamilnadu, India. Presently play the role of Teaching cum Research Assistant in one of the Premium Institute of VIT University and Managing Director of Mr.R BUSINESS CORPORATION (R&D), India and his research Interest is Soft Computing in Engineering. He is a Board member of Mr.R EDUCATIONAL SERVICES (NGO) and member of The Institution of Green Engineers (IGEN). He is a reviewer of various international journals in Elsevier and Springer Publications in the field of Manufacturing and Industrial Engineering. He got the esteemed awards of Raman Research Award (RRA) and Dr.A.P.J Abdul Kalam Award for his excellent research contribution.



Dr. John Rajan A is a Professor of Department of Manufacturing Engineering in School of Mechanical Engineering (SMEC), Vellore Institute of Technology (Institute of Eminence - IoE), Vellore-632 014, India. He received his Doctor of Philosophy from Anna University, Chennai. He has published several papers in international and national journals and presented Conference papers in the area of Operations Research, Supply Chain Management & Logistics, Wind turbine Manufacturers' supply chain and advanced Welding Techniques. His research interest includes application of decision-making tools and mathematical programming to supply chain management, Advanced Welding Techniques, Small wind turbines, Green Logistics, Solar PV Technology and Coating. He is a life member of Indian Society of Technical Education (ISTE), Indian Institute of Production Engineers (IPE) and Operational

	<p>Research Society of India (ORSI), International Association of Engineers (IAENG), Member in the Institution of Engineering and Technology (IET) and Member in Institute for Engineering research and publication (IFERP). He has produced four Ph.Ds and published eight patents. He is a reviewer of various international journals in Elsevier and Springer Publications in the field of Manufacturing and Industrial Engineering. He published several patents and seven Design Patents are awarded. He has completed a funded project from IGCAR, Kalpakkam and currently a doing project sanctioned by ISRO, Mahendragiri</p>
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