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Selection of polymer extrusion parameters by factorial experimental design-A decision making model

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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 Fusion Deposition Modeling (FDM) technology. This research paper is for an Indian electrical switch product-based manufacturing Micro Small and Medium Enterprises (MSME) 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 Field Emission Scanning Electron Microscope (FESEM) 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.

1. Introduction

The Fusion Deposition Modelling (FDM) 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, a Micro Small and Medium Enterprise (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 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. Zhau 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

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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 and Ahmad [24] were compared to single nozzle production method to multi-nozzle filament extrusion process and there are two types of filament extrusion described. Composeco-Negrete [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. Cherief 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 (UTS) of 5 (specimen) × 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 Field Emission Scanning Electron Microscope (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 represents 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 D638 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 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.

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

Parameters	Specimen I	Specimen-II	Specimen-III	Specimen-IV	Specimen-V
Extruder temperature [30-40]	200ºC	210ºC	215ºC	217ºC	219ºC
Platform temperature [9,30-40]	50ºC	0ºC	0ºC	0ºC	0ºC
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 35º	3D Infill	Triangle 55º
Shell thickness	0.80 mm	1.20 mm	0.80 mm	0.90 mm	1.10 mm
Exterior speed	0.40 mm	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. Tensile test result of specimens.

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**

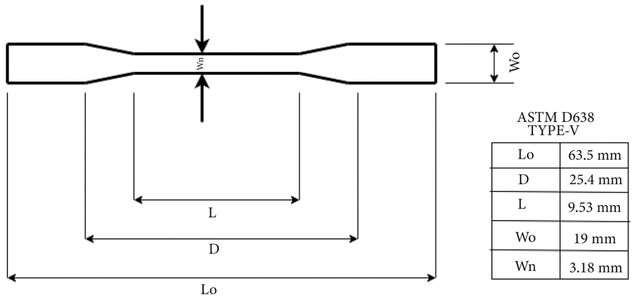

Figure 1. Specifications of tensile specimen as per ASTM D638.

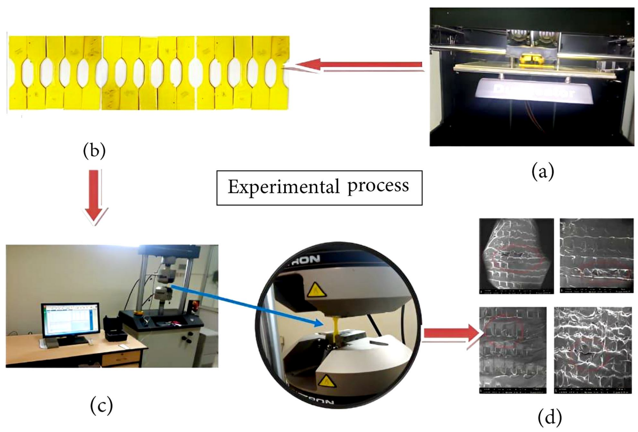

Figure 2. Experimental process of this research.

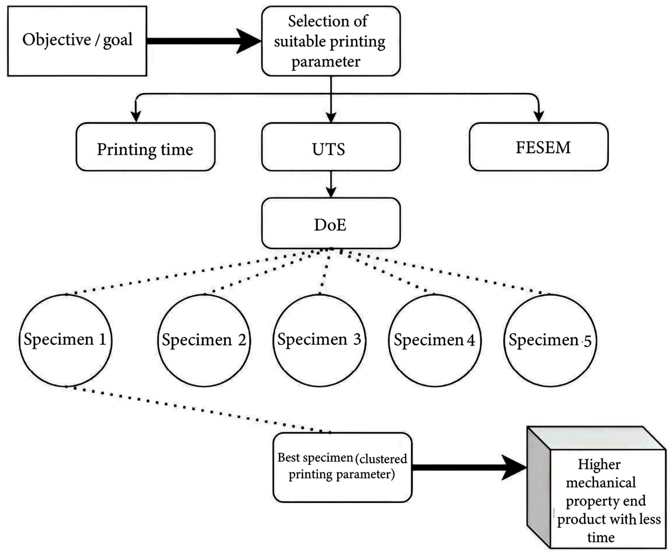

Figure 3. Entire research flow of this paper.

2.3. Tensile test

The manufactured ASTM D638 specimens are subjected to a tensile test and experiment results (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. 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 Figure 1.

Figure 2 shows the total experimental process of this research work. Figure 2 (A) has a 3D printer that print 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. Table 2 shows the results of the tensile test of each

Table 3. ANOVA (Analysis of Variance).

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**				

specimen and also the total for each row and the final total (*yi*).

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 Eq. (1):

$$Correction\ Factor\ (CF) = \frac{yi^2}{n} = \frac{738.44^2}{15},$$

$$Correction\ Factor\ (CF) = 36352.9089. \quad (1)$$

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

The following steps were involved to find the best result with comparison of tensile results by using single factorial experiment:

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 *CF*:

$$SST = [79^2 + 65.25^2 + \cdots + 42^2] - CF$$

$$= 38666.9052 - 36352.9089,$$

$$SST = 2313.9963.$$

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

$$SS\ Treatment = \frac{1}{3}[214.07^2 + 152.04^2 + 129.54^2 + 113.79^2 + 129^2] - CF$$

$$= 38437.3007 - 36352.9089,$$

$$SS\ Treatment = 2084.3918.$$

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*.

$$SSE = SST - SS\ Treatment,$$

$$SSE = 2313.9963 - 2084.3918,$$

$$SSE = 229.6045.$$

The SSE is obtained by subtracting SST with the SS Treatment.

Step 2. To find the Degrees of Freedom (DoF):
DoF were found for SST, Sum of Square of Treatment (SS Treatment), and Sum of Square of Error (SSE) according to the formulas given below (Eqs. (2)–(4)):

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

$$= 15 - 1$$

$$SST = 14,$$

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

$$= 3 - 1$$

$$SSE = 2,$$

$$SSE = SST - SS\ Treatment \quad (4)$$

$$SE = 14 - 2$$

$$SSE = 12,$$

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 DoF 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 tests.

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

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

The results are then written in ascending order and sorted.

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

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

Step 5. To find the Sustainable Yield Index (S_{Yi}):

Sustainable Yield Index (S_{Yi}) is found by the formula given below Eq. (5) and is multiplied by the k value of the Studential range data. This will make the Least Square Range (LSR) obtained [48].

$$S_{Yi} = \sqrt{\frac{MSE}{n}} = \sqrt{\frac{19.13}{3}},$$

$$S_{Yi} = 2.52520. \quad (5)$$

Here $k = 2,3,4,5$ and 'k' means clustering result to evaluate the performance:

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

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

$3.081,\quad 3.773,\quad 4.199,\quad 4.508$

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

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

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

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

Step 6. Test on mean comparison with LSR data:

IV V III II I

$37.93, 43, 43.18, 50.68, 71.356$

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

Step 7. 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 VS IV $= 71.356 - 37.93 = 33.426$

$= 33.426 > 11.383$

= S (Significant).

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

I VS V $= 71.356 - 43 = 28.356$

$= 10.60 < 28.356$

= S (Significant).

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

I VS III $= 71.356 - 43 = 28.356$

$= 28.176 > 9.528$

= S (Significant).

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

I VS II $= 71.356 - 50.68 = 20.676$

$= 20.676 > 7.780$

= S (Significant).

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

II VS IV $= 50.68 - 37.93 = 12.75$

$= 12.75 > 7.780$

= S (Significant).

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

II VS V $= 50.68 - 43 = 7.68$

$= 9.528 > 7.68$

= NS (Not Significant).

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

II VS III $= 50.68 - 43.18 = 7.5$

$= 7.780 > 7.5$

= NS (Not Significant).

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

III VS IV $= 43.18 - 37.93 = 5.25$

$= 9.528 > 5.25$

= NS (Not Significant).

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

III VS V $= 43.18 - 43 = 0.18$

$= 7.780 > 0.18$

= NS (Not Significant).

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

V VS IV $= 43 - 37.93 = 5.25$

$= 7.780 > 5.25$

= S (Significant).

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

Based on this, the UTS 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 specimens. Accordingly, the specimen I has a

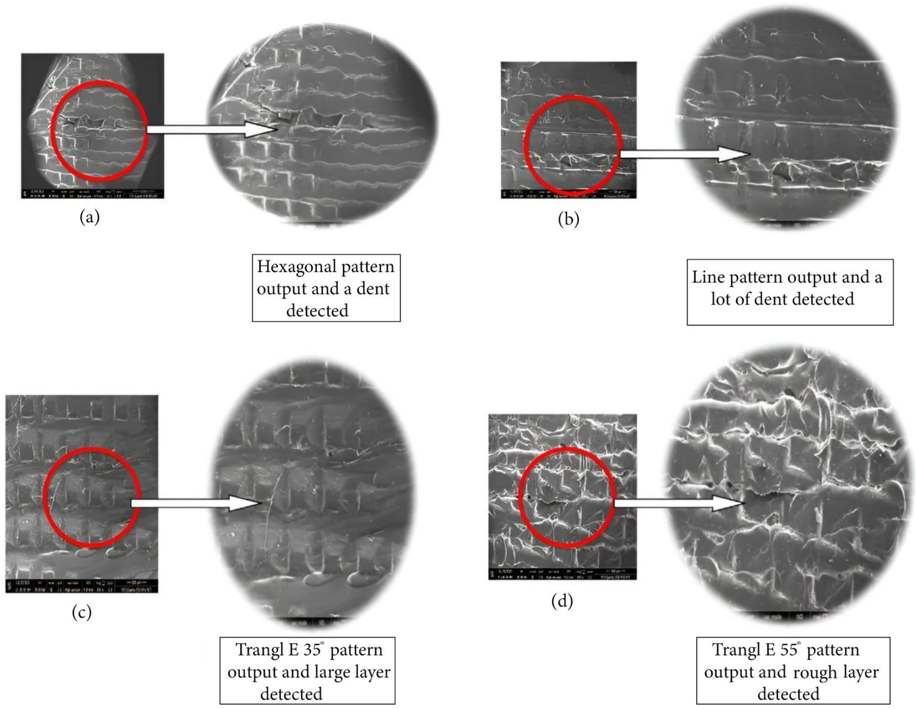

Figure 4. Microstructure of different specimens (caption: red/white color circles indicate the gaps, dents, flaws, and defect in structures).

Table 4. Slicing software time vs fabrication time.

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

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.

$$\text{Averagetime} = \frac{11+19+12+10+9}{5} = 12.2 \text{ minutes.}$$

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 UTS. 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 UTS, 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 Micro Small and Medium Enterprise (MSME) electrical switch manufacturing company to produce high-quality final products with modern Fusion Deposition Modeling (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 Field Emission Scanning Electron Microscope (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.

References

1. Antonio Travieso-Rodriguez, J., Zandi, M.D., Jerez-Mesa, R., et al. "Fatigue behavior of pla-wood composite manufactured by fused filament fabrication", *Journal of Materials Research and Technology*, **9**(4), pp. 8507–8516 (2020). DOI: 10.1016/j.jmrt.2020.06.003

2. Raja, S., and Rajan A., J. "Challenges and opportunities in additive manufacturing polymer technology: a review based on optimization perspective", *Advances in Polymer Technology*, **2023**, p. 18 (2023). DOI: 10.1155/2023/8639185

3. Cerda-Avila, S.N., Medellín-Castillo, H.I., Cervántes-Uc, J.M., et al. "Fatigue experimental analysis and modelling of fused filament fabricated pla specimens with variable process parameters", *Rapid Prototyping Journal*, **29**(6), pp. 1155-1165 (2023). DOI: 10.1108/RPJ-10-

4. Naranjo, J.A., Berges, C., Gallego, A., et al. "A novel printable high-speed steel filament: towards the solution for wear-resistant customized tools by AM alternative", *Journal of Materials Research and Technology*, **11**, pp. 1534–1547 (2021). DOI: 10.1016/j.jmrt.2021.02.001

5. Rosli, N.A., Alkahari, M.R., bin Abdollah, M.F., et al. "Review on effect of heat input for wire arc additive manufacturing process", *Journal of Materials Research and Technology*, **11,** pp. 2127–2145 (2021). DOI: 10.1016/j.jmrt.2021.02.002

6. Bhayana, M., Singh, J., Sharma, A., et al. "A review on optimized fdm 3d printed wood/pla bio composite material characteristics", *Materials Today: Proceedings*, (2023). DOI: 10.1016/j.matpr.2023.03.029

7. Al Rashid, A., Khan, S.A., G. Al-Ghamdi, S., et al. "Additive manufacturing of polymer nanocomposites: needs and challenges in materials, processes, and applications", *Journal of Materials Research and Technology*, **14**, pp. 910–941 (2021). DOI: 10.1016/j.jmrt.2021.07.016

8. Chen, S., Gao, H., Zhang, Y., et al. "Review on residual stresses in metal additive manufacturing: formation mechanisms, parameter dependencies, prediction and control approaches", *Journal of Materials Research and Technology,* **17**, pp. 2950–2974 (2022). DOI: 10.1016/j.jmrt.2022.02.054

9. Drummer, D., Cifuentes-Cuéllar, S., and Rietzel, D. "Suitability of pla/tcp for fused deposition modeling", *Rapid Prototyping Journal*, **18**(6), pp. 500–507 (2012). DOI: 10.1108/13552541211272045

10. Lee, W.C., Wei, C.C., and Chung, S.C. "Development of a hybrid rapid prototyping system using low-cost fused deposition modeling and five-axis machining", *Journal of Materials Processing Technology*, **214**(11), pp. 2366–2374 (2014). DOI: 10.1016/j.jmatprotec.2014.05.004

11. Torrado Perez, A.R., Roberson, D.A., and Wicker, R.B. "Fracture surface analysis of 3d-printed tensile specimens of novel abs-based materials", *Journal of Failure Analysis and Prevention*, **14**(3), pp. 343–353 (2014). DOI: 10.1007/s11668-014-9803-9

12. Mohamed, O.A., Masood, S.H., and Bhowmik, J.L. "Optimization of fused deposition modeling process parameters: a review of current research and future prospects", *Advances in Manufacturing*, **3**(1), pp. 42–53 (2015). DOI: 10.1007/s40436-014-0097-7

13. Azadeh, A., Gharibdousti, M.S., Firoozi, M., et al. "Selection of optimum maintenance policy using an integrated multi-criteria taguchi modeling approach by considering resilience engineering", *International Journal of Advanced Manufacturing Technology*, **84**(5–8), pp. 1067–1079 (2016). DOI: 10.1007/s00170-015-7733-7

14. Raja, S. and Rajeswari, N. "Optimization of acrylonitrile butadiene styrene filament 3d printing process parameters based on mechanical test", *International Journal of Mechanical and Industrial Engineering*, **4**(3), pp. 35–47 (2023). DOI: 10.47893/IJMIE.2022.1204

15. Effertz, P.S., Quintino, L., and Infante, V. "The optimization of process parameters for friction spot welded 7050-t76 aluminium alloy using a taguchi orthogonal array", *International Journal of Advanced Manufacturing Technology*, **91**(9–12), pp. 3683–3695 (2017). DOI: 10.1007/s00170-017-0048-0

16. Zhou, M., Kong, L., Xie, L., et al. "Design and optimization of non-circular mortar nozzles using finite volume method and taguchi method", *International Journal of Advanced Manufacturing Technology*, **90**(9–12), pp. 3543–3553 (2017). DOI: 10.1007/s00170-016-9675-0

17. Abdulkadir, L.N., Abou-El-Hossein, K., Abioye, A.M., et al. "Process parameter selection for optical silicon considering both experimental and AE results using taguchi L9 orthogonal design", *International Journal of Advanced Manufacturing Technology*, **103**(9–12), pp. 4355–4367 (2019). DOI: 10.1007/s00170-019-03788-x

18. Berrio Bernal, J.D., Silva, E.C.N., and Montealegre Rubio, W. "Characterization of effective young's modulus for fused deposition modeling manufactured topology optimization designs", *International Journal of Advanced Manufacturing Technology*, **103**(5–8), pp. 2879–2892 (2019). DOI: 10.1007/s00170-019-03747-6

19. Lin, S., Xia, L., Ma, G., et al. "A maze-like path generation scheme for fused deposition modeling", *International Journal of Advanced Manufacturing Technology*, **104**(1–4), pp. 1509–1519 (2019). DOI: 10.1007/s00170-019-03986-7

20. Ahmed Mustafa, M., Raja, S., Abdulrasool A.L. Asadi, L., et al. "A decision-making carbon reinforced material selection model for composite polymers in pipeline applications", *Advances in Polymer Technology*, **2023**, p. 9 (2023). DOI: 10.1155/2023/6344193

21. Zekavat, A.R., Jansson, A., Larsson, J., et al. "Investigating the effect of fabrication temperature on mechanical properties of fused deposition modeling parts using X-ray computed tomography", *International Journal of Advanced Manufacturing Technology*, **100**(1–4), pp. 287–296 (2019). DOI: 10.1007/s00170-018-2664-8

22. Paggi, R.A., Salmoria, G.V., Ghizoni, G.B., et al. "Structure and mechanical properties of 3D-printed cellulose tablets by fused deposition modeling", *International Journal of Advanced Manufacturing Technology*, **100**(9–12), pp. 2767–2774 (2019). DOI: 10.1007/s00170-018-2830-z

23. Zaman, U.K. uz, Boesch, E., Siadat, A., et al. "Impact of Fused Deposition Modeling (FDM) process parameters on strength of built parts using Taguchi's design of experiments", *International Journal of Advanced Manufacturing Technology*, **101**(5–8), pp. 1215–1226 (2019). DOI: 10.1007/s00170-018-3014-6

24. Baca, D., and Ahmad, R., "The impact on the mechanical properties of multi- material polymers fabricated with a single mixing nozzle and multi-nozzle systems via fused deposition modeling", *International Journal of Advanced Manufacturing Technology*, **106**(9–10), pp. 4509–4520 (2020). DOI: 10.1007/s00170-020-04937-3

25. Camposeco-Negrete, C. "Optimization of printing parameters in fused deposition modeling for improving part quality and process sustainability", *International Journal of Advanced Manufacturing Technology*, **108**(7–8), pp. 2131–2147 (2020). DOI: 10.1007/s00170-020-05555-9

26. Liu, W., Li, Y., Liu, B., et al. "Development of a novel rectangular–circular grid filling pattern of fused deposition modeling in cellular lattice structures", *International Journal of Advanced Manufacturing Technology*, **108**(11–12), pp. 3419–3436 (2020). DOI: 10.1007/s00170-020-05461-0

27. Feng, Q.Q., Liu, L., and Zhou, X. "Automated multi-objective optimization for thin-walled plastic products using taguchi, ANOVA, and hybrid ANN-MOGA", *International Journal of Advanced Manufacturing Technology*, **106**(1–2), pp. 559–575 (2020). DOI: 10.1007/s00170-019-04488-2

28. Cherief, M., Belaadi, A., Bouakba, M., et al. "Behaviour of lignocellulosic fibre- reinforced cellular core under low-velocity impact loading: taguchi method", *International Journal of Advanced Manufacturing Technology*, **108**(1–2), pp. 223–233 (2020). DOI: 10.1007/s00170-019-04488-2

29. Oemar, B. and Chang, W.C. "Taguchi method for optimizing process parameters in the production of activated carbon from rubber seed shell", *International Journal of Advanced Manufacturing Technology*, **107**(11–12), pp. 4609–4620 (2020). DOI: 10.1007/s00170-020-05344-4

30. Raja, S., Rajan, A.J., Kumar, V.P., et al., "Selection of additive manufacturing machine using analytical hierarchy process", *Scientific Programming,* **2022**(1596590), p. 20 (2022).

DOI: 10.1155/2022/1596590

31. Karthick, M., Meikandan, M., Kaliappan, S., et al. "Experimental investigation on mechanical properties of glass fiber hybridized natural fiber reinforced penta-layered hybrid polymer composite", *International Journal of Chemical Engineering*, **2022**(1864446), pp. 1–9 (2022). DOI: 10.1155/2022/1864446

32. Raja, S. and Rajan, A.J. "A decision-making model for selection of the suitable FDM machine using fuzzy TOPSIS", *Mathematical Problems in Engineering*, **2022**(7653292), p. 15 (2022).

DOI: 10.1155/2022/7653292

33. Olaiya, N.G., Maraveas, C., Salem, M.A., et al. "Viscoelastic and properties of amphiphilic chitin in plasticised polylactic acid/starch biocomposite", *Polymers*, **14**(11), p. 2268 (2022). DOI: 10.3390/polym14112268

34. Natrayan, L., Kaliappan, S., Sethupathy, S., et al. "Investigation on interlaminar shear strength and moisture absorption properties of soybean oil reinforced with aluminium trihydrate-filled polyester-based nanocomposites", *Journal of Nanomaterials*, **2022**(7588699), pp. 1–8 (2022). DOI: 10.1155/2022/7588699

35. Subramani, R., Kaliappan, S., Sekar, S., et al. "Polymer filament process parameter optimization with mechanical test and morphology analysis", *Advances in Materials Science and Engineering*, **2022**(259804), pp. 1–8 (2022). DOI: 10.1155/2022/8259804

36. Raja, S., Agrawal, A.P., Patil, P.P., et al. "Optimization of 3d printing process parameters of polylactic acid filament based on the mechanical test", *International Journal of Chemical Engineering*, **2022**(830869), pp. 1–7 (2022). DOI: 10.1155/2022/5830869

37. Subramani, R., Kaliappan, S., Arul, P., et al. "A recent trend on additive manufacturing sustainability with supply chain management concept, multicriteria decision making techniques", *Advances in Materials Science and Engineering*, **2022**(151839), pp. 1–12 (2022). DOI: 10.1155/2022/9151839

38. Raja, S., Logeshwaran, J., Venkatasubramanian, S., et al. "OCHSA: designing energy-efficient lifetime-aware leisure degree adaptive routing protocol with optimal cluster head selection for 5 g communication network disaster management", *Scientific Programming*, **2022**(424356), pp. 1–13 (2022).

    DOI: 10.1155/2022/5424356

39. Mannan, K.T., Sivaprakash, V., Raja, S., et al. "Effect of roselle and biochar reinforced natural fiber composites for construction applications in cryogenic environment", *Materials Today: Proceedings*, **69**(3), pp. 1361–1368 (2023). DOI: 10.1016/j.matpr.2022.09.003

40. Mannan, K.T., Sivaprakash, V., Raja, S., et al. "Significance of si 3 n 4 / lime powder addition on the mechanical properties of natural calotropis gigantea composites", *Materials Today: Proceedings*, **69**(3), pp. 1355–1360 (2023). DOI: 10.1016/j.matpr.2022.09.002

41. Benali, N., Hammami, D., Khlif, M., et al. "Optimization of fdm manufacturing parameters of a biodegradable thermoplastic (pla)", Lecture Notes in Mechanical Engineering, pp. 355–362 (2020). DOI: 10.1007/978-3-030-27146-6_38

42. Sodeifian, G., Ghaseminejad, S., and Yousefi, A. "Preparation of polypropylene/short glass fiber composite as Fused Deposition Modeling (FDM) filament", Results in Physics, **12**, pp. 205-222 (2019). DOI: 10.1016/j.rinp.2018.11.065

43. Sodeifian, G., Ardestani, N.S., Sajadian, S.A., et al. "Application of supercritical carbon dioxide to extract essential oil from cleome coluteoides boiss: experimental, response surface and grey wolf optimization methodology", *The Journal of Supercritical Fluids*, **114**, pp. 55-63 (2016). DOI: 10.1016/j.supflu.2016.04.006

44. Sekhar, K.C., Surakasi, R., Roy, P., et al. "Mechanical behavior of aluminum and graphene nanopowder-based composites", *International Journal of Chemical Engineering*, **2022**(10), pp. 1–13 (2022). DOI: 10.1155/2022/2224482

45. Velmurugan, G., Shankar, V.S., Kaliappan, S., et al. "Effect of aluminium tetrahydrate nanofiller addition on the mechanical and thermal behaviour of luffa fibre-based polyester composites under cryogenic environment", *Journal of Nanomaterials*, **2022**(5970534), pp. 1–10, (2022).
    DOI: 10.1155/2022/5970534

46. Ameri, A., Sodeifian, G., and Sajadian, S.A. "Lansoprazole loading of polymers by supercritical carbon dioxide impregnation: impacts of process parameters", *The Journal of Supercritical Fluids*, **164**, 104892 (2020). DOI: 10.1016/j.supflu.2020.104892

47. Sodeifian, G. and Ansari, K. "Optimization of ferulago angulata oil extraction with supercritical carbon dioxide", *The Journal of Supercritical Fluids*, **57**(1), pp. 38–43 (2011). DOI: 10.1016/j.supflu.2011.02.002

48. Pillaca- Pullo, O.S., Lopes, A.M., Rodriguez- Portilla, L.M., et al. "Optimizing medium composition with wastewater from coffea arabica processing to produce single- cell protein using candida sorboxylosa", *Journal of Chemical Technology & Biotechnology*, **98**(1), pp. 106–116 (2023). DOI: 10.1016/j.supflu.2011.02.002

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