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Application of Box-Behnken, ANN, and ANFIS Techniques for Identification of The Optimum Processing Parameters for FDM 3D Printing Parts

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Abstract

Fused Deposition Modeling, among the various 3D printing approaches, is becoming more and more popular because of its capacity to produce complicated parts quickly. The tensile strength of parts printed with polylactic acid (PLA) showed a significant variation of many factors such as printing speed, printing temperature, printing angle and infill pattern. This study presented an experimental investigation of collecting data with four input factors namely printing speed, printing temperature, printing angle and infill pattern with the tensile strength response. The research methodology of the RSM Box-Behnken DOE method, ANN (Artificial neural network), and ANFIS (Adaptive neuro-fuzzy inference systems) has been used to determine the optimum process 3D printing parameters. The obtained results based on RSM, ANN and ANFIS methods are used to predict the tensile strength of 3D printed FDM details. The best tensile value is 7,03303 MPa corresponding to print speed of 30,0003 mm/s, printing temperature of 211,594℃, printing angle of 90° with Honeycomb" infill printing pattern. Moreover, the results also highlighted that ANFIS is potential approach for forecasting the tensile strength of 3D printing parts more competitively.

Keywords : *FDM; 3D Printing; Box-Behnken; ANN; ANFIS; DOE*

INTRODUCTION

Fused Deposition Modeling, among the different 3D printing approaches, is becoming more and more popular because of its ability to produce complex parts quickly. In the FDM method, the effect of the infill rate on the parts made with FDM is analyzed and a good mechanical properties are obtained at a 100% infill rate. These are not unique, there are different complicated processes, parameters of which need to be fine-tuned to understand their influence on the characteristics of printed components. The location of the deposited layers is a factor that determines the bond strength between the layers and the durability of printed components under various loading modes. FDM inputs such as layer thickness, line width, printed part quality, and dimensional accuracy were analyzed using various methods such as the Taguchi technique. The effect of various factors on the tensile strength was presented and printing direction was considered as a potential influencing factor. The effect of various FDM inputs on the compressive strength was studied and it was stated that the strength could be enhanced by increasing the layer thickness and reducing the air gap between the printed layers. The mechanical characteristics of the parts decrease as the layer thickness increases, and better mechanical strength can be achieved at smaller layer thickness, lower print speeds and uniform orientation. The tensile strength of parts printed with polylactic acid (PLA) presented a significant variation according to the layer thickness. The influence of FDM inputs such as printing direction, layer height, and speed on the mechanical properties of PLA test sample is usually studied based on ANOVA and DOE (Design of Experiments) to characterize the optimal parameter. Various advanced optimization strategies are of recent interest, such as Taguchi, DOE, genetic algorithms (GA), factorial design, ANN, ANFIS, and their hybrid approaches are being applied by interested researchers to obtain optimum printing parameters that combine to improve the mechanical strength of FDM-based printed parts. The ability to estimate more accurately by ANN-based models and ANFIS models compared with arithmetic-based models makes this method promising for engineering prediction. Based on a review of the literature, it can be stated that in order to extract optimized inputs to maximize the strength of FDM components, many experiments need to be performed. The process parameters are determined through modeling and optimization techniques. Thus, the need for progressive modeling can suggest an optimal set of processing parameters for maximizing the strength of 3D printed parts. Many attempts have been implemented to estimate and predict the tensile of FDM parts using RSM, ANN modeling techniques. However, there are not many studies using RSM, ANN and ANFIS in improving the tensile strength of FDM 3D printed parts.

Research on additive manufacturing and focus on FDM printing technology, change some designs compared to 3D printer operating parameters in order to improve tensile strength of fabricated parts. The research procedure are as follows: To conduct a survey of technological parameters to the mechanical properties of products and experimental planning methods, optimizing parameters for the manufacturing process of products by FDM technology; To determine the technological parameters, planning, processing data, interpreting the results to determine the optimal set of technological parameters for the tensile strength of FDM products using the RSM method, ANN and ANFIS. The current study considered the impact of various process printing parameters on the tensile strength of FDM-printed PLA components. The CAD model sample is created first by Autodesk Inventor software and saved as *.STL file, then exported to Ultimaker CURA to generate the slice and saved as G-code file. The RSM are used to set the parameters and their levels in each run, and the ANOVA test is employed to explore the results. The ANN and ANFIS for predicting the tensile strength.

The remainder of the paper is structured as follows. In next section a related word is presented, and another section will present an experimental investigation and methodology followed by results and discussion. The final section conducts the conclusions with suggestions for future research.

RELATED WORKS

The characteristics of 3D printed components by additive manufacturing, depend on different process parameters of the printers. Process parameters are often used to optimize based on statistical methods to improve the functional capacity. Deshwal, Kumar and Chhabra [1] tested the tensile strength of a standard part based on the ASTM-D638-V fabricated on a PLA 3D printer using FDM method. In which, the samples were tested according to three different process parameters, namely infill density (20 ÷ 100%), printing speed (50 ÷ 150 mm/s) and printing temperature (190 ÷ 210℃). Dey and Yodo [2] identified FDM process parameters that have a significant influence on part properties and manufacturing efficiency. Some of the most common parameters like air gap, prototyping orientation, extrusion temperature, infill pattern, infill density layer thickness, number of shells, printing speed, raster angle, width, and processing temperature. Chohan, Kumar, Singh, Singh, Sharma, Singh, Mia, Pimenov, Chattopadhyaya, Dwivedi and Kapłonek [3] examined the effects of fabrication angle direction, temperature and finishing time on surface quality, strength and durability. Tensile and weight of the FDM part during surface polishing. Özen, Auhl, Völlmecke, Kiendl and Abali [4] have studied to optimize the fabrication parameters and the geometry of the tensile part for the FDM method with 3D PETG printing materials. Catana, Pop and Brus [5] compared simulation and experimental results when analyzing flexural stress for 3D printed structures using PLA and PLA materials mixed with glass. The prototypes were tested on a Create Bot DX-3D printer with two extruders, and the printing parameters set were layer height of 0.2 mm, printing temperature of 210℃, print angle of 45℃, printing platform temperature of 61℃, material infill rate of 100% and also filled on top and bottom faces, infill overlap of 10% and infill flow of 110%. Alharbi, Kong and Patel [6] simulated uniaxial strain and stress response for 3D printed parts with PLA materials using nonlinear finite element method. The precise simulation of the mechanical characteristics of 3D printed objects can create the good inputs in design and manufacturing. PLA materials are a renewable polymer with many potential applications. Hodžić, Pandžić, Hajro and Tasić [7] compared the strength of 3D printed parts with PLA made from printers of various manufacturers. These printers used FDM technology and had a price difference of up to 50%, and the printing parameters are set with a wire diameter of 2.85 mm, printing temperature from 190℃ to 235℃, extrusion hole diameter of 0.4 mm. Özsoy [8] analyzed the finite element to determine the stress for printed parts with PLA materials. The parameters for the printing process are print temperature of the extrusion head of 235℃, material extrusion hole diameter of 0.4 mm, layer height of 0.2 mm, print layer width of 1.2 mm, hexagon/honeycomb run-out pattern, bed temperature of 70℃ and print speed of 40 mm/s. Rahmatabadi, Aminzadeh, Aberoumand and Moradi [9] have presented the mechanical properties of FDM. Raster angle and orientation were considered to be the two main processing parameters affecting the strength of the printed part, and most failure mechanisms vary rapidly with these two parameters. The studies [10, 11] built two new theoretical models to forecast the tensile capacity and elastic modulus of PLA materials for different print angle and print thickness parameters. Printing parameters include printing layer height of 0.1 mm, 0.2 mm, and 0.3 mm; printing speed and infill density. The print bed temperature is controlled at 60℃ and the filament is heated to 220℃ during printing. The FDM AM test specimen complies with ISO 527-2-2012. The printed part pattern oriented to seven various printing angles (0°, 15°, 30°, 45°, 60°, 75° and 90°). Rajpurohit and Dave [12] investigated the impact of processing parameters such as raster angle, layer thickness, and raster width to study the influence on the tensile. Printed part conforming to ASTM D638. Samples are printed on the high-precision OMEGA printer. Durga Prasada Rao, Rajiv and Navya Geethika [13] reported the influence of printing parameters on the tensile of carbon fiber PLA materials. Their investigated parameters, including printing layer thickness, extrusion temperature, and infill pattern, affect the tensile strength. They used full factorial design with three parameters, each parameter has three levels: printing layer height (0.1 mm, 0.2 mm, 0.3 mm); infill pattern (cubic, subic sub division, quarter cubic) and print temperature (205℃, 215℃, and 225℃). Yao, Deng, Zhang and Li [14] presented a theoretical model to predict the maximum tensile strength of PLA FDM materials based on the reverse isotropic hypothesis, classical layer theory and Hill-Tsai criterion. Then, they tested the model experimentally. Test samples are ISO 527-2-2012 compliant with three print heights of 0.1 mm, 0.2 mm, and 0.3 mm. Altan, Eryildiz, Gumus and Kahraman [15] studied the influence of processing parameters on the quality of FDM-fabricated products, such as tensile strength and surface roughness. The PLA samples were fabricated on an FDM printer at various layer heights, nozzle temperatures and print velocities. Hikmat, Rostam and Ahmed [16] have now experimentally and statistically investigated the influence of various parameters such as built orientation, raster angle, nozzle diameter, extrusion temperature, infill density, number of layers and printing speed on tensile capacity when to use PLA wire (1.75 mm diameter). Their results depicted that the strength of the printed part is affected by the chosen process parameters, of which only three are, the built orientation, the nozzle diameter (0.5 mm) and infill density (100%) are in considerable influence. While printing direction has the greatest influence on tensile capacity (44.68%). In the study [17], 27 tensile test samples with various combinations of parameters were fabricated with a low-cost FDM 3D printer based on the ASTM D638-I to assess their tensile properties. Fixed parameters set for experiment included first layer thickness of 0.3 mm, bottom shell, line printed pattern, print speed of 30 mm/s, nozzle diameter of 0.3 mm, plastic wire diameter of 1.75 mm, extrusion temperature of 195℃, and printing platform temperature of 110℃.

In the study [18], the tensile strength testing was performed to analyze the tensile capacity of FDM printed PLA parts. The effect of printing parameters such as raster angle (0°, 45°, and 90° levels), layer thickness (0.1 mm, 0.2 mm and 0.3 mm) and raster width (0.5 mm, 0.6 mm and 0.7 mm) have been tested with print modes including 100% infill density, bed temperature of 70℃, nozzle temperature of 210℃, print speed of 50 mm/s, orientation along the X-axis, the print pattern is linear. Similarly, Vălean, Marșavina, Mărghitaș, Linul, Razavi and Berto [19] studied the tensile strength of FDM printed parts using three process parameters including print orientation (0°, 45° and 90°), specimen thickness (1.25; 2.15; 3.70; 4.0 or 8.0 mm) and specimen width (6, 7, 10, and 13 mm). Model according to ISO 527-1 (2012), Zwick Roell 005 gauge with 5 kN load capacity, 2 mm/min pull-to-break speed at room temperature. Ayatollahi, Nabavi-Kivi, Bahrami, Yazid Yahya and Khosravani [20] investigated the effect of in-plane raster angle on the tensile and fracture strength of PLA samples performed using the FDM technology. Four different raster orientations of 0/90°, 15/−75°, 30/−60° and 45/−45° were selected for the dog-bone and semicircular bent prints for investigation. Tensile strength and fracture behavior (mode I) of 3D printing of PLA materials. Grasso, Azzouz, Ruiz-Hincapie, Zarrelli and Ren [21] presented the effect of temperature on the tensile capacity of 3D printed PLA materials. Printed samples were subjected to static load testing in the thermal range of 20℃ to 60℃ considering various printing orientation. Temperature with five levels of 20-30-40-50-60℃ and printing directions 0°/90°, −30°/60°, and ±45°.

Rajpurohit and Dave [22] presented empirical test quantifying the influence of three process parameters such as raster orientation (0°, 45°, 90°), layer thickness (100, 200, 300 μm) and width raster (500, 600, 700 μm) on tensile capacity of FFF/FDM printed PLA, using OMEGA 3D printer, print space 500 × 500 × 500 mm, print layer resolution of 0.1 mm, position accuracy in X, Y axis is 11 μm, Z axis is 10 μm, extruder diameter is 0.4 mm, maximum printing speed is 150 mm/s. Other operating parameters for the machine are kept constant such as: 210℃ printing temperature, 70℃ printing platform temperature, 50 mm/s printing speed, 100% infill density, linear print pattern. Three process parameters namely raster angle, raster width and layer thickness were changed to study its effect on the tensile capacity of PLA-material component [23]. The tensile capacity of PLA material was analyzed based on the Taguchi approach [24]. The scissors were printed using FDM technique with various process factors - layer thickness (0.2, 0.4 and 0.6 mm), extruding speed (5, 10 and 15 mm/ s) and infill patterns (line, zig-zag and concentric). The study [25] compared print pattern and infill density created by CAD and FDM process. The mesh, triangle, zig-zag and concentric patterns with different densities follow the same structure of the FDM printer designed by CATIA software. Surface roughness and tensile capacity were performed to check the effect on dog-bone prints.

In study [26], the test samples printed from thermoplastics PLA and ABS have six various stacking sequencing at three levels of infill density (30%, 60% and 90%) and two raster angles (0° and 45°) and they are mechanically investigated the tensile strength. The study [27] presented the FDM process parameters including slice parameters (printing speed, nozzle diameter, layer thickness, printing angle, feeding speed, infill pattern, infill density, etc.), number of shells, raster angle, air gap), built orientation, and temperature modes.

The previous works presented the influence of several 3D printing process parameters, and they highlighted that the process parameters highly impacted on the 3D printed components, and the most significant factors are layer height, raster angle, built orientation, air gap, infill density, and raster width as mentioned above. Besides, several parameters can affect the component's tensile capacity and processing time, and printing cost; however, few researches investigated, for example, raster orientation and infill pattern. As these factors change, requires a modification in the tensile strength of printed part using FDM technology. Therefore, in the current study, this process has been completed with a consideration of printing speed, temperature, orientation angle, and infill pattern. Moreover, this work presented the impact of these factors together and its interaction on the tensile capacity of PLA material with FDM-based approach with the considerations of RSM, ANN and ANFIS methods.

EXPERIMENTAL INVESTIGATION

Research procedure

Procedure of research has been implemented in Figure 1. After the CAD sample model is designed based on Autodesk Inventor software and exported to *.STL file, with the support of MeshLab software, to check the errors existing in the *.STL file. The CAD sample will be layered and established the process parameters using Ultimaker CURA software. The software can work with the most popular 3D formats such as 3MF, STL, X3D, and OBJ to cut the print layer and generate a G-code file, which will be loaded into the machine used to program the printing product. From this Ultimaker CURA, we create the *.G-code file to be transferred into the FDM 3D printers for prototyping the models.

Response Surface Method

Step 1: Select the changing factors, the stable factors and the output parameters for the experiment.
Step 2: Choose the regression equation model.
Step 3: Determine the value domain of the factors - exploratory experiment.
Step 4: Choose the experimental planning method.
Step 5: Set up the experimental method.
Step 6: Conduct exploratory experiments. Check the output parameter with normal distribution. Determine the number of replicates for each experiment.
Step 7: Conduct the main experiment.
Step 8: Eliminate raw errors. Check the uniformity of the variance of the experiments, calculate the variance of the reproducibility.
Step 9: Calculate the regression coefficient of the mathematical model.
Step 10: Evaluate the value of the coefficient of the regression equation.
Step 11: Check the appropriateness and effectiveness of the regression model.
Step 12: Analyze the results.

FDM inputs such as printing temperature, printing speed and infill density can be selected from the previous works, to optimize and enhance the tensile capacity of the test sample. The RSM experimental design such as the central composite design (CCD) to identify the influence of inputs on the tensile capacity. To reduce the number of experiments, partial factor planning 2^{k-1} is used. Input factor levels are determined according to two maxima (+1) and minimum (-1). Points on the axis (high and low levels) and zero (point at center) for each input factor are employed. To test the interaction effect of the input factors on tensile capacity, we use the FCCD (face central composite design) method with three levels with consideration of the coefficient α.

$$R = \beta_0 + \sum \beta_i y_i + \sum \beta_{ii} y_i^2 + \sum \beta_{ij} y_i y_j$$

where, R is a predicted output, β_0 is regression constant, β_i are linear constant, β_{ii} are quadratic constants for each factor, β_{ij} are the first-ordered interaction efficiencies of the input factors.

These parameters change with three levels and keep the other parameters constant. The RSM model is considered for good fit, if the value of p (< 0.01) of the model is statistically significant and the relevance of the regression model (lack of fit) is not significant and moreover, the coefficient R^2 is close to 1. The test samples are tested for tensile strength on actual equipment.

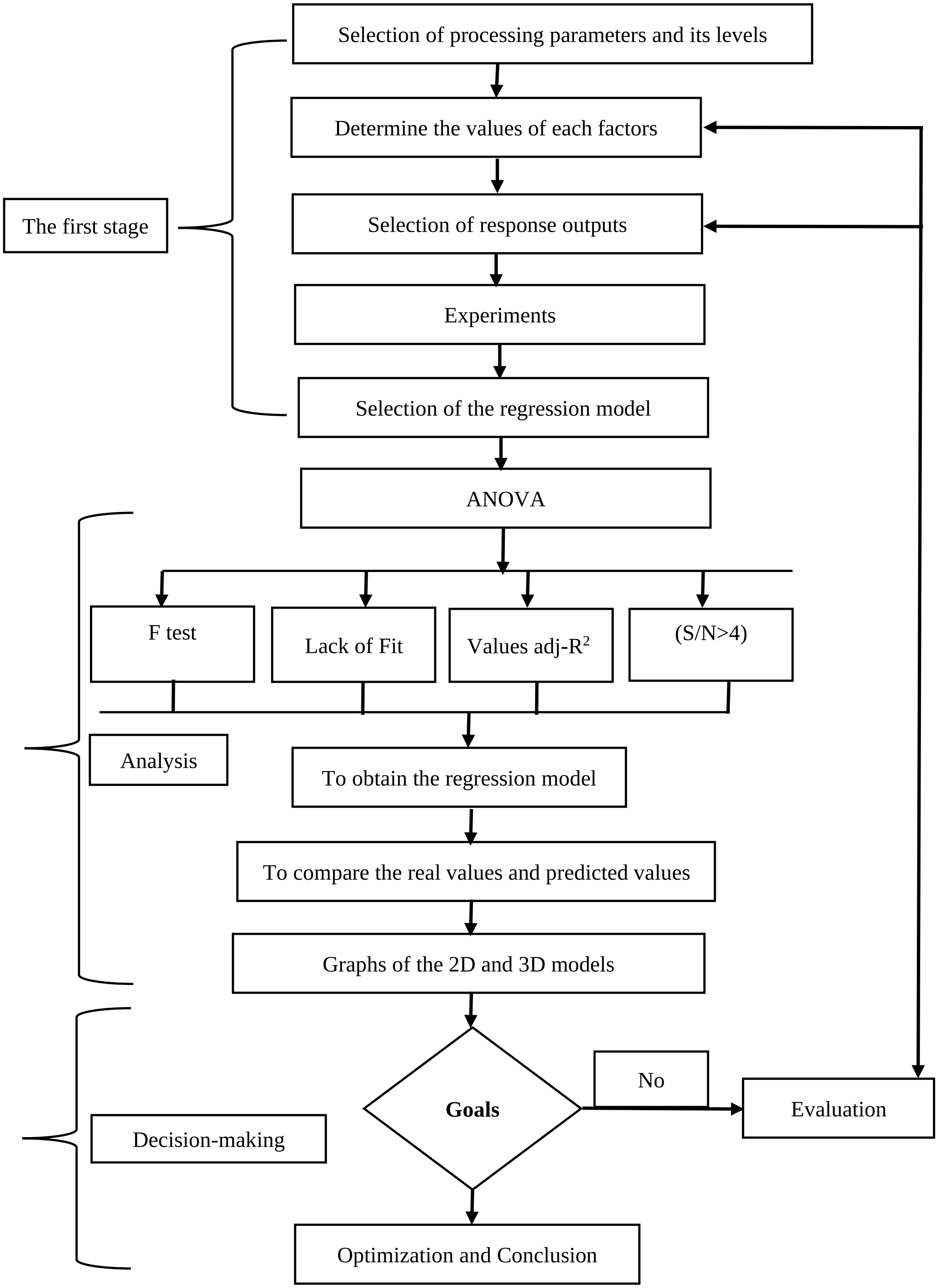


Figure 1. The flowchart of experimental implementation

CAD model

The conventional tensile test sample, according to many previous studies, has dimensions of 60 mm × 20 mm × 5 mm. Since the built orientation is an important parameter for the tensile capacity of the fabricated part, the test is performed by varying the orientations of the part in the process of printing. Many studies selected samples according to ASTM D638 and ISO527-1-2012 standards. However, this study conducted application testing for a typical product sample. The CAD sample was designed in Autodesk Inventor software and exported to an *.STL file (Figure 3). The *.STL file is imported into FDM software such as Ultimaker CURA. The designed part for tensile testing has a hook form that aims to optimize the tensile strength. From the actual needs of the customer, the selection and design of the product should meet the aesthetic requirements. This can help put the prototype into practical use instead of just being created as a prototype for the normal manufacturing process. Process parameters are selected for the experimental planning. The part is modeled and tested according to the ISO R527-1966 procedure for tensile testing.

FDM 3D Printing device

The FDM device for prototyping in this study is called Marbox (Figure 2) with basic specifications in Table 1.

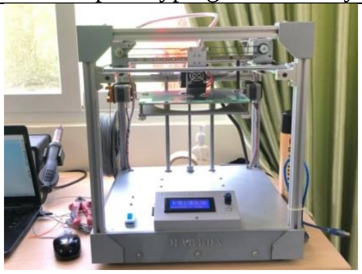
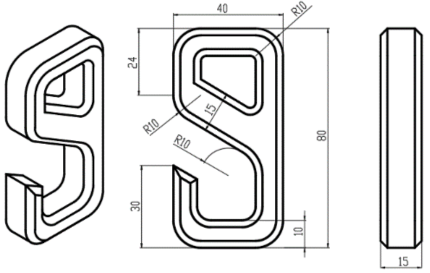
	

Figure 2. MARBOX prototyping machine by FDM 3D printing technology	***Figure 3. The CAD model for experimental study [28]***

Table 1. 3D printer parameters

Minimum layer thickness	0.05 mm
Maximum product dimensions	200×200×200 mm
Nozzle diameter	(0.4 ÷ 1) mm
Plastic wire diameter	1.75
Printing speed	(50 ÷100) mm/s
Maximum nozzle temperature	250℃

Process parameters of FDM based 3D printing

After careful review of relevant research and experience in the field of FDM 3D printing technology along with printer manufacturer recommendations, to the best of our knowledge of 3D printers, we proceed to select the following process parameters to perform the tensile testing for 3D printed parts as shown in Tables 2 and 3.

Table 2. Processing parameters and its experimental levels.

Parameters	Symbol	Unit	Level		
			Low (-1)	Mean (0)	High (1)
Printing speed	A	mm/s	30	50	70
Printing temperature	B	℃	190	210	230
Printing angle	C	°	0	45	90
Infill pattern	D		Concentric	Triangle	Honeycomb

Table 3. 3D printer operating parameters (fixed) during the test.

Parameters	**Values**	**Units**
Layer height	0,3	mm
Raster gap	0,6	mm
Bottom layer height	1,5	mm
Feeding speed	1	mm/s
Infill density	95	%
Cooling speed	%	50
Bed temperature	70	℃
Number of Extruders	01	
Nozzle diameter	0,4	mm
Number of shells	2	-
Extruding speed	20	mm/s
Support angle	68	°
Built orientation	X (0°) horizontal surface	

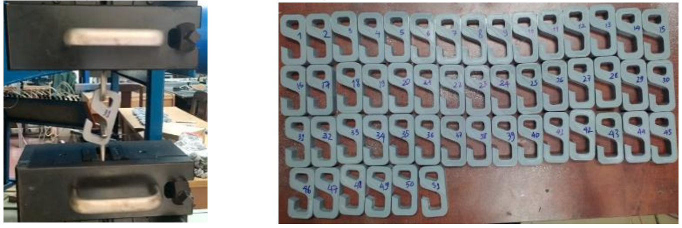
Experiments

The tensile strength is determined according to ISO R527:1966, representing the test piece geometry. For the tensile test piece at both ends, it is the same as that of a two-force bar when analyzing the strength of materials. Tensile testing was performed on an Instron 1195 machine with automatic material testing system, with automated pulling velocity from 10 mm/min to 15 mm/min. The load capacity was 50 kN with an accuracy of $\pm 0.5\%$ and integrated software included for data collection. Table 4 shows the operation parameters for implementing the experiment runs on the machine of tensile testing (Figure 4).

Table 4. Parameters of tensile testing machine

Sample type	:	ASTM
Sample speed	:	9.103
Pulling speed	:	(10 ÷ 15) mm/min
Range of pulling the sample	:	50 kN
Humidity	:	50%
Temperature	:	23℃

Figure 4. Equipment to pull samples and test samples



To build a regression model for tensile strength, full factor planning is derived based on the Box-Behnken design. The method is capable of finding the quadratic regression equation, and we can determine the optimal parameters for the FDM process. To perform this experiment, the factor planning table and the experimental levels of factors are given based on 3 levels (-1, 0, $+1$) presented in Table 5.

Table 5. Planning of factors and experimental levels of factors

	Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Response 1**
Run	**A:Print speed**	**B:Print temperature**	**C:Print angle**	**D:Infill pattern**	**Tensile strength**
Units	**mm/s**	**C degree**	**Degree**		**MPa**
1	50	190	0	Triangle	6.2
2	50	230	90	Honeycomb	6.6
3	70	210	0	Concentric	5.4
4	50	190	90	Honeycomb	6.3
5	50	210	45	Triangle	6.4
…	…	…	…	…	…

RESULTS AND DISCUSSION

Response Surface Method

Experiments were analyzed using Design-Expert software V13. Data testing and regression model selection are proposed as shown below. Factor analysis for output response is Tensile Strength (MPa). The results show that the quadratic regression model is appropriate and is proposed to be selected. In this problem, the quadratic model is also suitable to help us determine the optimal value of the factors (FDM process parameters).

Next, we perform ANOVA analysis for the quadratic regression model.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	45.40	17	2.67	9.51	< 0.0001	**significant**
A-print speed	0.1350	1	0.1350	0.4808	0.4929	
B-print temp.	3.53	1	3.53	12.56	0.0012	
C-print angle	0.0017	1	0.0017	0.0059	0.9391	
D-infill pattern	36.85	2	18.43	65.63	< 0.0001	
AB	0.0300	1	0.0300	0.1068	0.7458	
AC	0.0833	1	0.0833	0.2968	0.5896	
AD	1.69	2	0.8437	3.01	0.0632	
BC	0.2133	1	0.2133	0.7598	0.3897	
BD	0.5158	2	0.2579	0.9186	0.4090	
CD	0.0758	2	0.0379	0.1350	0.8742	
A^2	0.0114	1	0.0114	0.0405	0.8418	
B^2	2.23	1	2.23	7.94	0.0081	
C^2	0.0170	1	0.0170	0.0605	0.8073	
Residual	9.27	33	0.2808			
Lack of Fit	8.61	21	0.4098	7.45	0.0005	**significant**
Pure Error	0.6600	12	0.0550			
Cor Total	54.66	50				

Factor coding is **Coded**. Sum of squares is **Type II Classical**

The **Model F-value** of 9.51 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. **P-values** less than 0.0500 indicate model terms are significant. In this case B, D, B^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The **Lack of Fit F-value** of 7.45 implies the Lack of Fit is significant. There is only a 0.05% chance that a Lack of Fit F-value this large could occur due to noise. Significant lack of fit is bad -- we want the model to fit.

Fit Statistics

Std. Dev.	0.5299	**R^2**	0.8305
Mean	5.97	**Adjusted R^2**	0.7432
C.V. %	8.87	**Predicted R^2**	0.5357
		Adeq Precision	10.9166

The **Predicted R^2** of 0.5357 is not as close to the **Adjusted R^2** of 0.7432 as one might normally expect; i.e. the difference is more than 0.2. This may indicate a large block effect or a possible problem with your model and/or data. Things to consider are model reduction, response transformation, outliers, etc. All empirical models should be tested by doing confirmation runs.

Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 10.917 indicates an adequate signal. This model can be used to navigate the design space.

Coefficients in Terms of Coded Factors (Sum Contrasts)

Term	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	6.17	1	0.1368	5.89	6.45	
A-print speed	0.0750	1	0.1082	-0.1451	0.2951	1.0000
B-print temp.	0.3833	1	0.1082	0.1633	0.6034	1.0000
C-print angle	0.0083	1	0.1082	-0.2117	0.2284	1.0000
D[1]	-1.20	1	0.1049	-1.42	-0.9885	

Term	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
D[2]	0.6216	1	0.1049	0.4081	0.8351	
AB	0.0500	1	0.1530	-0.2612	0.3612	1.0000
AC	-0.0833	1	0.1530	-0.3945	0.2279	1.0000
AD[1]	0.3750	1	0.1530	0.0638	0.6862	
AD[2]	-0.1875	1	0.1530	-0.4987	0.1237	
BC	-0.1333	1	0.1530	-0.4445	0.1779	1.0000
BD[1]	0.2042	1	0.1530	-0.1070	0.5154	
BD[2]	-0.0708	1	0.1530	-0.3820	0.2404	
CD[1]	-0.0458	1	0.1530	-0.3570	0.2654	
CD[2]	-0.0333	1	0.1530	-0.3445	0.2779	
A^2	0.0300	1	0.1491	-0.2733	0.3333	1.01
B^2	-0.4200	1	0.1491	-0.7233	-0.1167	1.01
C^2	-0.0367	1	0.1491	-0.3400	0.2667	1.01

The coefficient estimate represents the expected change in response per unit change in factor value when all remaining factors are held constant. The intercept in an orthogonal design is the overall average response of all the runs. The coefficients are adjustments around that average based on the factor settings. When the factors are orthogonal the VIFs are 1; VIFs greater than 1 indicate multi-colinearity, the higher the VIF the more severe the correlation of factors. As a rough rule, VIFs less than 10 are tolerable.

The second order regression equation is summarized as below:

If the infill pattern is in the form of "Concentric":

Tensile strength (MPa) = $-48.73488 - 0.007083 \times \text{print\_speed} + 0.470792 \times \text{print\_temp} + 0.036537 \times \text{print\_angle} + 0.000125 \times \text{print\_speed} \times \text{print\_temp} - 0.000093 \times \text{print\_speed} \times \text{print\_angle} - 0.000148\ \text{print\_temp} \times \text{print\_angle} + 0.000075 \times \text{print\_speed}^2 - 0.001050 \times \text{print\_temp}^2 - 0.000018 \times \text{print\_angle}^2$

If the infill pattern is in the form of "Triangle":

Tensile strength (MPa) = $-42.63010 - 0.035208 \times \text{print\_speed} + 0.457042 \times \text{print\_temp} + 0.036815 \times \text{print\_angle} + 0.000125 \times \text{print\_speed} \times \text{print\_temp} - 0.000093 \times \text{print\_speed} \times \text{print\_angle} - 0.000148\ \text{print\_temp} \times \text{print\_angle} + 0.000075 \times \text{print\_speed}^2 - 0.001050 \times \text{print\_temp}^2 - 0.000018 \times \text{print\_angle}^2$

If the infill pattern is in the form of "Honeycomb":

Tensile strength (MPa) = $-42.12752 - 0.035208 \times \text{print\_speed} + 0.453917 \times \text{print\_temp} + 0.039315 \times \text{print\_angle} + 0.000125 \times \text{print\_speed} \times \text{print\_temp} - 0.000093 \times \text{print\_speed} \times \text{print\_angle} - 0.000148 \times \text{print\_temp} \times \text{print\_angle} + 0.000075 \times \text{print\_speed}^2 - 0.001050 \times \text{print\_temp}^2 - 0.000018 \times \text{print\_angle}^2$

The tensile strength in terms of actual input factors can be employed to create the predictions about the response of tension for given levels of each processing parameters. Here, the levels should be determined in the original units for each printing parameter. This equation should not be used to specify the relative effect of each process parameter because the coefficients are scaled to accommodate the units of each input parameter and the intercept is not at the center of the design space.

Optimization analysis to find optimal parameters: Set design goals with maximum tensile strength (MPa).

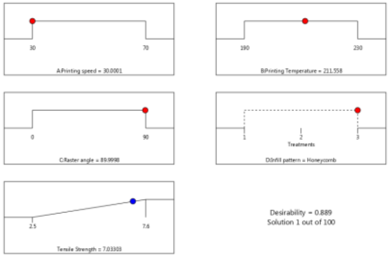
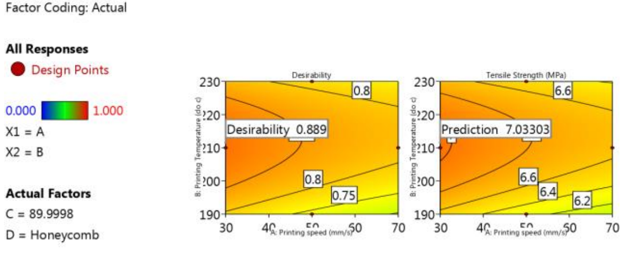
	

Figure 5. Optimum processing parameters for FDM 3D printing	***Figure 6. Optimum process parameters of printing speed and temperature***

After running the model on Design-Expert, the results are shown as shown in Figures 5. Figure 6 shows the Best Tensile Strength value of 7.03303 MPa corresponding to printing speed of 30,0003 mm/s, printing temperature of 211,594℃, printing angle of 90° with "Honeycomb" printing pattern. The design point is shown in Figures 5 and 6.

Artificial Neural Network (ANN): In total, we have 51 samples, we choose 66% of samples for training and 34% of the remaining samples for validation of the ANN model as shown below. ANN analysis is supported by JMP Pro V16 statistical software, running on Windows 10 64bit, Intel 7 Chip, 16 GB RAM. From the "***Analysis***" menu, select the "***Prediction***" predictive analysis method, and the Neural sets model. Then, select the output response as "Tensile strength", the input factors as "**Print speed**", "**Printing temperature**", "**Printing angle**", and "**Printing pattern**". Finally, set "Validation" with the "Validation" column created from the previous step. ANN prediction model is presented in Figure 7.

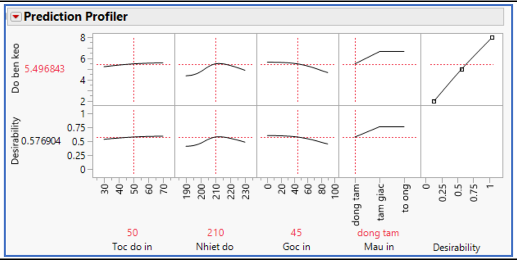
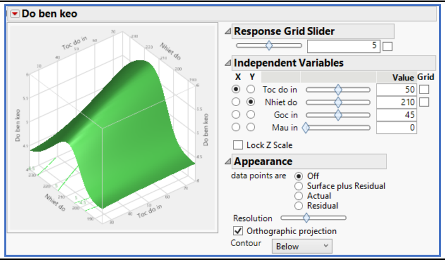
	

Figure 7a. Optimum parameters from ANN model *(Notes: Toc do in = "Printing speed", "Nhiet do in = printing temperature", "Goc in = Raster angle", "Mau in = Infill pattern", "Do ben keo = Tensile Strength")*	***Figure 7b. Response surface of tensile strength with respective to the printing speed, printing temperature and printing angle for concentric-based infill pattern.***

Adaptive Neuro-Fuzzy Inference System (ANFIS)

We have 51 samples of experimental data. Performing the predictive analysis of Tensile Strength using the ANFIS engine in Mathworks Matlab 2009b software, running on Windows 7 Ultimate 64 bit, 8GB RAM.

The membership functions used in the model have a triangular shape (fuzzy number). The membership function for printing temperature, the membership function for the printing angle, and the membership function for the infill print pattern. Importing data file `data_mts12fdm.csv` containing 51 samples and 4 input parameters including print speed, print temperature, printing angle and infill pattern. In this data set, there is one output which is tensile strength (MPa). Using the `trn_data` and `chk_data` variables to generate training and validation data sets.

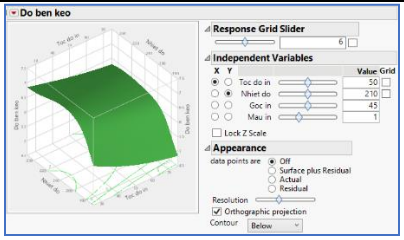
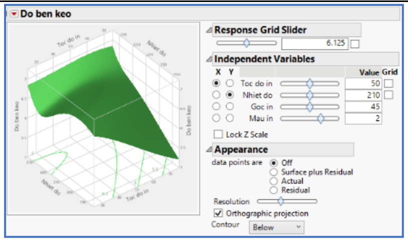
	

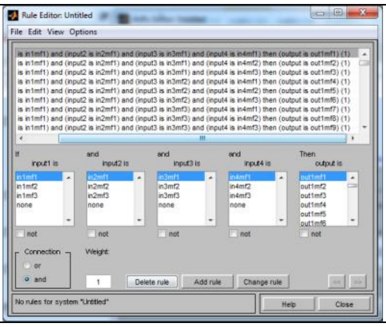
Figure 7c. Tensile response surface for "printing speed", "printing temperature", "printing angle" for 1 "triangle" infill pattern.	***Figure 7d. Tensile response surface for "print speed", "print temperature", "print angle" for "honeycomb" infill pattern.***

These two datasets will be used to train the ANFIS model. Using the following scripts to prepare data for the ANFIS model as follows.

```
trn_data=data_mts12fdm(1:2:end,:); chk_data=data_mts12fdm(2:2:end,:);
input_name =str2mat('speed','temp','angle','pattern','tensile'); anfisedit;
```

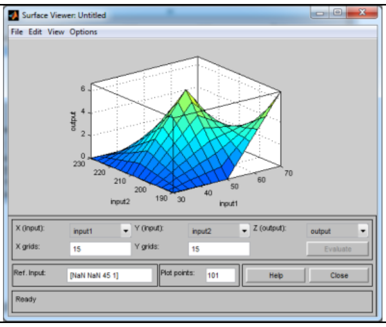
After loading the training data and testing data from the workspace (computation space), we have the image below (Figure 8) after conducting "Train Now" with the number of Epochs 40:

The ANFIS model that there are 4 inputs and 1 outputs and membership functions. The structure of the ANFIS model to predict the tensile strength is shown in Figure 8. Thus, the number of fuzzy rules is determined to be 81, shown in the Figure 8. These rules can be checked and corrected according to the technician's experience.



```
is in1mf1) and (input2 is in2mf1) and (input3 is in3mf1) and (input4 is in4mf1) then (output is out1mf1) (1)
is in1mf1) and (input2 is in2mf1) and (input3 is in3mf1) and (input4 is in4mf2) then (output is out1mf2) (1)
is in1mf1) and (input2 is in2mf1) and (input3 is in3mf1) and (input4 is in4mf3) then (output is out1mf3) (1)
is in1mf1) and (input2 is in2mf1) and (input3 is in3mf2) and (input4 is in4mf1) then (output is out1mf4) (1)
is in1mf1) and (input2 is in2mf1) and (input3 is in3mf2) and (input4 is in4mf2) then (output is out1mf5) (1)
is in1mf1) and (input2 is in2mf1) and (input3 is in3mf2) and (input4 is in4mf3) then (output is out1mf6) (1)
is in1mf1) and (input2 is in2mf1) and (input3 is in3mf3) and (input4 is in4mf1) then (output is out1mf7) (1)
is in1mf1) and (input2 is in2mf1) and (input3 is in3mf3) and (input4 is in4mf2) then (output is out1mf8) (1)
is in1mf1) and (input2 is in2mf1) and (input3 is in3mf3) and (input4 is in4mf3) then (output is out1mf9) (1)
```

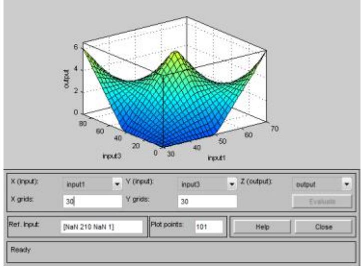
input1 is: in1mf1, in1mf2, in1mf3, none
input2 is: in2mf1, in2mf2, in2mf3, none
input3 is: in3mf1, in3mf2, in3mf3, none
input4 is: in4mf1, in4mf2, in4mf3, none
output is: out1mf1, out1mf2, out1mf3, out1mf4, out1mf5, out1mf6
Weight: 1
No rules for system "Untitled"



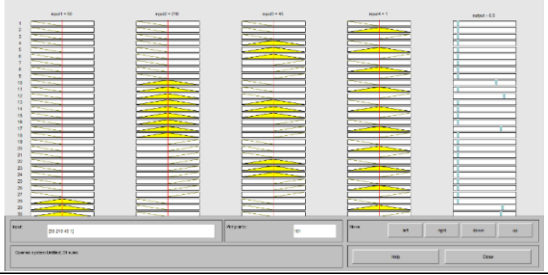
X (input): input1
Y (input): input2
Z (output): output
X grids: 15
Y grids: 15
Ref. Input: [NaN NaN 45 1]
Plot points: 101
Ready

Figure 8a. ANFIS rules | **Figure 8b. Response surface from ANFIS model**

The predicted response surface of tensile strength for two input variables of print temperature and print speed is as shown below Figure 8b. The predicted response surface of tensile strength for two input variables is print direction angle and print speed as shown in Figures 8c.



X (input): input1
Y (input): input3
Z (output): output
X grids: 30
Y grids: 30
Ref. Input: [NaN 210 NaN 1]
Plot points: 101
Ready



Input: [50 210 45 1]

Figure 8c. Response surface from ANFIS model | **Figure 9. ANFIS model for prediction of optimum process parameters for FDM 3D printing**

Thus, the ANFIS model used to predict the overall tensile strength according to 4 input factors with automatic fuzzy inference rules is presented as shown in Figure 10, that helps us to predict any input parameter and gives the resulting tensile response output for the 3D printed part. Based on the data results in Figure 9, it helps us to predict the values of ANFIS in the Table 6, corresponding to each experimental value in the quadratic RSM Box-Behnken experimental planning table.

Benchmarking of RSM, ANN and ANFIS

We arrange the calculation/forecast results from the RSM, ANN, and ANFIS methods in the experimental planning table, with the actual values taken from the experimental samples as shown in Table 6.

Table 6. Benchmarking of RSM, ANN and ANFIS

	Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Exp.**	**RSM**	**ANN**	**ANFIS**
Run	**A:print speed**	**B:print temp.**	**C:print angle**	**D:infill pattern**	**Tensile strength (MPa)**			
Units	**mm/s**	**C degree**	**Degree**		**Exp.**	**RSM**	**ANN**	**ANFIS**
1	50	190	0	Triangle	6.2	5.92	6.23	6.20
2	50	230	90	Honeycomb	6.6	6.50	6.48	6.58
…	…	…	…	…	…	…	…	…
21	30	210	90	Triangle	7.6	6.96	7.25	6.00
22	50	210	45	Honeycomb	6.6	6.75	6.66	6.55
…	…	…	…	…	…	…	…	…
48	30	230	45	Honeycomb	6.5	6.68	6.48	6.57
49	50	210	45	Concentric	5.8	4.97	5.50	6.55
50	70	190	45	Honeycomb	6.0	5.95	5.51	6.20
51	30	210	90	Concentric	4.4	4.56	4.52	4.50

Now we determine the deviations among the predicted values of RSM, ANN, and ANFS compared with experimental values. The results showed that the ANFIS method accurately predicts up to 96.35% of the optimal parameters for FDM 3D printing technology with the collected data. The RSM and ANN models have a prediction accuracy of nearly 94%. The RSM method is more competitive because the ANN has not yet chosen the functional model well. However, with an accuracy of over 90%, it shows that all three methods RSM, ANN and ANFIS are very valuable in predicting tensile strength (MPa) according to the values of four input factors, which are printing speed (mm/s), printing temperature (Celsius degrees), print angle (degrees) and infill pattern.

CONCLUSION

This study presented an experimental method of collecting data with four input factors namely printing speed, printing temperature, printing angle and infill pattern with the output data to be measured as tensile strength. The second-order experimental planning is based on the RSM Box-Behnken quadratic programming method with 51 experiments required. The CAD product samples, printers, and on-board measurements are also presented. Analytical results based on RSM, ANN and ANFIS methods are carried out to predict the tensile strength of FDM-based 3D printed parts. The value of the best tensile strength is 7,03303 MPa corresponding to print speed of 30,0003 mm/s, printing temperature of 211,594℃, printing angle of 90° with “Honeycomb” infill printing pattern. The assessment of the accuracy of three research methods is given to confirm that the ANFIS model has a high accuracy. The ANFIS method accurately predicts up to 96.35% of the optimal parameters for FDM 3D printing technology with the collected data from four input factors. The RSM and ANN models have a prediction accuracy of nearly 94%. The RSM method is more competitive because the ANN has not chosen well the learning function model. RSM and ANN models are competitive when it comes to predicting tensile strength according to four selected process parameters.

REFERENCES

[1] Deshwal, S., Kumar, A., and Chhabra, D., 2020, "Exercising hybrid statistical tools GA-RSM, GA-ANN and GA-ANFIS to optimize FDM process parameters for tensile strength improvement," CIRP Journal of Manufacturing Science and Technology, 31, pp. 189-199.

[2] Dey, A., and Yodo, N., 2019, "A Systematic Survey of FDM Process Parameter Optimization and Their Influence on Part Characteristics," Journal of Manufacturing and Materials Processing, 3(3).

[3] Chohan, J. S., Kumar, R., Singh, T. B., Singh, S., Sharma, S., Singh, J., Mia, M., Pimenov, D. Y., Chattopadhyaya, S., Dwivedi, S. P., and Kapłonek, W., 2020, "Taguchi S/N and TOPSIS Based Optimization of Fused Deposition Modelling and Vapor Finishing Process for Manufacturing of ABS Plastic Parts," Materials, 13(22).

[4] Özen, A., Auhl, D., Völlmecke, C., Kiendl, J., and Abali, B. E., 2021, "Optimization of Manufacturing Parameters and Tensile Specimen Geometry for Fused Deposition Modeling (FDM) 3D-Printed PETG," Materials, 14(10).

[5] Catana, D., Pop, M.-A., and Brus, D.-I., 2021, "Comparison between the Test and Simulation Results for PLA Structures 3D Printed, Bending Stressed," Molecules, 26(11).

[6] Alharbi, M., Kong, I., and Patel, V. I., 2020, "Simulation of uniaxial stress–strain response of 3D-printed polylactic acid by nonlinear finite element analysis," Applied Adhesion Science, 8(1), p. 5.

[7] Hodžić, D., Pandžić, A., Hajro, I., and Tasić, P. J. T. J., 2020, "Strength comparison of FDM 3D printed PLA made by different manufacturers," 9, p. 966.

[8] Özsoy, K., "A Comparative Finite Element Stress Analysis Of Isotropic Matrix And 3D Printed PLA Material, November 14-16, 2019," Proc. Proceedings on 2nd International Conference on Technology and Science.

[9] Rahmatabadi, D., Aminzadeh, A., Aberoumand, M., and Moradi, M., 2021, "Mechanical Characterization of Fused Deposition Modeling (FDM) 3D Printed Parts," Fused Deposition Modeling Based 3D Printing, H. K. Dave, and J. P. Davim, eds., Springer International Publishing, Cham, pp. 131-150.

[10] Zhao, Y., Chen, Y., and Zhou, Y., 2019, "Novel mechanical models of tensile strength and elastic property of FDM AM PLA materials: Experimental and theoretical analyses," Materials & Design, 181, p. 108089.

[11] Yao, T., Ye, J., Deng, Z., Zhang, K., Ma, Y., and Ouyang, H., 2020, "Tensile failure strength and separation angle of FDM 3D printing PLA material: Experimental and theoretical analyses," Composites Part B: Engineering, 188, p. 107894.

[12] Rajpurohit, S. R., and Dave, H. K., 2018, "Effect of process parameters on tensile strength of FDM printed PLA part," Rapid Prototyping Journal, 24(8), pp. 1317-1324.

[13] Durga Prasada Rao, V., Rajiv, P., and Navya Geethika, V., 2019, "Effect of fused deposition modelling (FDM) process parameters on tensile strength of carbon fibre PLA," Materials Today: Proceedings, 18, pp. 2012-2018.

[14] Yao, T., Deng, Z., Zhang, K., and Li, S., 2019, "A method to predict the ultimate tensile strength of 3D printing polylactic acid (PLA) materials with different printing orientations," Composites Part B: Engineering, 163, pp. 393-402.
[15] Altan, M., Eryildiz, M., Gumus, B., and Kahraman, Y., 2018, "Effects of process parameters on the quality of PLA products fabricated by fused deposition modeling (FDM): surface roughness and tensile strength," Materials Testing, 60(5), pp. 471-477.
[16] Hikmat, M., Rostam, S., and Ahmed, Y. M., 2021, "Investigation of tensile property-based Taguchi method of PLA parts fabricated by FDM 3D printing technology," Results in Engineering, 11, p. 100264.
[17] Samykano, M., 2021, "Mechanical Property and Prediction Model for FDM-3D Printed Polylactic Acid (PLA)," Arabian Journal for Science and Engineering, 46(8), pp. 7875-7892.
[18] Dave, H. K., Prajapati, A. R., Rajpurohit, S. R., Patadiya, N. H., and Raval, H. K., 2020, "Investigation on tensile strength and failure modes of FDM printed part using in-house fabricated PLA filament," Advances in Materials and Processing Technologies, pp. 1-22.
[19] Vălean, C., Marșavina, L., Mărghitaș, M., Linul, E., Razavi, J., and Berto, F., 2020, "Effect of manufacturing parameters on tensile properties of FDM printed specimens," Procedia Structural Integrity, 26, pp. 313-320.
[20] Ayatollahi, M. R., Nabavi-Kivi, A., Bahrami, B., Yazid Yahya, M., and Khosravani, M. R., 2020, "The influence of in-plane raster angle on tensile and fracture strengths of 3D-printed PLA specimens," Engineering Fracture Mechanics, 237, p. 107225.
[21] Grasso, M., Azzouz, L., Ruiz-Hincapie, P., Zarrelli, M., and Ren, G., 2018, "Effect of temperature on the mechanical properties of 3D-printed PLA tensile specimens," Rapid Prototyping Journal, 24(8), pp. 1337-1346.
[22] Rajpurohit, S. R., and Dave, H. K., 2019, "Analysis of tensile strength of a fused filament fabricated PLA part using an open-source 3D printer," The International Journal of Advanced Manufacturing Technology, 101(5), pp. 1525-1536.
[23] Rajpurohit, S. R., and Dave, H. K., "Tensile Strength of 3D Printed PLA Part," Proc. Advances in Additive Manufacturing and Joining, M. S. Shunmugam, and M. Kanthababu, eds., Springer Singapore, pp. 103-114.
[24] Naik, T. P., Rana, R. S., Mishra, R. R., Singh, I., and Sharma, A. K., "Parametric Optimization of FDM Process for Fabricating High-Strength PLA Parts," Proc. Advances in Engineering Design, P. K. Rakesh, A. K. Sharma, and I. Singh, eds., Springer Singapore, pp. 15-22.
[25] Lalegani Dezaki, M., Ariffin, M. K., Serjouei, A., Zolfagharian, A., Hatami, S., and Bodaghi, M., 2021, "Influence of Infill Patterns Generated by CAD and FDM 3D Printer on Surface Roughness and Tensile Strength Properties," Applied Sciences, 11(16).
[26] Dave, H. K., Patel, B. H., Rajpurohit, S. R., Prajapati, A. R., and Nedelcu, D., 2021, "Effect of multi-infill patterns on tensile behavior of FDM printed parts," Journal of the Brazilian Society of Mechanical Sciences and Engineering, 43(1), p. 23.
[27] Heidari-Rarani, M., Ezati, N., Sadeghi, P., and Badrossamay, M. R., 2020, "Optimization of FDM process parameters for tensile properties of polylactic acid specimens using Taguchi design of experiment method," Journal of Thermoplastic Composite Materials, p. 0892705720964560.
[28] Tho N.H., Minh T.C., Tai N.P., “The effect of infill pattern, infill density, printing speed and temperature on the additive manufacturing process based on the FDM technology for the hook-shaped components”, Jurnal Polimesin, 18(1) (2020).