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3D Print Continuation Process Parameter Setting to Optimize the Tensile Strength

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Abstract— **The research on the tensile strength of the product that has been continued is very limited. Therefore, this study aims to find out the relationship between the results of the continuation process with its tensile strength, even further to find out how to set the parameters of the continuation process so that the optimum connection's tensile strength is obtained. The printing process is carried out using polylactic acid (PLA) 1.75 mm material and C01 (Centra Teknologi Indonesia Corp.) 3D printer machine type Fused Deposition Modelling (FDM). Meanwhile, the G-code ASTM D638 Type V was modified to stop and resume the printing process for the continuation process. The results of the continuation process are then tensile-tested with HT-2402 (HungTa-brand testing machine). The tensile test data is processed using variance analysis (ANOVA) to determine the relationship between tensile strength and setting the connection process parameters. In comparison, the response surface method (RSM) is used to optimize the tensile strength. Parameters that influence the tensile strength of the continuation process are temperature, printing speed, number of layers, and overlap. In contrast, the interaction between parameters has not been proven to affect the tensile strength of the connection. The parameter setting to get the optimal connection's tensile value is an overlap of 0.4 mm, printing temperature of 195°C, the printing speed of 20 mm/s, and 6 number of layers.**

Keywords— **FDM; continuation process; RSM; PLA; tensile strength.**

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I. INTRODUCTION

Additive manufacturing, known as 3D printing, is a new technology that is widely developed today because the process is easy and has many advantages [1]. The term additive manufacturing describes the process in this technology due to its adding material layer by layer, so it is frequently called layer manufacturing [2]–[8]. Meanwhile, the term 3D printing is more often used to describe the products of this technology, in the form of a 3-dimensional product. The term of 3D printing is usually more popular than other terms because it is easier to understand.

One of the most commonly used 3D printing processes is Fused Deposition Modeling (FDM). This process is easier, cheaper, and more flexible than other processes [9]–[11]. This process starts from making a 3-dimensional design in software which is then converted into the stereolithography file format (STL). The design parameters are then set (overlap, printing temperature, printing speed, and a number of layers), and the product will be sliced according to the parameters entered. The result of this slice is the reference in making g-code like in CNC. G-code is the input to the 3D printer machine used to determine the 3D printer machine movement from the first slice to the last [11]–[16].

FDM has been used in many industries, for example, automobile, aerospace, medicine, electronics, and other industrial products [17]. However, FDM still has limitations. One of the limitations of the FDM process is the quality that decreases due to errors and power outages during the process [18]. In addition, failure can also cause the process to stop before the product is finished perfectly. For this reason, it is necessary to do a continuation process so that there is no need to repeat the process from the beginning. However, this continuous process affects its quality, especially its connection's tensile strength [19]. Until now, the research on this field is very limited. Therefore, this study aims to prove these allegations and determine how to set the parameters of the continuation process so that the optimum tensile strength is obtained.

II. Materials and Method

A. Material

The product used in this study is ASTM D638 Type V (Fig. 1) which has been widely used [20], [21]. ASTM D638 is a standard test method for the tensile properties of plastic. The machine used is a 3D printer machine C01 (Centra Teknologi Indonesia Corp.) with a working space of 200 x 200 x 200 mm (Fig. 2), and the material used is polylactic acid (PLA) with a diameter of 1.75mm.

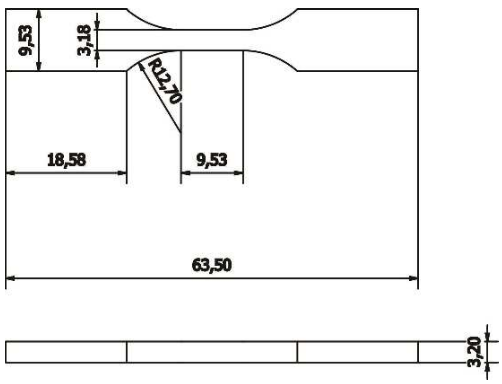

Fig. 1 ASTM D638 Type V

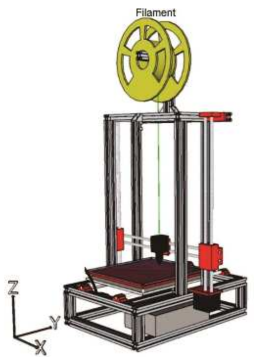

Fig. 2 3D Printer machine C01 (Centra Teknologi Indonesia Corp.)

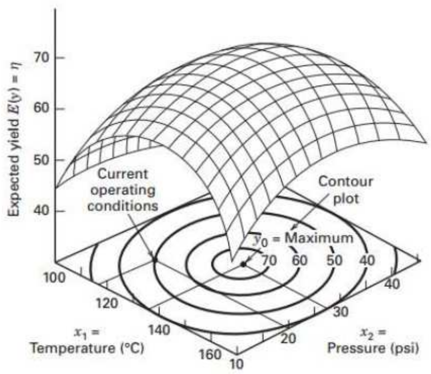

Fig. 3 Three Dimensional response surface [22]

B. Experimental Design

This study uses the response surface method to get the best results due to its advantage. First, the Response surface method can be used to find out the relationship between the response y with the independent variables x and error ε, as seen in (1). The second is that this method can be expressed with graphs in three-dimensional images to show the shape of the contour (Fig. 3). This method is a part of the experimental design that uses statistical analysis and mathematical techniques to model a problem. This method aims to see the effect of several quantitative variables on a variable's response and optimize it [23], [24]. This method is also used by other studies and has been used successfully, such as research conducted by [25], [26], and [27].

$$y = f(x_1, x_2) + \varepsilon \qquad (1)$$

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i \qquad (2)$$

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} {x_i}^2 + \sum_{i=1,j=2}^{k-1,k} \beta_{i,j}\, x_i x_j + \varepsilon \qquad (3)$$

y	=	Observation Response / Response Variable
β_o	=	Intercept
β_i	=	Linear coefficient
β_{ii}	=	Quadratic coefficient
β_{ij}	=	Treatment interaction coefficient
x_1	=	Treatment code / explanatory variable for parameter i
x_j	=	Treatment code / explanatory variable for parameter j
k	=	number of parameters tested

The optimal response point can be determined by using differential on each explanatory variable. The results of the optimal explanatory variable can be used to optimize the response variable (mathematical optimization). If in equation (2) there is no lack of fit, then the optimization value that looked for is not in that area. The level of parameters studied must be shifted towards either upward or downward optimization. Then axial points are added to the experiment to meet the quadratic points in the model. Equation (3) shows the increase of polynomial degree from equation (2) which has 1 order (linear) to 2 orders (quadratic). The response surface method aims to determine the optimal operating conditions in a system or to find the area of the parameters in which the specifications of the operation can be fulfilled [28].

C. Experimental Parameter

This study aims to find the parameters of the 3D print product continuation process that are stopped before completion to obtain optimal tensile test strength. The parameters used are overlapped (distance from the breaking point to the starting point of continuation process) (Fig. 4), print temperature [29], [30] (temperature on the extruder), print speed [29], [31], and number of layers (number of layers in the connection point) (Fig. 5). The discussion results also found the level for each parameter seen in Table I.

TABLE I
Process Parameter

Parameter	**Unit**	***Level***		
		-1	***0***	**+1**
Overlap	mm	0.1	0.25	0.4
Temperature	°C	195	205	215
Print Speed	mm/s	40	60	80
Number of Layers	layer	5	10	15

In this study, the first-order design consisted of a 2^k factorial design coupled with 4 central point's so that there were 20 observations (Table II). Whereas the second-order design was a central composite design consisting of 2^4 factorial designs plus 7 central points and 8 axial points, there were 31 observations (Table II).

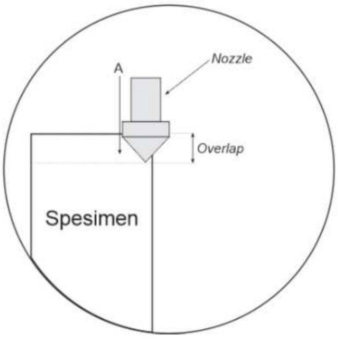

Fig. 4 Overlap illustration

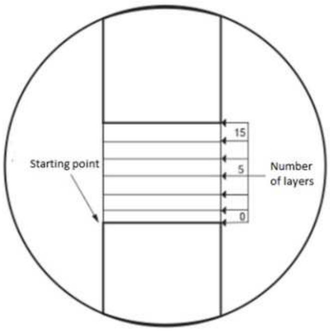

Fig. 5 Number of layers illustration

D. Response Variables

The response variables of this study are the tensile strength of the 3D print products that have been continued. The continuation process is conducted by modifying the g-code from the slicer. The principle is to continue the g-code in the last part, provided that the nozzle or extruder can do homing towards points connection breaking point (Fig.6). The printing process was deliberately modified to stop during the printing process to reach the midpoint of the specimen. After that, a second modified g-code was used to continue the printing process from the last stop point to the end of the process.

Tensile strength measurements were carried out using the HT-2402 (HungTa-brand testing machine). In the Tensile test, the specimen is loaded with a tensile force that increases continuously with one axis, and the extension is measured using an extensometer (Fig. 7).

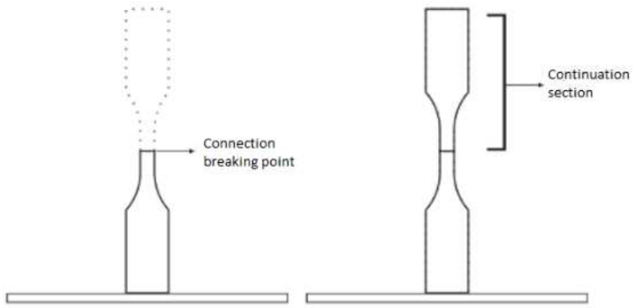

Fig. 6 Illustration of Splicing Engineering Process in ASTM D638 Type-V

TABLE II
RSM DESIGN

Run Test	First-order			
	Overlap (mm)	Temperature (°C)	Print Speed (mm/s)	Number of layers (pieces)
1	0.1	195	40	5
2	0.4	195	40	5
3	0.1	215	40	5
4	0.4	215	40	5
5	0.1	195	80	5
6	0.4	195	80	5
7	0.1	215	80	5
8	0.4	215	80	5
9	0.1	195	40	15
10	0.4	195	40	15
11	0.1	215	40	15
12	0.4	215	40	15
13	0.1	195	80	15
14	0.4	195	80	15
15	0.1	215	80	15
16	0.4	215	80	15
17	0.25	205	60	10
18	0.25	205	60	10
19	0.25	205	60	10
20	0.25	205	60	10

Run Test	Second-order			
	Overlap (mm)	Temperature (°C)	Print Speed (mm/s)	Number of layers (pieces)
1	0.1	195	40	5
2	0.4	195	40	5
3	0.1	215	40	5
4	0.4	215	40	5
5	0.1	195	80	5
6	0.4	195	80	5
7	0.1	215	80	5
8	0.4	215	80	5
9	0.1	195	40	15
10	0.4	195	40	15
11	0.1	215	40	15
12	0.4	215	40	15
13	0.1	195	80	15
14	0.4	195	80	15
15	0.1	215	80	15
16	0.4	215	80	15
17	-0.05	205	60	10
18	0.55	205	60	10
19	0.25	185	60	10
20	0.25	225	60	10
21	0.25	205	20	10
22	0.25	205	100	10
23	0.25	205	60	0
24	0.25	205	60	20
25	0.25	205	60	10
26	0.25	205	60	10
27	0.25	205	60	10
28	0.25	205	60	10
29	0.25	205	60	10
30	0.25	205	60	10
31	0.25	205	60	10

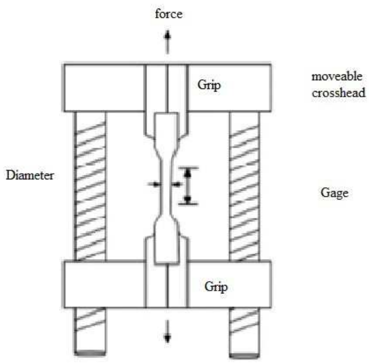

Fig. 7 Illustration of Tensile Strength Testing

In general, the experimental design can be seen in Fig. 8.

III. Results and Discussions

A. First-Order Model Analysis

In the first-order model, the tensile test was carried out in 20 experiments with three replications per experiment averaged (Table III). The tensile test results data are then made in the form of a first-order model that describes the relationship of the independent variable to the response variable (4). Y_{TS} is a predictive value for tensile strength on connection as a response variable, O is a variable code value for overlap, T is a variable code value for temperature, S is a variable code value for printing speed, and JL is a variable code value for the number of layers. The regression analysis equation (4) obtained the coefficient of determination (R^2) of 51.30%. The greater the value of R^2, the greater the influence of the independent variable on the response variable.

$$y_{TS} = 108.4 + 8.13O + 0.426T - 0.1518S - 0.277JL \quad (4)$$

TABLE III
AVERAGE TEST DATA OF TENSILE STRENGTH FOR FIRST-ORDER

No	Average (Mpa)	No	Average (Mpa)
1	17.58	11	4.9
2	21.45	12	5.57
3	5.59	13	8
4	12.73	14	7.09
5	10.81	15	3.14
6	12.67	16	3.73
7	4.1	17	11.52
8	4.8	18	23.11
9	14.75	19	18.25
10	20.34	20	15.56

The next step is to test the lack of fit. This test is conducted to determine whether the model presents response rates as a function of the factor level. Lack of fit is seen in the results of analysis of variance (ANOVA) with confidence level 95% or $\alpha = 0.05$, df1 = 1, and df2 = 3. Two conditions state this model: the p-value of lack of fit is greater than α, and the F-value on the lack of fit is smaller than the value table of $F_{a,\, df1,\, df2}$. The results of this test can be seen in Table IV. It can be seen that the P-value for the temperature and printing speed is below 0.05, which means that these parameters have a significant effect on tensile strength. While the overlap and number of layers do not have strong evidence to conclude that these parameters significantly impact tensile strength at the connection because the P-value is more than 0.05.

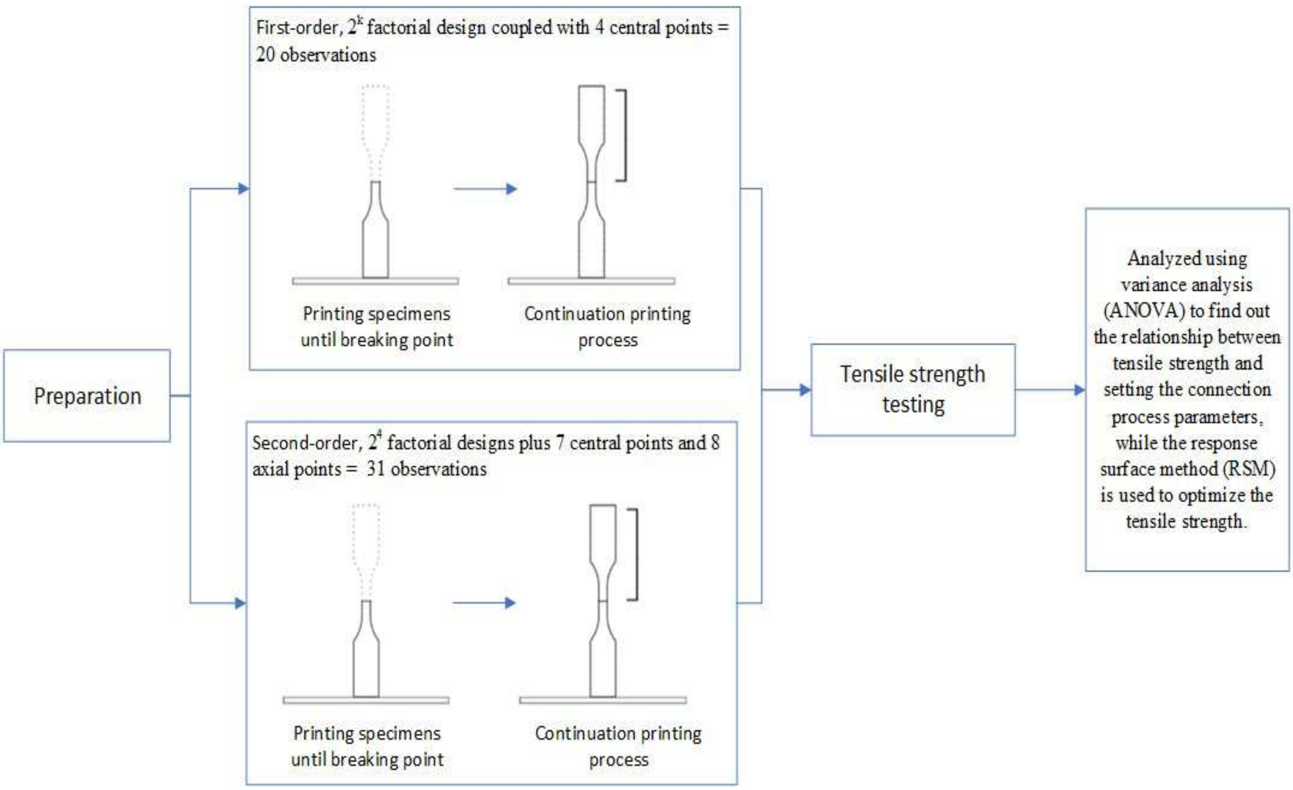

Fig. 8 Experimental design

TABLE IV
ANALYSIS OF VARIANT FOR CONNECTION'S TENSILE STRENGTH RESPONSE IN FIRST ORDER

Source	DF	Adj SS	Adj MS	F-*Value*	P-*Value*
Model	4	492	123.001	6.01	0.004
Linear	4	492	123.001	6.01	0.004
O	1	23.8	23.798	1.16	0.298
T	1	290.02	290.021	14.17	0.002
S	1	147.42	147.42	7.2	0.017
JL	1	30.77	30.766	1.5	0.239
Error	15	307.02	20.468		
Curvature	1	169.59	169.595	17.28	0.001
Lack-of-Fit	11	66.48	6.043	0.26	0.96
Pure *Error*	3	70.95	23.651		
Total	19	799.03			

After the lack of fit test, the next step is to test the adequacy of the first-order model (Table V). In the table, the p-value is greater than α, which means it fails to reject H_0 and F-value is smaller than $F_{0.05,11,}$ which means it also fails to reject H_0. It shows that the first-order regression model for the tensile response on the connection is sufficient to describe the relationship between the independent variable and the response variable represented by a linear line. However, to look for better and more appropriate values.

TABLE V
ADEQUACY TEST FOR FIRST-ORDER MODELS

Response	P-value	α	F-value	$F_{0.05;11;3}$	Status
Connection's tensile strength	0.96	0.05	0.26	8.8	Fail to reject H

TABLE VI
AVERAGE TEST DATA OF TENSILE STRENGTH FOR SECOND-ORDER

No	Average (Mpa)	No	Average (Mpa)
1	15.1	17	11.52
2	20.29	18	19.52
3	5.59	19	18.25
4	12.73	20	15.56
5	10.81	21	21.45
6	15.41	22	11.25
7	4.1	23	18.37
8	4.8	24	11.04
9	14.75	25	26.51
10	20.34	26	15.75
11	4.9	27	20.62
12	5.57	28	11.52
13	13.14	29	23.11
14	7.09	30	18.25
15	3.14	31	15.56
16	3.73		

B. Second-order Model Analysis

The second-order design uses a central composite design that can be arranged by adding the first-order design. This addition was carried out with additional experiments on six axial points and two center points. The tensile test result of this second-order experiment can be seen in Table VI. The data in this table are then processed to obtain a second-order model seen in equation (5). Y is the predictive value for the tensile strength response in the connection, O is the variable code value for overlap, T is the variable code value for temperature, S is the variable code value for printing speed, and JL is the variable code value for the number of layers.

$$y = -999 + 84O + 10.25T - 0.39S + 2.24JL - 69.80^{*}O - 0.02631T^{*}T - 0.00281\,S^{*}S - 0.0614JL^{*}JL - 0.0100O^{*}T - 0.391O^{*}S - 1.400O^{*}JL + 0.0344T^{*}S - 0.0045T^{*}JL + 0.0001S^{*}JL \quad (5)$$

TABLE VII
ANALYSIS OF VARIANT FOR CONNECTION'S TENSILE STRENGTH RESPONSE IN SECOND ORDER

Source	DF	Adj SS	Adj MS	F-*Value*	P-*Value*
Square	4	294.65	73.663	4.23	0.016
O*O	1	70.52	70.518	4.05	0.061
T*T	1	197.91	197.911	11.37	0.004
S*S	1	36.03	36.027	2.07	0.17
JL*JL	1	67.3	67.3	3.87	0.067
2-Way *Interaction*	6	48.06	8.01	0.46	0.827
O*T	1	0	0.003	0	0.989
O*S	1	21.97	21.973	1.26	0.278
O*JL	1	17.7	17.703	1.02	0.328
T*S	1	7.58	7.576	0.44	0.519
T*JL	1	0.81	0.806	0.05	0.832
S*JL	1	0	0.001	0	0.994
Error	16	278.49	17.406		
Lack-of-Fit	10	144.29	14.429	0.65	0.743
Pure *Error*	6	134.2	22.366		
Total	30	1189.85			

TABLE VIII
ADEQUACY TEST FOR SECOND-ORDER MODELS

Response	P-value	α	F-value	$F_{0.05;11;3}$	Status
Connection's tensile strength	0.743	0.05	0.65	4.06	Fail to reject H

TABLE IX
OPTIMAL PARAMETER VALUES

Order	Optimal parameter				The predicted value of a response
	O (mm)	T (°C)	S (mm/s)	JL (pieces)	Tensile strength (Mpa)
1	0.4	195	40	5	21.1835
2	0.4712	195.501	20	6	24.32

TABLE X
COMPARISON OF EXPERIMENTAL AND PREDICTIVE VALUES

Order	Replication			Average (Mpa)	Target (Mpa)	Error (%)
	1 (Mpa)	2 (Mpa)	3 (Mpa)			
1	24.64	20.18	19.52	20.29	21.18	4.20
2	26.47	24.82	24.37	25.22	24.32	3.57

The next step is to do an analysis of variance (ANOVA) on the response of connection's tensile strength (Table VII) and the lack of fit test to show the adequacy of the model (Table VIII). From the ANOVA test results, all interaction parameters have not strong enough evidence to conclude that interaction parameters affect the connection's tensile strength. However, from the ANOVA test results that have been conducted, it can be seen that the interaction that has the highest significance is Overlap and Printing speed. The interaction effect on 3D print connection's tensile strength can be seen in Fig. 9.

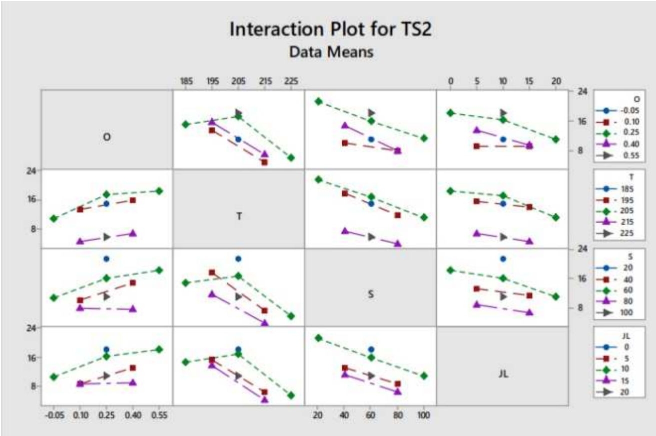

Fig. 9 Interaction plot of connection's tensile strength response

In Table VIII, P-value is greater than α, and F-value is smaller than $F_{0.05.10.6}$, it shows that the conclusions obtained fail to reject H_0. With these results, the suitable model describes the relationship of independent variables with response variables are quadratic polynomials. According to the second-order results, the next step is to optimize the combination of parameters against the response.

C. Optimization of the Combination of Parameters against the Response

The response surface method can provide an overview through the model in the form of surface contours or surface plots and provides information about the optimal points of each response to the parameters that influence it. Fig. 10 shows the surface plot for the first order, and Fig. 11 shows the second-order surface plot. The next step is to optimize the value of parameter set to produce the optimal response for the highest tensile strength on the connection. This optimization is conducted with software to obtain the exact parameter values and plot optimization.

Optimization plots for the first order can be seen in Fig.12, while the second-order can be seen in Fig. 13. From the optimization plot, the parameter setting values are obtained to optimize the tensile strength, as shown in Table IX

D. Validation of Optimization Results

Validation test is conducted by doing three replications with optimal parameters for each order. The results are averaged and compared with predictive values (Table X). From the tests that have been conducted, it is found that the error value for the second order is smaller than the first order. It shows that the second-order is more appropriate for describing this phenomenon.

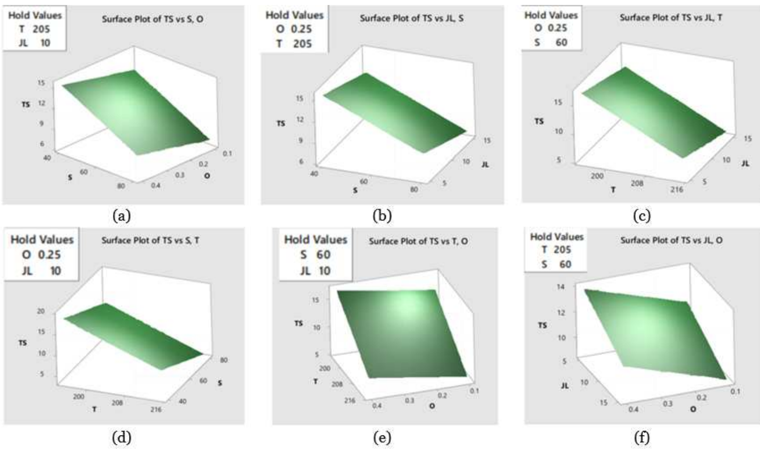

Fig. 10 First-order surface plots (a) TS vs S, O; (b) TS vs JL, S; (c) TS vs JL, T; (d) TS vs S, T; (e) TS vs T, O; (f) TS vs JL, O

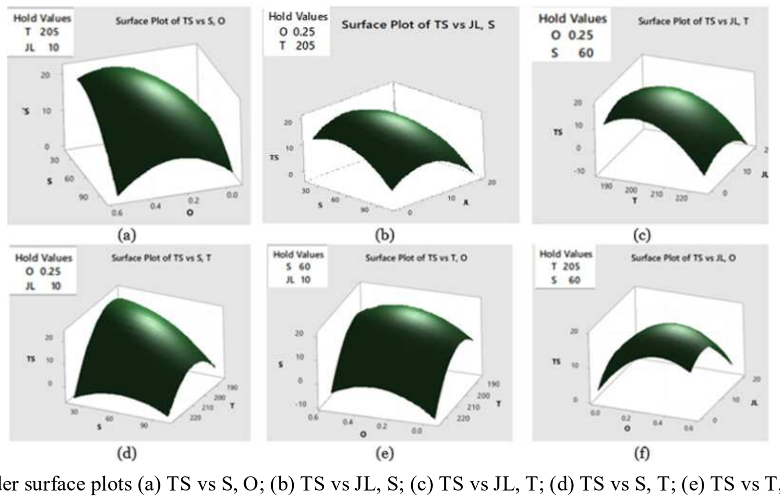

Fig. 11 Second-order surface plots (a) TS vs S, O; (b) TS vs JL, S; (c) TS vs JL, T; (d) TS vs S, T; (e) TS vs T, O; (f) TS vs JL, O

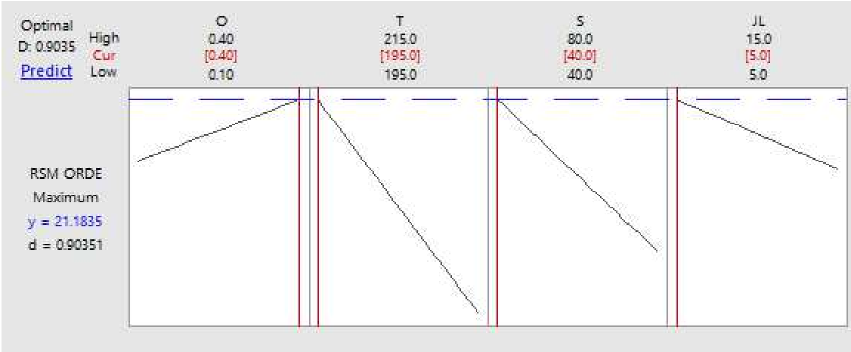

Fig. 12 First-order optimization plot

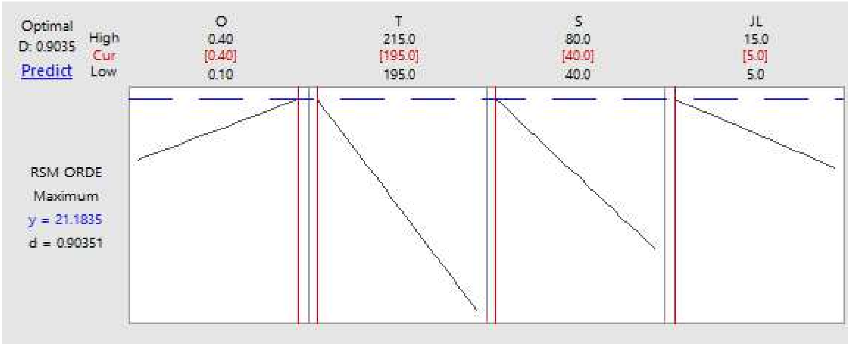

Fig. 13 Second-order optimization plot

E. Analysis of the Main Effect on Connection's Tensile Strength

The main parameters that proved to influence the tensile strength of the connection are the temperature and printing speed (Table IV). A high temperature will change the content of the physical form of the part that is continued during the process. The part that is exposed to heat from the nozzle will become semi-liquid; it can stick well during the continuation process. If the temperature is not high enough, the possibility of the continuation process is not maximal. The relationship between the effect of temperature on the strength of the nature of the results of the 3D print process has also been proven by Grasso *et al* [32]. Meanwhile, a low printing speed will produce better tensile strength, as in Fig. 14.

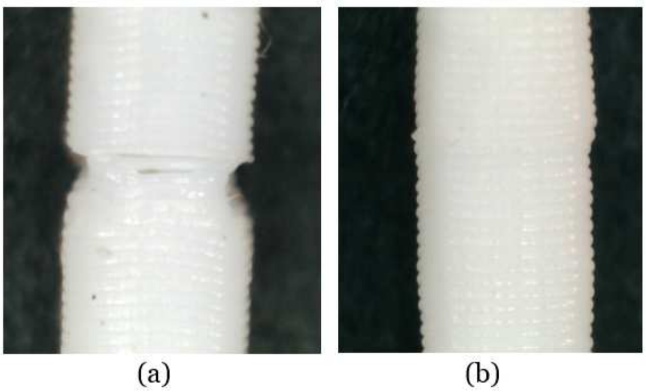

Fig 14. Porosity in a 3D print connection (a), and normal 3D print connection (b)

If the printing speed is too high, the deposition process will produce porosity, and imperfect joints (Fig. 14a) due to the movement of the nozzle is too fast, so the connection becomes weak. The connection is quite different from the normal ones (Fig. 14b); the normal ones look sturdier. The effect of speed on tensile strength is also stated by Torres *et al* [33], which in his research states that lower speeds impact tensile strength even if only slightly. However, different results are stated by Coogan and Kazmer [14] and Pan *et al* [34], which states that high print speed increases bond strength. More research is needed to prove the effect of speed on tensile strength.

F. Comparison with Non-continued Specimens

The Tensile strength test was carried out on the non-continued specimen for comparison. The average tensile strength obtained was 29.69 MPa. Thus, when the connection process is carried out, a decrease in tensile strength is 31.67% in the first order and 15.06% in the second order. The quality reduction is also reinforced by research conducted by Sinha and Meisel [19], which states a decrease in tensile strength for products that experience an interruption. However, the study conducted by Sinha and Meisel [19] stated that the reduction in tensile strength was 48%. This value is still bigger than the results of this study. The use of parameters in this study can optimize tensile strength better. However, further research still needs to be done, especially for other parameters proving their influence on tensile strength. The aim is that more optimal parameter settings can be found to reduce the impact of errors in the printing process.

G. Future Research Direction

From the second-order results, it is found that all the interaction parameters do not show strong evidence in influencing the tensile strength. However, this research found the highest significance of the interaction between overlap and printing speed (Table VII). Overlap itself is a new variable that has not been studied much. Although it does not have a significant value in the first order, overlap values can be considered in the second order. Therefore, further research is suggested to explore the overlap parameters further. Besides, the parameters used in the study are still very limited. To get better results, additional parameters can be done, for example, layer thickness. The next research can also do a combination by doing post-processing such as heat treatment on the joints to obtain different results from this study.

IV. Conclusion

Based on the results of the research that has been conducted, the main continuation process parameter that proved to influence tensile strength are the temperature and printing speed. Another parameter (number of layers and overlap) does not have strong evidence to conclude that these parameters significantly impact tensile strength at the connection. The similar result obtained from the interaction between parameters that have not been proven to have an effect on the tensile strength of the connection. However, the parameter setting to get the better tensile strength are obtained from the second-order optimization. The setting of the continuation process is an overlap of 0.4712 (0,4) mm, print temperature of 195,501 (195) °C, printing speed of 20 mm/s, and the number of layers is 6 layers. Future research should consider other parameters that can prove their influence on the tensile strength.

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