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Optimization of Surface Roughness in Additive Manufacturing Processes via Taguchi Methodology

Anjian Chen, Joseph C. Chen

Abstract**—**This paper studies a case where the targeted surface roughness of fused deposition modeling (FDM) additive manufacturing process is improved. The process is designing to reduce or eliminate the defects and improve the process capability index Cp and Cpk for an FDM additive manufacturing process. The baseline Cp is 0.274 and Cpk is 0.654. This research utilizes the Taguchi methodology, to eliminate defects and improve the process. The Taguchi method is used to optimize the additive manufacturing process and printing parameters that affect the targeted surface roughness of FDM additive manufacturing. The Taguchi L9 orthogonal array is used to organize the parameters' (four controllable parameters and one non-controllable parameter) effectiveness on the FDM additive manufacturing process. The four controllable parameters are nozzle temperature [°C], layer thickness [mm], nozzle speed [mm/s], and extruder speed [%]. The non-controllable parameter is the environmental temperature [°C]. After the optimization of the parameters, a confirmation print was printed to prove that the results can reduce the amount of defects and improve the process capability index Cp from 0.274 to 1.605 and the Cpk from 0.654 to 1.233 for the FDM additive manufacturing process. The final results confirmed that the Taguchi methodology is sufficient to improve the surface roughness of FDM additive manufacturing process.

Keywords**—**Additive manufacturing, fused deposition modeling, surface roughness, Six-Sigma, Taguchi method, 3D printing.

I. INTRODUCTION

CASTING is a process where molten metal is poured into a mold and allowed to solidify. This production method has been around since 4000 B.C. [1]. The ancient people used to use bronze to cast products and weapons. The casting production is one of the main factors that influenced the world economy. The annual capacity of casting production was over 91 million metric tons in 2010 [2]. In the market, almost 90 percent of the production parts have one or more metal castings [3]. There are many different metals for casting such as iron, copper, and lead. From the existing casting process, the sand casting is a cost-effective and time-efficient casting process [4]. The sand casting method had 75% of global metal casting production mass in 2012 [5].

Production of a mold is a vital step in the sand casting process. Fig. 1 (b) shows that the pattern makes the casting part's external shape. Fig. 1 (f) shows that there is a sand core inside the sand mold which is to produce internal cavities and reentrant angles and to make a sand core that requires a core-box [6]. Making a good pattern and core-box is an important part of sand casting, and there are different materials to make them. The common ones are wood, metal, and plastic. The metal patterns are costlier than the wood. The wooden patterns wear out fast due to its low resistance to sand abrasion [7]. The plastic pattern is more commonly used in today's sand casting industry due to its high strength and high resistance to wear. To make a plastic pattern, the industry commonly uses injection molding method, but it can be costly. Another method is to use additive manufacturing as an alternative solution for injection molding.

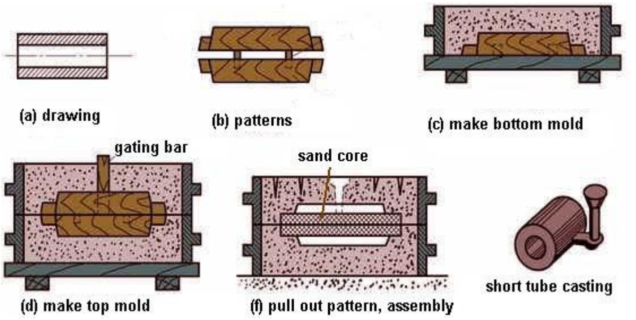

Fig. 1 The process of two parts molding of a short tube [8]. In the past few years, the foundry industry tried to use 3D printing technology to produce their patterns and core boxes [9]. The first additive manufacturing technology was developed by 3D Systems of Valencia, CA, USA in 1986 [10]. There are different ways to print a part, the most common one is FDM additive manufacturing. The FDM additive manufacturing process is fast, reliable, and cost-effective. But, due to the lack of training, the operator cannot make the surface roughness to meet the requirements of the blueprints. So, there is a need to find a proper method to develop a system to improve the FDM additive manufacturing process' surface roughness. The common way to set up an experiment is the trial and error method [11]

In this study, the trial and error method is not the efficient way to do it, because the Taguchi Method has the advantage of this study. In the 1950s, Dr. Genichi Taguchi, as known as "Father of Quality Engineering," introduced a new offline quality control technique, called Taguchi parameter design [12]. The Taguchi method is a technique for optimizing a process that has controllable inputs and measurable outputs. Cesarone used Taguchi methodology as the base to developed a theoretic plan for experiment. Due to the parameters differences, Cesarone suggests use Taguchi method is quicker and easier to find the optimum outputs [13].

In this research, the goal was to create a framework of a

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Taguchi based system that can guide people to solve the similar situation. To meet industry's requirement, that finds the current process capability C_p, and the process capability index C_{pk} can show that the current FDM additive manufacturing processes have a lot of defective parts because surface roughness did not reach the requirement. The Taguchi method can improve the surface roughness of the FDM 3D printed parts by optimizing the controllable parameters. Fig. 2 shows the flowchart of this research process. The goal is to make C_p greater than 1.33 and C_{pk} greater than 1.

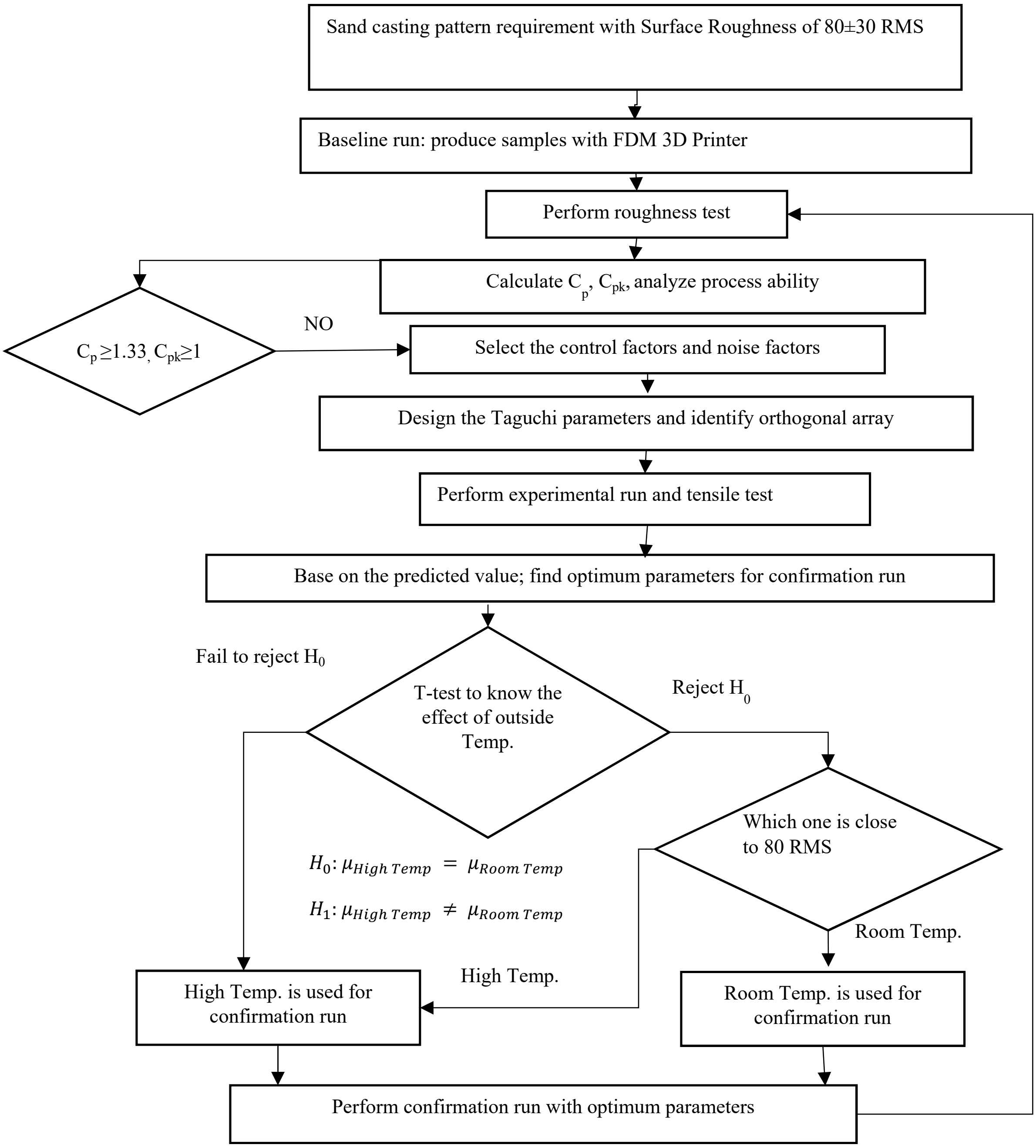

Fig. 2 The Taguchi method flowchart for FDM additive manufacturing

II. CURRENT 3D PRINTING CAPABILITY

The current 3D printing capability should be defined as the baseline of the research. A sample group of six specimens, with designed dimensions (Fig. 3), were printed by FDM 3D printer. The ABS used for specimens are provided by Hatchbox (3D ABS-1KG1.75-318C). The FDM 3D printer for this project is Monoprice Maker Ultimate 3D Printer MK11. After the specimens were made, a Zegage Profilometer was used to find the current 3D printing capability. The measurement point will be the center of the XY plane, which is 0.5 inch from the edges.

For this experiment, the acrylonitrile butadiene styrene

(ABS) was chosen to be the printing material. The ABS is a thermoplastic polymer that commonly used in industrial applications and is also a common material for costing pattern. The FDM ABS has 65 to 72 percent of tensile strength and 80 to 90 percent of the compressive strength of injection molded ABS [14]. The ABS has high toughness and heat resistance. Also, ABS has high chemical resistance, which makes it very popular on the market. Due to the low price and high performance, that makes ABS the best material for this study.

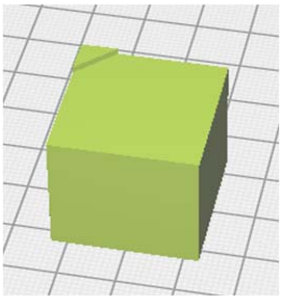

Fig. 3 The 3D Model of Specimen

From Table I, the key process input variables (KPIV) are the Nozzle Temperature, Layer Thickness, Nozzle Moving Speed, and Extruder Filling Speed. The baseline specimens were printed with the input parameters shown in Table I.

TABLE I
BASELINE PARAMETER SETTING

KPIV	Unit	Input Parameters
Nozzle Temperature	°C	240
Layer Thickness	mm	0.15
Nozzle Moving Speed	mm/s	40
Extruder Filling Speed	%	100

III. ANALYZE

A. Taguchi Method

The Taguchi orthogonal array method and hypothesis test are used to evaluate the current process and figure out the optimum printing parameters [15]. The KPIV is the project's controllable parameters. The non-controllable parameter is the environmental temperature. Table II shows A, B, C, and D; four different controllable factors with three different levels and one non-controllable factor with two levels. For Table II, (1) (nominal-the-better criterion), was used to find the signal-to-noise (S/N) ratio.

$$\eta = 10\log(\frac{\bar{y}}{s^2}) \qquad (1)$$

η is the S/N ratio, $\bar{y}$ is the mean of surface roughness, and s^2 is the variance between η and $\bar{y}$.

The L_9 orthogonal array was used to find the optimum printing parameters. In Table III, the column of L_9-Inner control factor array is used different combinations of levels that makes total 18 test runs, and two specimens per each run.

TABLE II
THE FOUR CONTROLLABLE PARAMETERS AND ONE NON-CONTROLLABLE PARAMETER

Designation	**Input Variables**	**Unit**	**Levels** 1	2	3
	Controllable Factors				
A	Nozzle Temperature	°C	220	240	260
B	Layer Thickness	mm	0.05	0.15	0.25
C	Nozzle Moving Speed	mm/s	20	40	60
D	Extruder Filling Speed	%	80	100	120
	Non-Controllable Factors				
1	Environment temperature – High Temperature: 40 – 60 °C				
2	Environment temperature – Room Temperature: 20 – 30 °C				
	Output variable		Surface Roughness (RMS)		

TABLE III
TAGUCHI L_9 ARRAY AND DATA OF THE EXPERIMENT

L9 - Inner Control Factor Array					Normal Temp. (40 -60 °C)		Room Temp. (20 -30 °C)		Calculated Value		
X	A	B	C	D	N1	N2	N1	N2	$\bar{y}$	S^2	η
1	1	1	1	1	121	284	132	133	167	6067	-15.59
2	1	2	2	2	126	147	198	130	150	1094	-8.63
3	1	3	3	3	192	226	195	192	201	279	-1.41
4	2	1	2	3	76	88	199	184	137	4083	-14.75
5	2	2	3	1	127	106	129	120	121	104	0.63
6	2	3	1	2	192	205	136	150	171	1088	-8.05
7	3	1	3	2	67	79	105	105	89	350	-5.95
8	3	2	1	3	225	245	217	201	222	324	-1.65
9	3	3	2	1	140	171	164	127	151	416	-4.41

IV. RESULTS AND DISCUSSION

The targeted surface roughness is 80 ± 30 RMS, and the L_9 array was used to find the closest value to targeted surface roughness. The response table is made of the surface roughness and S/N ratio based on the value which close to targeted surface roughness value. Table IV shows the three levels values for the four controllable parameters. Fig. 4 shows the four parameters vs. Surface roughness and S/N ratio.

TABLE IV
RESPONSE TABLE FOR SURFACE ROUGHNESS AND S/N RATIO

Surface Roughness	A	B	C	D
Level 1	172.91	131.04	186.60	146.17
Level 2	142.61	164.18	145.85	136.52
Level 3	153.87	174.18	136.95	186.71
S/N Ratio	A	B	C	D
Level 1	-8.54	-12.10	-8.43	-6.46
Level 2	-7.39	-3.22	-9.26	-7.54
Level 3	-4.00	-4.62	-2.25	-5.94

From the response table, that shows the closest value to the targeted surface roughness. Then, we use (2) to calculate the roughness values and S/N ratio values.

$$Y_{predicted} = (\bar{Y}_A + \bar{Y}_B + \bar{Y}_C + \bar{Y}_D) - 3\bar{Y}_{all} \qquad (2)$$

The combination of surface roughness value is $A_2B_1C_3D_2$, and the result is 77.72 RMS. The combination of S/N ratio value is $A_3B_2C_3D_3$, and the result is 172.32 RMS. The $A_3B_1C_3D_2$'s result is better than $A_2B_1C_3D_2$, so the $A_3B_2C_3D_3$ is the optimal parameter setting for this study. Table V shows the optimal parameter settings.

There is a non-controllable value in this study, and that is environmental temperature. It affects the results of the surface roughness test. A single-sample T-test was conducted to determine if a statistically significant difference in surface roughness existed between the high-temperature and the room-temperature:

$$H_o: \mu_{\text{High temp.}} - \mu_{\text{Room temp.}} = 0$$
$$H_1: \mu_{\text{High temp.}} - \mu_{\text{Room temp.}} \neq 0$$

TABLE V
OPTIMAL PARAMETER SETTING

KPIV	Unit	Input Parameters
Nozzle Temperature	°C	260
Layer Thickness	mm	0.05
Nozzle Moving Speed	mm/s	60
Extruder Filling Speed	%	100

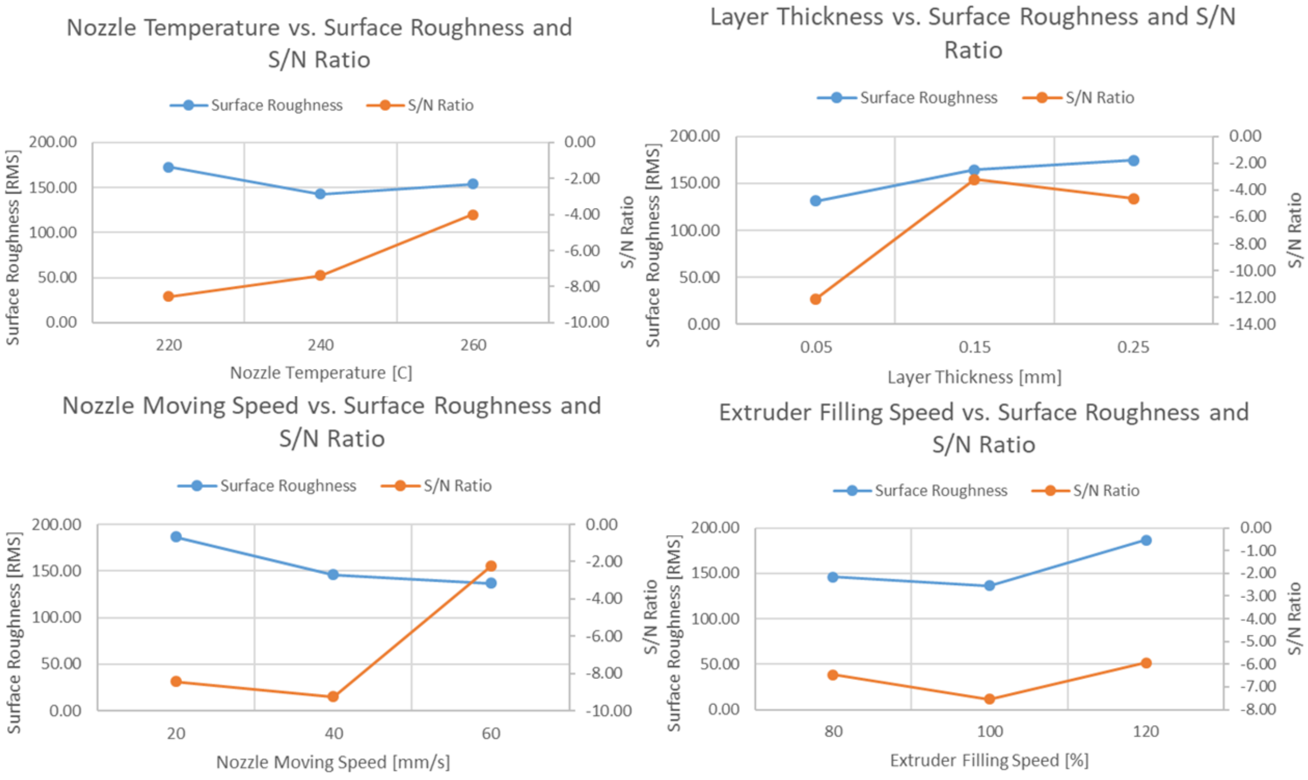

Fig. 4 The plots of the four parameters vs. surface roughness & S/N ratio

There was no significant difference in surface roughness for the high-temperature (M=156, SD=58) and the room-temperature (M=156, SD=35) conditions; T(16)=2.921, p=0.000105727 with alpha level 99%. This means there is not enough evidence to prove that environment temperature has a significant effect on this experiment. The confirmation run will be at room temperature.

V. IMPROVE

The experiment used the Table V's optimal parameter setting for the confirmation run. There are ten specimens made with the optimum setting $A_2B_1C_3D_2$. The mean of the surface roughness is 73.06 RMS, and the stand deviation is 6.57 RMS. Also, these data were used to calculate the C_p and C_{pk}, they are 1.605 and 1.233, respectively. There is a significant improvement in the optimized parameter. After the improvement, 99.99% of specimens are between the 110 to 50 RMS, which is the target 80 ± 30 RMS.

VI. CONCLUSION

In this study, there are four controllable parameters for the FDM additive manufacturing. They are nozzle temperature, layer thickness, nozzle moving speed, and extruder filling speed. An L_9 orthogonal array was used to find out the effectiveness of the four parameters and to optimize the surface roughness due to the changes made for four parameters. The study reaches the target surface roughness 80 ± 30 RMS. The result is 70.06 RMS based on the adjusted optimized parameter confirmation run. The final results show that the C_p and C_{pk} have improved, from 0.274 and 0.654 to 1.605 and 1.233, respectively. This study also approved that Taguchi methodology is an effective tool for this study. In the future, this Taguchi based system can guide operators to improve similar processes.

From the above results, it shows that FDM additive manufacturing process can be an alternative way for the pattern and core-box. It is going to save company's time,

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overall cost, and manufacturing cost. Further research could find out the different lifetime between the 3D printed pattern and aluminum pattern.

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