OPTIMIZATION OF SURFACE ROUGHNESS USING TAGUCHI METHOD FOR SELECTIVE LASER MELTING OF INCONEL 718

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Abstract: The Selective Laser Melting process is one of the major powder bed processes for additive manufacturing. Laser based processes are finding more attention of researchers and industrial world due to capability to build any complex geometry. Quality of SLM fabricated part is one of the major challenges to implement as full fledges commercial technology. Present study involves investigations of influence of process parameters on surface roughness of selective laser melted Inconel 718 super alloy. The objective of the study was to optimize process parameters namely laser power, scanning speed, and layer thickness and build orientation. In this work, the experiments were carried out as per the Taguchi experimental design and an L16 orthogonal array was implemented to study the influence of various combinations of process parameters .Analysis of variance (ANOVA) was performed to determine the significance of each process parameters on response. Results indicate that the most significant factor influencing surface roughness is layer thickness followed by orientation, power and scan speed. The work is useful in selecting optimal process parameters that would minimize the surface roughness and to obtain improved quality with minimal post processing requirements.

Keywords—Selective Laser Melting (SLM), Inconel 718, Taguchi, Analysis of variance (ANOVA), surface roughness, optimization

1. INTRODUCTION:

Additive manufacturing can fabricate full functional customized parts directly from 3 D CAD model. One of the significant powder bed processes for metals is Selective Laser Melting (SLM) finds wide spread applications for producing components with intricate geometries in the field of aerospace, automobile, biomedical and nuclear engineering. During the SLM process, successive layers of powders are completely melted and joined by energy of laser beam. This process is able to obtain fully dense parts with mechanical properties comparable to those of bulk material [1-3]. Poor surface finish common problem encountered with SLM process. A good surface finish is highly important to determine the quality of product and it is essential to improve corrosion resistance, fatigue resistance and appearance of the product. [7]Due to this limitation, a final finishing process becomes necessity for SLM built components. Another challenge to be addressed is porosity of built component due to some inherent process characteristics. Porosity of built component affects micro structural and mechanical properties [10]. Some studies are available to improve the part quality processed by SLM. Inconel 718 is one of the most promising metals for industrial applications of SLM manufactured parts. The objectives of the study are to investigate the influence of process parameters and to obtain optimal process parameters to minimize the surface roughness and porosity. The selection of optimal process parameters using optimization technique helps to obtain better quality of products and process reliability [4-6]. Additive Manufacturing is growing technology; hence there is need for systematic and methodological tool for optimization of process parameters. The statistical analysis was performed using Taguchi method which proposes a quadratic loss function for finding the best levels of control factors. This technique permits both to reduce the experimental plan and to have robustness against the noise introduced by uncontrolled variables. [11-14]

Nomenclature		Abbreviations	
P	Laser Power W	SLM	Selective Laser Melting
v	Scan speed mm/s	SS	Sum of Squares
t	Layer thickness mm	MS	Means of Squares
ɵ	Build orientation	DF	Degree of Freedom
Ra	Surface roughness	OA	Orthogonal Array
n	Number of trials		
η	Signal to Noise ratio (S/N)		

2. MATERIAL, METHOD & EXPERIMENTAL PLAN:

2.1 Material:

718 is one of most promising super alloy for industrial applications especially in the field of automobile, aerospace and nuclear engineering due to attributes like high strength at elevated temperature, excellent corrosion resistance and fabricability. For gas atomized Inconel 718 (CL 100 NB) with average particle size 38 µm the composition are as following:

Table 1 Composition of Inconel 718 (CL 100 Nb) powder

Component	Indicative Value %g	Component	Indicative value (%)
Ni	50.0 - 55.0	C	0.0 – 0.08
Cr	17 – 21	Mn	0.02 – 0.35
Nb	4.75 - 5.5	Si	0.02 – 0.35
Mo	2.8 – 3.3	P	0.0 – 0.015
Ti	0.65 – 1.15	S	0.0 – 0.015
Al	0.02 – 0.008	B	0.0 – 0.006
Co	0.0 – 1.0	Cu	0.0 – 0.3

2.2Taguchi Method Overview:

Genichi Taguchi suggested a unique and reliable technique for product or process quality improvement. It is more structured and efficient method that is relatively simple compared to classical design of experiments (DoE). Taguchi proposed strategy for optimization in three step approach: system design parameters (factors) design and tolerance design. The parameter design is key step to achieve high quality characteristic without increasing cost. It uses a special design of orthogonal arrays to study the entire parameter space with small number of experiments. Taguchi method which proposes a quadratic loss functions for finding the best levels of control factors. This technique is popular among researchers as it permits reduced the experimental plan, reduced time and cost for experimentation with robustness against the noise introduced by uncontrolled variables[16]. The experimental results are than transformed into signal to noise (S/N) ratio. The S/N ratio is used as a measuring index for quality characteristic deviating from nearness to the desired value.

In this analysis of S/N ratio, the lower is better is considered for the response parameter surface roughness. Quality characteristic is determined by:

For smaller is better $$\frac{S}{N}ratio(\eta) = -10\log 10\left(\frac{1}{n}\sum y\,i^2\right) \quad (i)$$

For larger is better $$\frac{S}{N}ratio(\eta) = -10\log 10\left(\frac{1}{n}\sum \frac{1}{{y_i}^2}\right) \quad (ii)$$

For nominal the best $$\frac{S}{N}ratio(\eta) = -10\log 10\left(\frac{1}{n}\sum \frac{yi^2}{s^2}\right) \quad (iii)$$

Where y_i = observed response value
n = number of replications
s = variance

In this study, the four control factors are selected namely, layer thickness, laser power, scan speed and build orientation for response surface roughness with smaller is better.

2.3 Experimental Plan:

Based on the selected factors and their level, L 16 orthogonal array for Taguchi Design of Experimental plan was implemented with software Minitab 16. Four levels of following parameters were selected with permissible operating limits of machine:

Table 2 Parameter Levels

Sr. No.	Parameter	Level 1	Level 2	Level 3	Level 4
1	Laser Power W	160	170	180	190
2	Scan speed (mm/s)	500	600	700	800
3	Layer thickness mm	0.03	0.04	0.05	0.06
4	Build orientation degrees ɵ	0	10	20	30

A three dimensional CAD(Computer Aided Design) model of specimen was created using Creo 3.0.A cube of 10mm X 10 mm X 10mm is created. The specimen are built with Concept laser M1 with for selected material(CL 100 NB) Inconel 718.Surface roughness values Ra was measured for each specimen by using Maxell surface roughness tester with displacement of 4 mm.

Figure 1 Experimental Set up Concept Laser M1

Figure 2 Build specimen

3. RESULTS & ANALYSIS:

Table 3 Response table for Ra

Sr. No.	Parameter Level				Response Ra µm
	A	B	C	D	
	Power W	Scan speed mm/s	Layer thickness mm	Orientation degrees	
1	160	500	0.03	0	5.1
2	160	600	0.04	10	10.4
3	160	700	0.05	20	10.2
4	160	800	0.06	30	14
5	170	500	0.03	0	7.5
6	170	600	0.04	10	3.87
7	170	700	0.05	20	8.8
8	170	800	0.06	30	11.6
9	180	500	0.03	0	8.8
10	180	600	0.04	10	9.7
11	180	700	0.05	20	8
12	180	800	0.06	30	6.3
13	190	500	0.03	0	10.1
14	190	600	0.04	10	5.5
15	190	700	0.05	20	8.4
16	190	800	0.06	30	5.17

Table 4 S/N ratios for Ra

Level	P	v	t	ɵ
1	-15.43	-17.49	-14.19	-15.75
2	-17.46	-16.69	-14.70	-15.11
3	-16.53	-16.09	-17.50	-17.33
4	-16.14	-15.29	-19.18	-17.36
Delta	2.03	2.20	4.99	2.26
Rank	4	3	1	2

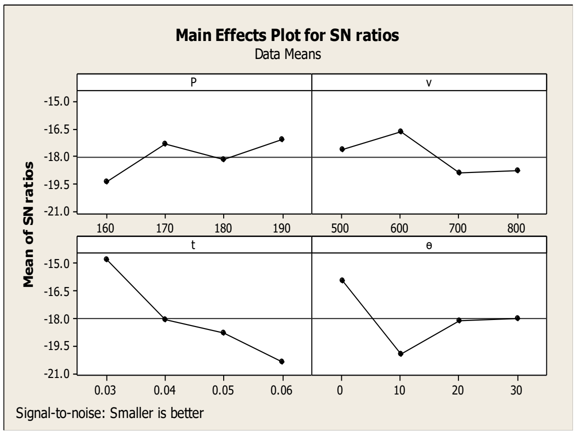


Figure 3 (a) Main Effect Plots for Ra

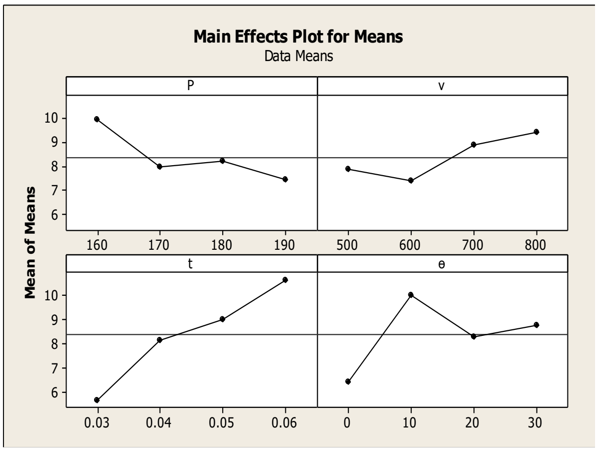


Figure 3 (b) Main Effect Plots of Means for Ra

Response graphs for means and S/N ratio provide graphical presentation of quantitative and qualitative influence of factors within specified range. From figure 3 (a) and (b) for it is revealed that the most dominating factor is layer thickness, than followed by orientation, power and scan speed respectively for surface roughness.

3.1 ANOVA

ANOVA is statistical technique to determine the degree of difference or similarity between two or more groups of data. It is based on the comparison of average value of common component. It is helpful to select optimum combination of process parameters more accurately. Table 5 represent the ANOVA table for surface roughness. The total sum of squared deviations adjusted SS can be calculated by equation (iv)

$$SS = \sum_{i=1}^{n}(n_i - n_m)^2 \quad \text{(iv)}$$

Where, n_i = number of experiments in OA; n_m=mean of response (Ra for the experiment)

%ge contribution can be calculated as: $P\% = \frac{Seq\ SS_D}{Seq\ SS_T}$ (v)

Where $Seq\ SS_D$ =Sum of squared deviations. The ANOVA results are shown in table .Statistically a tool called F test (named after Fisher) to determine the most significant quality characteristic. The P values indicates the significance level.

Table 5 ANOVA Table for Ra

Source	DF	Seq SS	Adj MS	F	P
P	3	14.091	4.697	4.28	0.132
v	3	10.165	3.388	3.09	0.189
t	3	51.917	17.306	15.78	0.024
ɵ	3	26.756	8.919	8.19	0.059
Error	3	3.290	1.097		
Total	15	106.219			

Predictor	Coef	SE Coef	T	P
Constant	9.198	7.444	1.24	0.242
P	-0.07243	0.03858	-1.88	0.087
v	0.006058	0.003858	1.57	0.145
t	158.23	38.58	4.10	0.002
ɵ	0.05277	0.03858	1.37	0.199

S = 1.04725 R-Sq = 96.90% R-Sq(adj) = 84.51%

Table 5.2 % ge contribution for Ra

Process Parameter	Contribution P %ge Ra
P	14.091
v	10.165
t	51.917
ɵ	26.756

3.2 REGRESSION ANALYSIS:

Multiple linear regression equations were modelled to evaluate surface roughness for any combinations of factor levels in a specified range. Model for multiple regressions is:

$$y = B_0 + B_1 + B_1 x_1 + B_2 x_2 + B_3 x_3 + \cdots + B_p x_p + \varepsilon \qquad \text{(vi)}$$

Where, y = dependent variable, B_0, B_1, B_2, B_3, B_p are regression parameters;

$$x_1, x_2, x_3, \ldots, x_p \text{ are independent factors and } \varepsilon \text{ is residue}$$

Expected value for surface roughness can be obtained by equation (vii) for any combination of parameters with equation. The parametric equation was obtained by least square method.

$$Ra = 9.20 - 0.0724\,P + 0.00606\,v + 158\,t + 0.0528\,\theta \qquad \text{(vii)}$$

Percentage error ranges between 1.34 to 24.9% for surface roughness with good agreement with measured and predicted values.

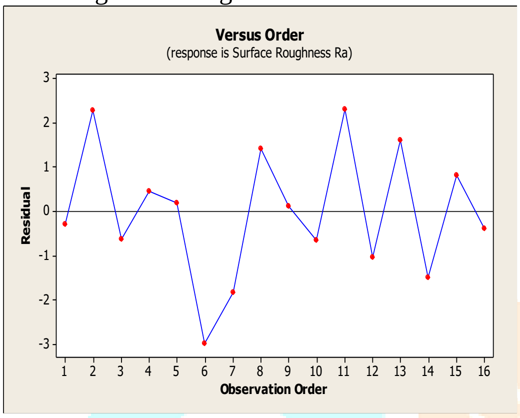


Figure 6 (a) Residual plot for Ra

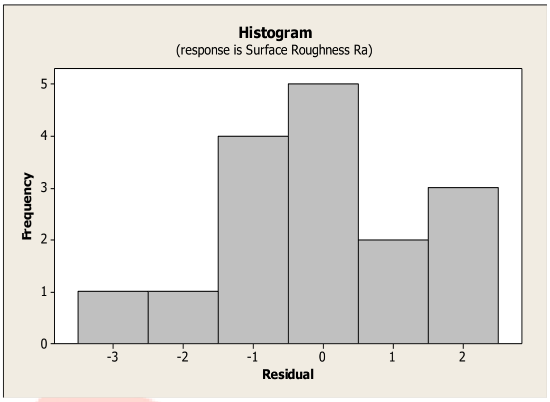
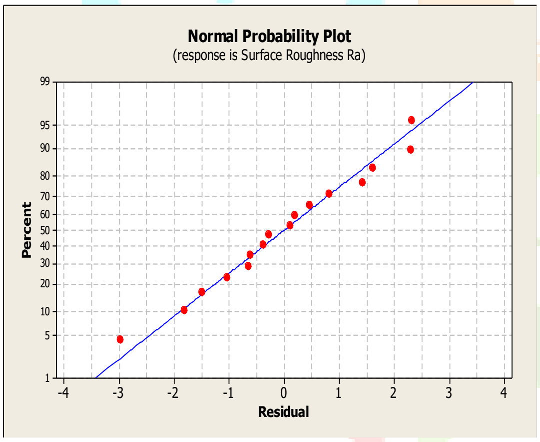


Figure 6 (b) Histogram for Ra



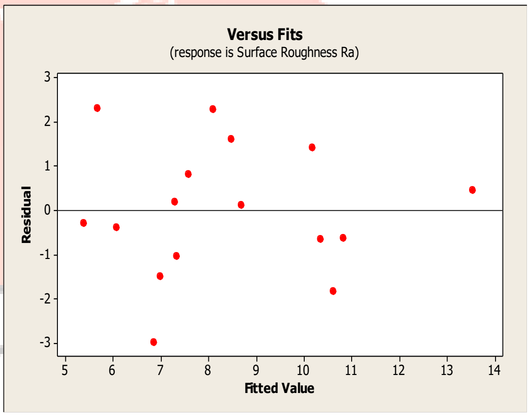


Figure 6 (c) Residual plots for fitted value

Figure 6(d) Normal probability plot for Ra

The diagnostic checking has been performed with residual analysis of developed model. The normal probability plot of residuals falls on straight line shows that errors terms are distributed normally that is observed from figure 6 (c) and (d) .

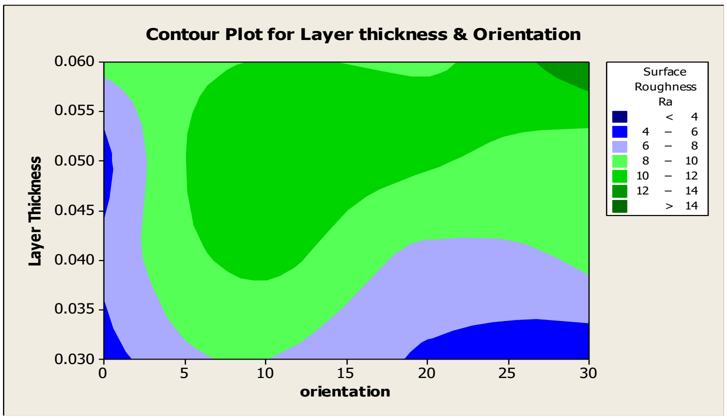


Figure 7 Contour plot for Layer thickness and Orientation for Ra

Figure 7 indicates the contour plot which helps to visualize with range of surface roughness with two most significant parameters layer thickness and orientation. The darker regions show higher values of Ra. It can be observed that lower values of surface roughness are available in very narrow range of combinations of layer thickness and orientation.

4. CONCLUSIONS & FUTURE SCOPE:

Experimental investigations were carried out for selective laser melting process with Inconel 718 powder to study the influence of process parameters on surface roughness built part at four levels by employing Taguchi technique to determine optimal process parameters. The conclusions of the investigations are:

The ANOVA revealed that the layer thickness is the most significant parameter that has highest influence on surface roughness followed by orientation, power and scan speed.

Multiple regression model was developed for evaluating surface roughness of SLM built part. The validation experiment was conducted to obtain minimum surface roughness with optimal combination of process parameters at layer thickness 0.03 mm, build orientation 0, scan velocity 550 mm/s, power 160 W . The predicted value of Ra with equation (vii) deviates by 1.91%ge with measured value of 5.8 µm that is in fair agreement with the developed model. Model is reasonably accurate and can be used for prediction within limits.

The present work may be extended to study the effects of other process parameters like laser spot diameter, hatch spacing, scan strategy etc. and for other quality response characteristics like geometrical accuracy, porosity, mechanical and micro structural properties.

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