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Optimization of Surface Roughness in Selective Laser Sintered Stainless Steel Parts

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Abstract: Decreasing surface roughness (RS) during selective laser sintering process improves quality and functionality of the metal parts. This paper emphasized thoroughly the effect of process parameters likely laser power, orientation and scan spacing on surface roughness. Taguchi's design of experiments approach L9 orthogonal array (OA) was selected and optimum level of parameters was chosen by lower-the-better signal-to-noise (S/N) ratio for this investigation. Also Analysis of variance (ANOVA) was utilized and found that the scan spacing was the most important parameter in finalizing upward-facing surface roughness and developed the empirical model. Finally an optimum level of parameters was used in confirmation test and confirmed that the predicted values in both methods ie., regression model and the equation of predicted S/N ratio were close enough themselves and also in experimental values.
Keywords: Infiltration,lasers,optimization,roughness, sintering, taguchi, steels, prototyping.

Introduction

The selective laser sintering (SLS) and selective laser melting (SLM) are the widely used rapid prototyping (RP) processes for making functional parts in metal. The primary challenge of this process is to choose the correct working parameter to achieve the preferred shape, size, strength, microstructure, quality and hence improve the functionality of the product [1-3]. SLS & SLM are such an additive layering processes utilizing CO_2 laser and powder material (polymers, metals, ceramics and composites) to build a 3-D part without molds or support [4]. SLS is mainly used for the fabrication of functional metal parts in small batches and enables the production of relatively large objects compared to other RP processes. The production speed of this technology is also very high. But SLM which uses high powered laser and it leads to high temperature causes an increase in spatter generation as well as metal vaporization during the process [5]. Hence SLS has been chosen for this study. Today there are lot of rapid prototyping technologies commercially available in the field of tool making, medical and aerospace application and also it has been analyzed the quality of the surface tends to decrease [6, 7]. The surface roughness is a main drawback in the SLS process as it can affect the accuracy, post processing cost and functionality of the parts. The details on the minimum surface roughness of stainless steel functional parts in SLS by optimizing the process parameters using Taguchi method fulfill the industry need.

Several studies have demonstrated that the part surface roughness and mechanical properties depend on the type of RP technology, the base material, laser type, and layer thickness, build strategy, and post-processing [8-10]. Thus the surface roughness is an important quality objective of parts obtained in RP technologies. Many papers revealed that the Taguchi technique has been used for optimization of surface roughness in various RP process and machining operations [11-14]. The different post processing methods like shot peening and cold isostatic pressing of components reporting hardness and roughness have also been discussed [15,16].

The main objective of this study is to minimize the surface roughness of stainless steel metal parts in SLS by optimizing the process parameters using Taguchi method. Among the many parameters which influence the required surface quality of SLS parts the laser power determines the temperature gradient, Orientation causes stair stepping effect and scan spacing [8] are the most essential parameters. The parameter levels were finalized based on the potential of SLS machine and the preliminary experiment done. Taguchi's design of experiments (DOE) approach L9 OA was used for this investigation. Taguchi techniques [17, 18], such as OA, S/N ratio, and ANOVA have been generally applied to optimize the various process. Then ANOVA was used and consequently developed the empirical model. Finally, confirmation experiment at an optimum level of parameters are confirmed that the predicted values in both methods were close enough themselves and also in experimental values.

Experiments

The different parameters, designation and values at all levels are finalized and described in Table 1.A wedge shaped samples were modeled in Design software as shown in Fig.1 is used to find the roughness characteristics. This figure clearly shows the build orientation (Φ) and direction of surface roughness measurement .A mean diameter of 23 µm LaserForm ST-100 powder material was utilized in this experimental work. The particles were coated with a mixture of thermoplastics (phenolic resin). The build orientation and positions were finalized and fixed accordingly in the software (Fig.2). Consequently the sliced files in layers of 0.01mm thickness were repaired and transferred to SLS system. The SLS green part fabricated was then subjected to bronze infiltration. The final composition obtained after infiltration is 40% bronze and 60% 420 stainless steel. Typical samples were built in the DTM siterstation® 2500 plus SLS system and SURFCOM 130A roughness tester measured the surface roughness. The photography of the manufactured samples are shown in Fig.3.

Table.1 Parameters, Designation and levels for experiments

Parameter (i)	Designation	Unit	Level 1	Level 2	Level 3
Laser power	P	[Watts]	58	60	62
Orientation	O	[Degree]	0	45	90
Scan spacing	SS	[mm]	0.08	0.09	0.10

The L9 orthogonal array and mean surface roughness value for the parameters and their levels are illustrated in Table 2. In this study the interaction among the parameters was not considered.

Table.2 Experimental results of L9 orthogonal array for Surface Roughness

Experimental run j	Laser power [Watts]	Orientation [Degree]	Scan spacing [mm]	Mean Surface Roughness [Microns]
1	1(58)	1(0)	1(0.08)	5.952
2	1(58)	2(45)	2(0.09)	8.129
3	1(58)	3(90)	3(0.10)	7.334
4	2(60)	1(0)	2(0.09)	6.799
5	2(60)	2(45)	3(0.10)	8.281
6	2(60)	3(90)	1(0.08)	6.284
7	3(62)	1(0)	3(0.10)	9.246
8	3(62)	2(45)	1(0.08)	7.674
9	3(62)	3(90)	2(0.09)	9.307

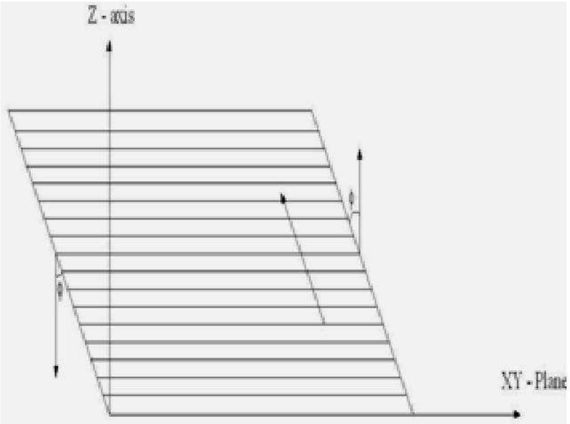

Fig.1 Wedge Part model for surface roughness characteristics

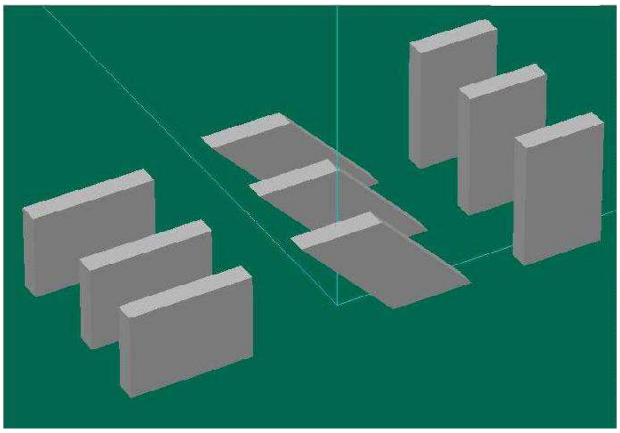

Fig.2 Preparations of samples for fabrication in machine software

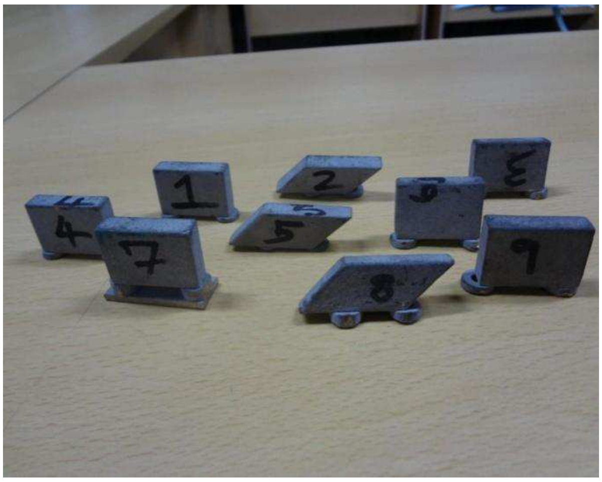

Fig.3 Fabricated samples by SLS process.

Result Analysis and Discussion

After the experiment results have been collected, the Taguchi's parameter approach with lower-the-better S/N ratio was used to find the optimum process parameter [12]. Signal-to-noise ratio 'n_j' in dB is defined as

Lower the better

$$n_j = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \qquad (1)$$

Where, n is the number of recurrence (now n = 1) and y_k is the measured value of surface roughness of k^{th} trial (here $y_k = RS_j$). Since n is equal to 1, Eq. 1 reduces to

$$n_j = -10\log_{10}\left(y_k^2\right)$$

Table 3 provides the calculated values of S/N ratio, average S/N ratio and rank for all parameters and its levels. To achieve the minimum surface roughness of the stainless steel parts produced by SLS process the lower S/N ratio value and corresponding level is selected as the optimum level as mentioned below. The Fig. 4-6 shows the main effect of parameter (P, O and SS) on S/N ratios at all levels and lower values of S/N ratios are considered as the optimum levels.

Power : 60 Watts (Level 2, S/N: 16.99),
Orientation : 0 Degree (Level 1, S/N: 17.15)
Scan spacing : 0.08 mm (Level 1, S/N: 16.38).

Next step, the ANOVA was applied to identify the parameter which influences the surface roughness. Obviously the maximum percentage of contribution is the most influence parameter to the surface roughness. Now the ANOVA table 4 was done based on the standard procedure [19] and identified the significant parameter.

Table.3 S/N Ratio of each parameter and level for Surface Roughness

Parameter i	Level	Experimental run j	Mean Surface Roughness RS_j	(S/N) ratio n_j	Average(S/N) ratio n_{ave}	Δ(maximum-minimum value)	Rank
P	1	1	5.952	-15.493	17.00	1.80	2
		2	8.129	-18.200			
		3	7.334	-17.306			
	2	4	6.799	-16.648	**16.99**		
		5	8.281	-18.361			
		6	6.284	-15.964			
	3	7	9.246	-19.319	18.79		
		8	7.674	-17.700			
		9	9.307	-19.376			
O	1	1	5.952	-15.493	**17.15**	0.93	3
		4	6.799	-16.648			
		7	9.246	-19.319			
	2	2	8.129	-18.200	18.08		
		5	8.281	-18.361			
		8	7.674	-17.700			
	3	3	7.334	-17.306	17.54		
		6	6.284	-15.964			
		9	9.307	-19.376			
SS	1	1	5.952	-15.493	**16.38**	1.94	1
		6	6.284	-15.964			
		8	7.674	-17.700			
	2	2	8.129	-18.200	18.07		
		4	6.799	-16.648			
		9	9.307	-19.376			
	3	3	7.334	-17.306	18.32		
		5	8.281	-18.361			
		7	9.246	-19.316			

Over all mean surface roughness = 7.66 Over all mean S/N ratio value = -17.60
Bold letters indicate the optimum levels.

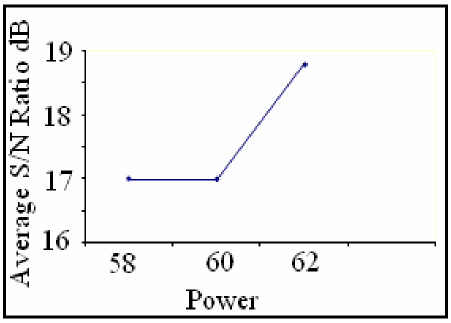

Fig.4 Effect of power on S/N ratio

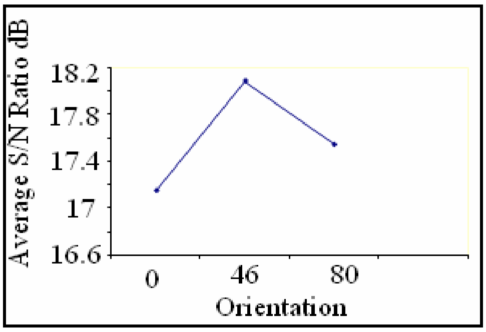

Fig.5 Effect of orientation on S/N ratio

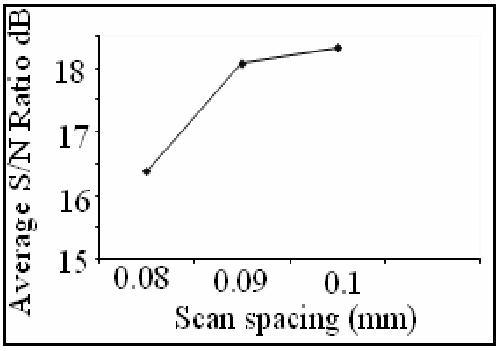

Fig. 6 - Effect of scan spacing on S/N ratio

Table.4 ANOVA for Surface Roughness

Parameter i	Sum of Squares SS_i	Degrees of freedom DOF_i	Mean Sum of Squares MSS_i	$F_{statistic}$	$F_{(0.025), 2, 2\text{-}tabulated}$	Percentage of contribution $(P_{RS})_i$
P	4.33	2	2.17	217	39.00	37.80
O	1.42	2	0.71	71		12.37
SS	5.70	2	2.85	285		49.65
Error	0.02	2	0.01			0.17
Total	11.47	8				

Significant at 97.5% confidence level

Due to various reasons the uncertainties of estimated surface roughness are unavoidable. The estimated surface roughness [8] is Ra ± ΔRa, where

$$\Delta Ra = t_{\alpha/2,\ DF}\sqrt{V_e} \qquad (2)$$

The calculated ΔRa value is equal to 0.43 µm (α =0.05) arrived by taking the values from Table 4. The establishment of a mathematical model gives more useful information of roughness on process parameters. This model equation provides the surface roughness value well in advance for the parameter fixed by the designer or RP machine user before fabricating the parts. The model is derived from an orthogonal polynomial method with orthogonal array data. The following Eq. 3 is proposed to establish a mathematical model between surface roughness (response variable) and process parameters [19].

$$RV = \beta_0 + \sum_{i=1}^{g}\left[\beta_{1i} P_1(i) + \beta_{2i} P_2(i)\right] + \in \qquad (3)$$

Where, RV: response variable (RS: surface roughness)

The regression Eq.3 for the process parameters which is influencing the surface roughness (response variable) is written as -

$$RS = \beta_2 p \times 3 \times \left[p^2 - \left[\frac{L_P^2 - 1}{12}\right]\right] + \beta_1 p \times 1 \times [p] + \beta_2 o \times 3 \times \left[o^2 - \left[\frac{L_O^2 - 1}{12}\right]\right] + \beta_1 o \times 1 \times [o] + \beta_2 ss \times 3 \times \left[ss^2 - \left[\frac{L_{SS}^2 - 1}{12}\right]\right] + \beta_1 ss \times 1 \times [ss] + \beta 0 \quad (4)$$

Similarly Table 5 provides the calculated values of coefficients for all the parameters. The results are as follows.

β_{1P} = 4.81/6 = 0.8016; β_{1O} = 1.01/6 = 0.1683; β_{1SS}= 4.96/6 = 0.8266

β_{2P} = 5.29/18 =0.2938; β_{2Oi} = -3.35/18 =-0.1866; β_{2SS} = -3.50/18 = -0.1944

$\beta 0$= 68.90/9 =7.7667

By substituting the parameters indicated above in Eq.4, the process model for surface roughness (RS) is derived and given in Eq. 5 below.

$$RS = 0.8814\ P^2 + 0.8016\ P - O.5583\ O^2 + 0.1683\ O - 0.5832\ SS^2 + 0.8266\ SS + 7.9401 \quad (5)$$

Table.5 Values of constant and coefficients

j	RS_j	Coded value of the levels			Orthogonal contrast for linear term C^1_{ij}			Orthogonal contrast for non-linear term C^2_{ij}			$(\beta^j_1)_p$	$(\beta^j_2)_p$	$(\beta^j_1)_o$	$(\beta^j_2)_o$	$(\beta^j_1)_{ss}$	$(\beta^j_2)_{ss}$
		P	O	SS	P	O	SS	P	O	SS						
1	5.952	-1	-1	-1	-1	-1	-1	1	1	1	-5.95	5.95	-5.95	5.95	-5.95	5.95
2	8.129	-1	0	0	-1	0	0	1	-2	-2	-8.13	8.31	0	-16.2	0	-16.26
3	7.334	-1	1	1	-1	1	1	1	1	1	-7.33	7.33	7.33	7.33	7.33	7.33
4	6.799	0	-1	0	0	-1	0	-2	1	-2	0	-13.4	-6.70	6.70	0	-13.40
5	8.281	0	0	1	0	0	1	-2	-2	1	0	-16.5	0	-16.5	8.28	8.28
6	6.284	0	1	-1	0	1	-1	-2	1	1	0	-12.5	6.28	6.28	-6.28	6.28
7	9.246	1	-1	1	1	-1	1	1	1	1	9.25	9.25	9.25	9.25	9.25	9.25
8	7.674	1	0	-1	1	0	-1	1	-2	1	7.67	7.67	7.67	-15.3	-7.67	7.67
9	9.307	1	1	0	1	1	0	1	1	-2	9.30	9.30	9.30	9.30	0	-18.60

Confirmation Test

In the present research to validate the model equation derived, the confirmation experiment and $[S/N]_{predicted}$ methods were adopted at an optimum level of parameters. Table 6 shows the variation between experiment and predicted values in both methods of surface roughness at an optimum setting.

The average minimum roughness of part attained in confirmation experiment at an optimum parameter was 6.08 µm. The following equation is used to calculate the predicted S/N ratio by utilizing the optimal process parameters [13].

$$\left[\frac{S}{N}\right]_{predicted} = \left[\frac{S}{N}\right]_m + \sum_{i=1}^{n} \left(\left[\frac{S}{N}\right]_i - \left[\frac{S}{N}\right]_m \right) \quad (6)$$

In the current study by substituting the optimal values from Table 3 in the above Eq. 6 and get the predicted S/N ratio as -15.34dB and thus Eq. 1 become as shown below.

$$-15.34 = -10\log 10\ y^2$$

Then the value of predicted surface roughness is calculated as 5.85 microns. Obviously from the Table 6, the predicted values in both methods were close enough themselves and to the experimental value at an optimum settings. Thus the optimum parameters and their levels are A2, B1 and C1 of laser power 60 watts, orientation 0° and scan spacing 0.08 mm.

Table.6 Comparison between experimental and predicted values for Surface Roughness

Settings	P	O	SS	Experiment value E.V	Regression value From Eq. 5 RS	Predicted S/N ratio Value $[S/N]_{predicted}$
OptimalSetting	60	0	0.08	6.08	5.80±0.43	5.85±0.43

Conclusion

The process parameters that influence the surface roughness of SLS stainless steel part has been analyzed in this paper successfully. The details on the minimum surface roughness of stainless steel metal parts in SLS by optimizing the process parameters using Taguchi method has been done in this research to avoid additional finishing operation. A process Engineer can use this research to conclude the parameter values well in advance before manufacturing the parts. From the results the following points also concluded.

1) Among all the three parameters considered for the analysis, the scan spacing was the important contributing factor affecting the upward-facing surface roughness.
2) The confirmation experiment was done at an optimum level of parameters and confirmed that the estimated values in both methods were close enough themselves (regression equation value 5.80±0.43 µm) (Equation of S/N value 5.85±0.43 µm) and also in experimental values. (6.08 µm).
3) It is found that the optimal process parameter for upward-facing surface roughness of the SLS metal parts are power of 60 watts, orientation 0 ^{o}and scan spacing 0.08 mm.

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