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Selective Laser Melting Parametric Optimization for Microhardness of 17-4 PH Stainless Steel

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The 17-4 PH stainless steel is a structural material possessing inherent properties suitable for employment in industrial applications. Selective Laser Melting (SLM) technology has overcome many shortcomings of conventional processing routes to fabricate structural parts possessing higher hardness and strength. Hardness is the most dominant factor that affects the quality of structural parts. Laser power, scan speed, and hatch distance affect the microhardness of 17-4 PH stainless steel parts. Taguchi method is applied to conduct experiments and perform statistical analysis and optimization for higher microhardness of SLM parts. Laser power showed the highest contribution equal to 87.76%, followed by a scan speed of 12.05% and hatch distance of 0.18% towards microhardness. The Taguchi method determined the optimal conditions (laser power: 300 W, scan speed: 1000 mm/s and hatch distance: 0.08 mm) resulting in a higher microhardness value equal to 351.2 HV.

Keywords: *17-4 PH Stainless Steel, Microhardness, Pareto ANOVA, SLM Process, Taguchi Method*

1.0 Introduction

Additive Manufacturing (AM) employs 3D printing, wherein the parts are built in an extract layer-by-layer to obtain the desired geometry[1]. This technology is versatile (adaptability, flexibility) and could be able to manufacture components which are geometrically complex and almost impossible with conventional processes[2]. AM technology possesses a significant advantage over traditional or subtractive manufacturing in fabricating near-net-shaped components with reduced raw materials and producing complex designed parts[3]. In the last two decades, AM technology has been used for the production of parts with a wide range of materials and alloys with an emphasis on rapid plastic prototyping to metallic ready-for-use components[4]. The quality of additive manufactured products is influenced by process variables[5]. Therefore, the study of process variables is of industrial relevance.

In recent years, the precipitate-hardened steels (17-4 PH, 17-7 PH, and PH-8 Mo) possessing up to 49 HRC were used to fabricate industrial parts possessing excellent characteristics (such as corrosion resistance, high strength, and less distortion)[6,7]. The said materials offer excellent strength, and corrosion resistance and exhibited reduced loss of ductility during the service life of the components[6]. These attractive characteristics help engineers to use the said materials in many engineering applications including automotive and aerospace parts[7-10]. A Selective Laser Melting (SLM) processing route is applied to fabricate 17-4 P.H. steel parts suitable for use in the aviation industry[11,12]. Since the properties of printed

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parts are dependent on the solidification phenomenon involved in laser melting, understating their behaviour was industrial relevance.

In recent years, several researchers tried to detail the process insights by studying the process variables on the performance of fabricated parts viz. traditional trial-and-error experiments, analytical and statistical design of experimental approach. SLM process is applied to study the influencing process variables (scan rate, slice depth, and hatch distance) on the physical, microstructure and mechanical properties of 17-4PH stainless steel[13]. The optimal parameters that could maximize the throughput are not determined for this research work. The effect of energy density on porosities and microstructure of 17-4 PH steel is studied by applying SLM process[14]. The effect of the scanning strategy on the density of 17-4 PH steel was studied by applying a traditional experimental approach[15]. The use of the traditional one-factor-at-a-time approach results in local solutions and requires costly (material, and energy waste, time-consuming and labour) experimental runs[16]. More recently, numerical and analytical methods have been developed to study the heat transfer characteristics during building the parts viz. selective laser melting process[17,18]. There are many assumptions (uniform powder temperature, no specific heat loss, semicircular cross section for melt tracks) being made in developing the numerical and analytical model which are often difficult to meet with practical experiments[18,19]. Therefore, the methods that could limit waste during experimentation and detail the process insights (estimating factor effects and determining optimal parametric conditions) at reduced costs are of industrial relevance.

In recent years, the Taguchi method has been applied to conduct minimum experiments, which help to analyze and optimize the factors that could maximize the performance in various manufacturing processes[20-23]. The Taguchi method has proven its effectiveness in offering better quality parts fabricated viz. in the additive manufacturing processes (laser additive manufacturing, fused deposition modelling, binder jetting). Taguchi method proves their effectiveness and ensures this method can be applied to obtain the desired performance in build parts.

The hardness of the build parts possesses a direct relationship with other mechanical and microstructure characteristics in the SLM process[24,25]. The characteristics and properties are reliant on the process variables. To ensure desired quality characteristics an accurate control of process variables is indeed essential. Not many efforts being made to study the most influencing variables (laser power, scan speed and hatch distance) on the effect of microhardness of 17-4 PH steel build parts are not presented and discussed in the literature.

Therefore, the present work aims to study the process variables (laser power, scan speed and hatch distance) on the microhardness of build parts. Taguchi method is applied to perform experiments and analyse the factor effects. The parametric significance in estimating the factor effects is performed by applying Pareto analysis of variance. The optimal factor combination that could maximize the microhardness in the build parts is determined and validated by conducting confirmation experiments.

2.0 Material and Methodology

The present work uses 17-4PH stainless steel to build parts possessing major alloying elements as given in Table 1. SLM parts were built using commercially viable 17-4 PH Stainless Steel metal powders. The procured metal powders possess ~50 ± 10 μm in size. The samples were fabricated to a cubic dimension possessing 10 x 10 x 10 mm. The samples were built using the SLM 280 machine. During experimentation, few parameters are maintained constant (refer to Table 2). The scan strategy is roamed which is rotating based on the control factor values specified in the Taguchi matrix between the two successive layers.

Table 1. 17-4PH steel chemical composition

Elements	Wt. (%)
Cr	15-17.5
Ni & Cu	3-5 each
Mn and Si	Max. 1.0 each
Nb	0.15 – 0.45
Mo	Max. 0.5

Table 2. SLM Machine parameters held constant

Variables	Value
Laser spot diameter	0.2 mm
Operational Beam Focus	100 µm
Minimum Scan Line	100 µm
Layer thickness	40 µm

The microhardness of SLM parts is influenced by three significant process variables (laser power, scan speed and hatch distance). The levels of each parameter are decided after conducting the pilot experimental trials in the research laboratory (Table 3).

Table 3. Variables and operating levels of the SLM process

Control Variables	Levels
Laser power (LP)	240, 270, 300 W
Scan speed (SS)	600, 800, 1000 mm/s
Hatch distance (HD)	0.08, 0.10, 0.12 mm

3.0 Experimental Details and Measurements

Taguchi method is employed to perform experiments. The L_9 experimental plan is employed for three factors operating at three respective levels (Table 4).

Microhardness measurements are carried out to examine the effects of process variables on the build

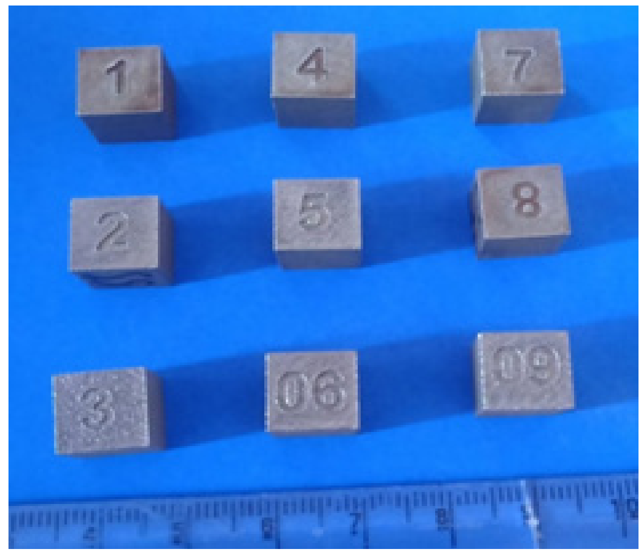

Figure 1. 17-4PH Steel-built samples using SLM.

Table 4. Hardness results of 17-4PH stainless steel sample

Designation/ Exp. No.	LP, W	SS, mm/s	HD, mm	Microhardness (HV)
1-SS	240	600	0.08	309.50 ± 4.3
2-SS	240	800	0.10	314.44 ± 2.8
3-SS	240	1000	0.12	321.61 ± 3.1
4-SS	270	600	0.10	330.60 ± 2.5
5-SS	270	800	0.12	332.64 ± 1.9
6-SS	270	1000	0.08	344.52 ± 4.1
7-SS	300	600	0.12	341.64 ± 2.5
8-SS	300	800	0.08	343.50 ± 2.8
9-SS	300	1000	0.10	348.21 ± 2.6

parts. Vickers microhardness equipment (Shimadzu HMV-G) is used to record the microhardness of SLM parts. At five distinct locations on a cube specimen the microhardness values are recorded. The applied load and their duration during microhardness measurements are maintained equal to 500 g and 15 s, respectively. Each trial is repeated thrice, and the average of 15 microhardness (five measurements on three replicates) values of build parts were recorded for performing the analysis (refer to Table 4). A few samples of SLM build parts are presented in Figure 1.

4.0 Result and Analysis

The results of the experimental input-output data collected according to Taguchi L_9 matrices are discussed in this section. The analysis and optimal conditions for the SLM process are determined based on Pareto Analysis of Variance.

4.1 Experimental Data Collection and Analysis

Taguchi L_9 experiments are conducted corresponding to three influencing variables (operating at three levels) and recorded the microhardness data (Table 4). The measured experimental Microhardness (MH) data is transformed to Signal-to-Noise (S/N) ratio data with higher-the-better quality characteristics using Equation (1). The S/N ratio

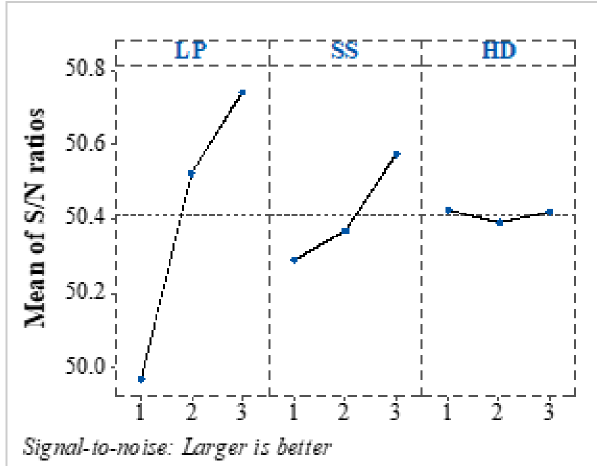

Figure 2. Main factor effects based on mean values of S/N ratio data.

(η_{ij}) is calculated for each experimental trial (say i^{th}) and corresponds to the j^{th} output.

$$S/N_{MH} = \eta_{ij} = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{(y_{ij})^2}\right) \quad .....(1)$$

n = 1, 2,.......m; j = 1, 2,........p

Table 5 presents the S/N ratio data for the microhardness of SLM parts corresponding to L_9 experimental runs.

The transformed output data (S/N ratio) is analyzed to determine the factor effects. Note that, to obtain

Table 5. Hardness results of 17-4PH stainless steel sample

Designation/ Exp. No.	Microhardness (HV)	S/N Ratio (dB)
1-SS	309.50 ± 4.3	49.81
2-SS	314.44 ± 2.8	49.95
3-SS	321.61 ± 3.1	50.15
4-SS	330.60 ± 2.5	50.39
5-SS	332.64 ± 1.9	50.44
6-SS	344.52 ± 4.1	50.74
7-SS	341.64 ± 2.5	50.67
8-SS	343.50 ± 2.8	50.72
9-SS	348.21 ± 2.6	50.84

Table 6. Pareto ANOVA results for MH

Factors	Levels	LP	SS	HD	Total
SFL	1	149.9	150.8	151.3	453.7
	2	151.6	151.1	151.2	
	3	152.2	151.7	151.3	
SSD		8.55	1.17	0.02	9.74
PC		87.76	12.05	0.18	100
OL	$LP_3SS_3HD_1$				

better properties in build parts higher microhardness is always desirable. The Pareto analysis of variance table is constructed based on the values of the S/N ratio to explain the factor's effect. It is important to note that the higher the values of the S/N ratio better the quality characteristics. The S/N ratio values corresponding to each level for a factor are estimated (referred to as Sum at Factor Levels: SFL) to explain the factor effects. The Sum of Squares of Differences (SSD) for each factor is calculated and could help to determine the Per cent Contribution (PC) of individual factors on the analyzed outputs. The Optimal Levels (OL) for each parameter are determined based on the higher SFL value corresponding to each level of that factor. The results of Pareto ANOVA for the response microhardness are presented in Table 6.

The main factors' contributions are determined by computing the mean values corresponding to each level for a factor (Figure 2). It was observed that the laser power showed the highest contribution (i.e., 87.76%) followed by a scan speed of 12.05% and hatch distance of 0.18% towards the microhardness (Table 6).

An increase in laser power tends to increase the microhardness of the SLM build parts. All the available metal powders tend to melt when the laser power is increased from 240 to 300 W. Note that low values of laser power (240 W) resulted in lesser energy density. The low energy density offered by laser power may not be fully sufficient to melt all the metal powders causing discontinuities or voids in the build parts, which finally results in low values of MH[26]. As the scanning speed increases from 600 to 1000 mm/s results in higher

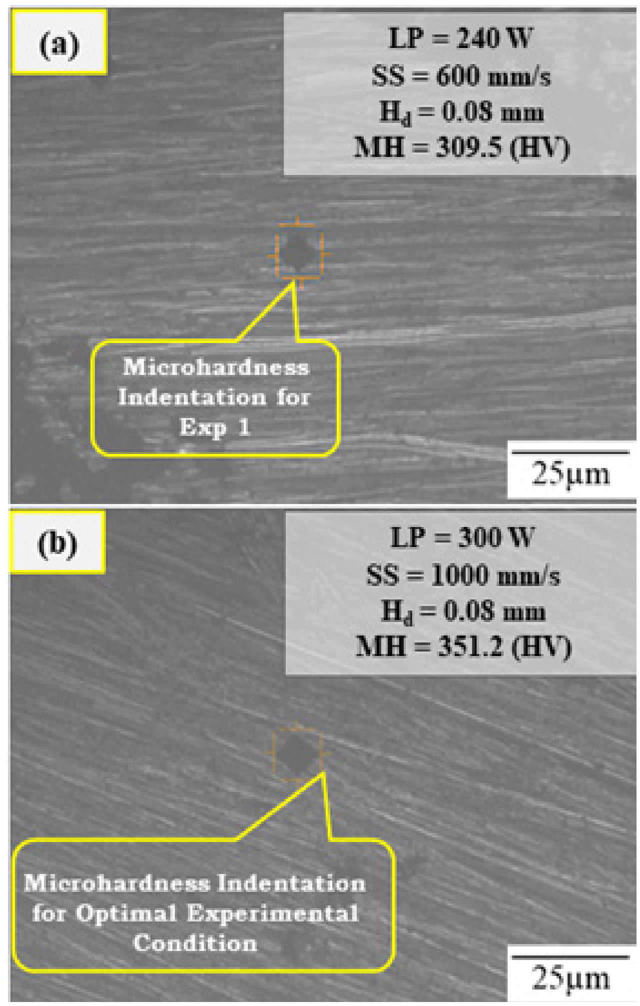

Figure 3. Microhardness of 17-4PH Steel parts: **a)** initial condition (refer Table 4, 1-SS) and **b)** Optimal condition determined by Taguchi method (Table 6).

microhardness values. Low values of scan speed require higher temperatures to melt all the metal powders. Low melting temperature as a result of lower scanning speed causes un-melted regions due to the dense morphology of powdered particles leading to the formation of voids or pores in the build parts[27]. Thereby low scanning speed results in lower microhardness in SLM build parts. An increase in scan speed tends to melt all metal powders and ensure better fusion characteristics between the metal powders. Hatch distance was found to have negligible contribution towards microhardness of 17-4 PH stainless steel parts. Similar observations are reported on Inconel 625 materials built with the SLM process[26]. It was observed that the optimal conditions (laser power: 300 W, scan speed: 1000 mm/s and hatch distance: 0.08 mm) were determined viz. Pareto analysis of variance was found to be different from those of L_9 experiments. Therefore, confirmation experiments are conducted to justify the model stability in predicting the optimal condition for maximum microhardness values.

The optimal conditions determined by the Taguchi method resulted in better microhardness values compared to L_9 experiments. The marginal improvement in microhardness value (348.21 HV to 351. 2 HV) for optimal condition compared to the 9th experimental condition (Table 4) is attributed to the same factor levels with the major contributing factors (LP: 300 W, and SS: 1000 mm/s) coupled with negligible effect of hatch distance. The hardness indentations obtained for optimized and initial experimental conditions are presented in Figure 3. Although the hatch distance is found to have a negligible effect, their influence tends to improve the 3 HV microhardness values in SLM build parts.

5.0 Conclusion

17-4 PH stainless steels were found to have distinguished applications in structural parts. The SLM technology possesses distinguished benefits over traditional processing routes due to inherent properties (higher hardness, strength, less distortion, corrosion resistance and so on) and therefore an attempt is made to fabricate the 17-4 PH stainless steel parts. The following conclusions are drawn from the present work:

- Taguchi L_9 experimental trials were used to analyze the most influencing process variables (laser power, scan speed, and hatch distance) on the microhardness of SLM parts.
- Laser power showed the highest contribution equal to 87.76%, followed by scan speed of 12.05% and hatch distance of 0.18%, respectively.
- The combination of high values of laser power and scan speed showed higher values of microhardness. Higher laser power and scan speed generate high intense heat which could be sufficient to melt the dense metal powders and fuse to get strong bonding.
- The optimal conditions (laser power: 300 W, scan speed: 1000 mm/s and hatch distance: 0.08 mm) determined viz. Pareto analysis of variance is different from those of L_9 experiments. The confirmation experiments conducted for the optimal conditions resulted in a better microhardness value equal to 351.2 HV. The better microhardness value obtained from the Taguchi method and corresponding Pareto analysis of variance justify that the model can be employed at an industrial scale for analysis and optimizing any process.

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