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Statistical analysis of porosity of 17-4PH alloy processed by selective laser melting

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Abstract. Selective Laser Melting (SLM) is a powder-bed type Additive Manufacturing (AM) process, where parts are built layer-by-layer by laser melting of powder layers of metal. There are several SLM process parameters that affect the accuracy and quality of the metal parts produced by SLM. Therefore, it is essential to understand the effect of these parameters on the quality and properties of the parts built by this process. In this paper, using Taguchi design of experiments, the effect of four SLM process parameters namely laser power, defocus distance, layer thickness and build orientation are considered on the porosity of 17-4PH stainless steel parts built on ProX200 SLM direct metal printer. The porositywas found to be optimum at a defocus distance of -4mm and a laser power of 240 W with a layer thickness of 30 µm and using vertical build orientation.

1. Introduction

Selective Laser Melting (SLM) is an additive manufacturing process that produces metal parts by fusing metal powders through a high-powered laser beam. The fusing occurs through the melting and rapid solidification of metal powder by scanning a laser beam over metal powder spread on a platform via a 3D path created by processing software [1-3]. There is a growing need for SLM to create fully dense parts, where mechanical, thermal and other properties are comparable to those of wrought materials. However, the properties and quality of built parts depend a great deal on proper selection and optimisation of a combination of several key SLM process parameters for the specific metal powder used in the system.

SLM is a complex process with many process parameters, making it very challenging to evaluate each and every parameter [4, 5]. The SLM can produce near net shape complex geometries, which are not normally producible by conventional manufacturing methods. In SLM, it is possible to alter the final material properties by adjusting the process parameters. Some of the main parameters that are varied in SLM are laser power, scan speed, layer thickness, scanning space, laser diameter, focal distance, powder size, and powder temperature. These parameters can also vary according to materials used, machine types and build volumes[6]. The density and surface roughness of the parts are strongly affected by the variation of the parameters namely scanning speed, scan spacing and laser power.

Several researchers have investigated the influence of SLM process parameters on different mechanical properties of the SLM processed materials. Literature search shows that titanium and stainless steel are the most commonly used materials by SLM users. Spierings et al [7] have investigated the effects of several SLM process parameters such as laser power, scan speed, layer thickness and build orientation on E-modulus and ultimate strength of 17-4PH stainless steel parts made by SLM. Lu et al [8] have carried out a study on the effect of differing island scanning strategy of SLM process on the microstructure, mechanical property and residual stress of SLM Inconel-718 alloy. Childs et al [9] have investigated the relationship between energy and fabricated tracks in SLM using several types of stainless steel powders with different particle sizes. Di et al [10] have also carried out experimental study on the energy input and its influence on fabrication quality using 316 L stainless steel in SLM and obtained a high-density part with smooth surface.

In this paper, the focus is on the effect of four key process parameters of ProX200 SLM machine on the densification of 17-4PH stainless steel by eliminating porosity through the application of the Taguchi method with fractional factorial design approach. The four process parameters considered are the laser power, defocus distance, layer thickness and build orientation at three different levels. The 17-4PH is a martensitic precipitation hardened stainless steel material, which finds wide application in aerospace, chemical, petrochemical, food processing industries. The 17-4PH has outstanding combination of high strength, good corrosion resistance, and toughness. The chemical composition of 17-4PH has 17% Ni and 4% Cr and 4% Cu which provide high tensile strength, corrosive resistance and conductivity.

2. Material and methods

In this study, the 17-4PH stainless steel is used to investigate the effect of laser power, build orientation, layer thickness and defocus distance on the porosity of the parts produced by 3D Systems ProX200 SLM direct metal printer. A fibre laser with a maximum power of 300 W and a wavelength of 1070 nm is used in this machine. The porosity was evaluated by measuring the relative density of the samples. Cylindrical 17-4PH samples of size 25 mm height and15 mm diameter were produced on ProX200 as per ASTM E9 standard.

An experimental design was developed to study the interaction effects of the process parameters of the SLM process on the porosity of 17-4PH parts. The four parameters namely laser power (A), build orientation (B), layer thickness (C) and de-focus distance (D) were varied at three levels (-1, 0, +1) as shown in Table 1. Laser power was selected at 80 %, 85 % and 90% of the maximum laser power. The orientations of the built part were horizontal, inclined with respect to the X-axis in the X-Z plane, and vertical. Similarly, layer thicknesses were 30, 35 and 40 microns while the defocus distance selected was -6, -3 and -1 mm. In the ProX200 SLM machine, the defocus distance is the distance between the focal plane (which gives minimum laser beam diameter) and the build surface, where the powder is spread. The defocus distance can be positive or negative.

Table 1. The levels of SLM parameters in Experimental Design

Parameter	**Unit**	**Code**	**Levels**		
			-1	**0**	**+1**
Laser power	% of (300 W)	A	80	85	90
Orientation	degree	B	Horizontal	Inclined	Vertical
Layer Thickness	µm	C	30	35	40
Defocus distance	mm	D	-6	-3	-1

Instead of 4^3 levels, the experiment was narrowed down to the manufacturing and testing of 9 samples through the application of the orthogonal array in Taguchi method. The orthogonal array was based on the experimental design shown in Table 2. Minitab 16 software was used for the statistical analysis of the experimental data. The results of measured porosity from the experiments conducted according to the orthogonal array are also shown in Table 2. The objective was to minimise the porosity of the built part in the SLM process. Equation (1) was used to define Signal to Noise (SN) Ratio for each response, with the theme ‘smaller is better’.

$$\text{SN Ratio(Smaller is better)} = -10 \times Log10\left(\sum \frac{(Y^2)}{n}\right) \tag{1}$$

Porosity is measured using the relative density method, and is given by Equation (2).

$$\text{Porosity} = \left(1 - \frac{\rho 1}{\rho 2}\right) * 100 \tag{2}$$

where ρ1 is the measured density of the sample and ρ2 is the theoretical density of the material.

Table 2. Results of experiments for orthogonal array

Run	Coded factors A	B	C	D	% Porosity
1	-1	-1	-1	-1	4.491
2	-1	-1	0	0	3.248
3	-1	-1	+1	+1	3.733
4	0	0	0	+1	4.142
5	0	0	+1	-1	4.698
6	0	0	-1	0	2.853
7	+1	+1	+1	0	3.250
8	+1	+1	-1	+1	3.606
9	+1	+1	0	-1	4.496

3. Results and discussion

The principal interest in SLM is the density of the part produced. The higher the density of the material, the lesser the porosity. From Table 2, the porosity was found to be at its lowest in experiment no. 6, where the sample was built using a combination of laser power at 85% of maximum power, inclined orientation, 30 µm layer thickness and -3 mm defocus distance, giving a dense part. Figure 1 and 2 show the main effects plots for percentage porosity and percentage SN ratios. As shown in figure 1, the increase in laser power from 80% to 85%, represented by code A, caused a considerable increase in the porosity. A similar trend can be observed for code B, where the inclination from a vertical to an inclined orientation led to an increase in porosity. Laser re-melting reduces porosity while improving density [11].

The plot of main effects suggests that the defocus distance -3 mm is the best distance for building the part; however, when the SN ratio is taken into account, a defocus distance of -6 mm is shown as optimum. In this study, the actual built part had -4 mm as the defocus distance for the fresh metal powder loaded into the SLM machine. This complies with the machine manufacturer's guidelines. The laser energy and heat transferred to the powder significantly affect the precision of fabrication if the defocus distance fluctuates [12].

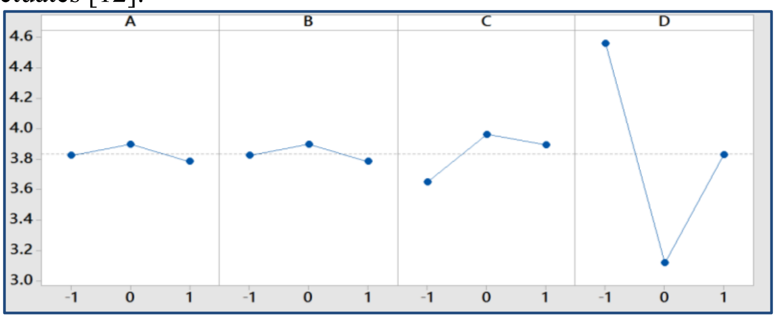

Figure 1. Main effects plot: Means of % porosity.

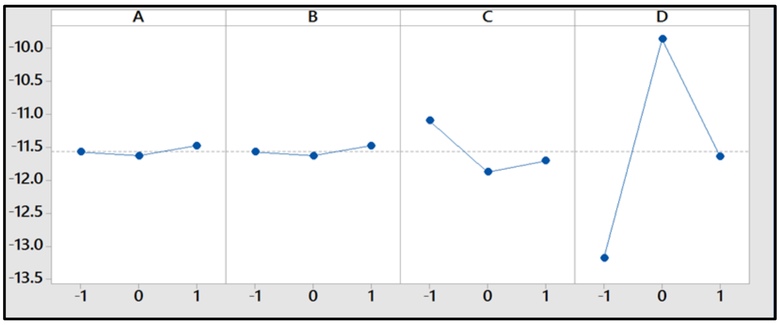

Figure 2. Main effects plot: SN ratios of % porosity.

In figure 2, the analysis of signal to noise ratio shows that at 85% of maximum laser power, the SN ratio is smaller. Similarly, the inclined orientation, layer thickness of 35 µm and defocus distance of -6 mm are observed to have the least SN ratio. Figure 2also shows that the vertical orientation has the main effect on porosity, and the SN ratio suggests that there will be maximum noise if vertical orientation is taken into consideration. However, a similar study has reported that vertically-built samples have an optimised combination of strength and ductility [13].

Figure 3 shows the interaction plots for porosity. In this plot, where the laser power (A) and build orientation (B) interact, the least porosity is observed at vertical orientation. Similar findings have been reported where struts built in a horizontal direction were found to have more pores than the vertically-built samples [14]. In the interactions between laser power and other parameters, a layer thickness of 30 µm, and a defocus distance of -3 mm were observed to cause less porosity. Similarly, with regard to the interaction between orientationand other parameters, a 30 µm layer thickness (the lowest-possible layer thickness) and a -3 mm defocus distance were observed to be better. It is essential that the layer thickness be the least possible, as the powder has to go through rapid heating and cooling cycles. Finally, the interaction of layer thickness and defocus distance also suggests that 30µm layer thickness and -3 mm defocus distance is the best combination, while the laser spot diameter remains the optimum for melting the metal powder.

In this study, a lower laser power of 240 W was sufficient to cause the melting. However, the literature review demonstrates that a lower laser power leads to the formation of a limited liquid phase. Therefore, the viscosity of the melt pool increases, which has a negative influence on the flowability of the liquid [15]. The consequences of these mechanisms are that caves and crevices can form inside the part, with many un-melted and half-melted particles. While high laser power with high scan speed leads to porosity, the low scan speed leads to the formation of crevices [16].

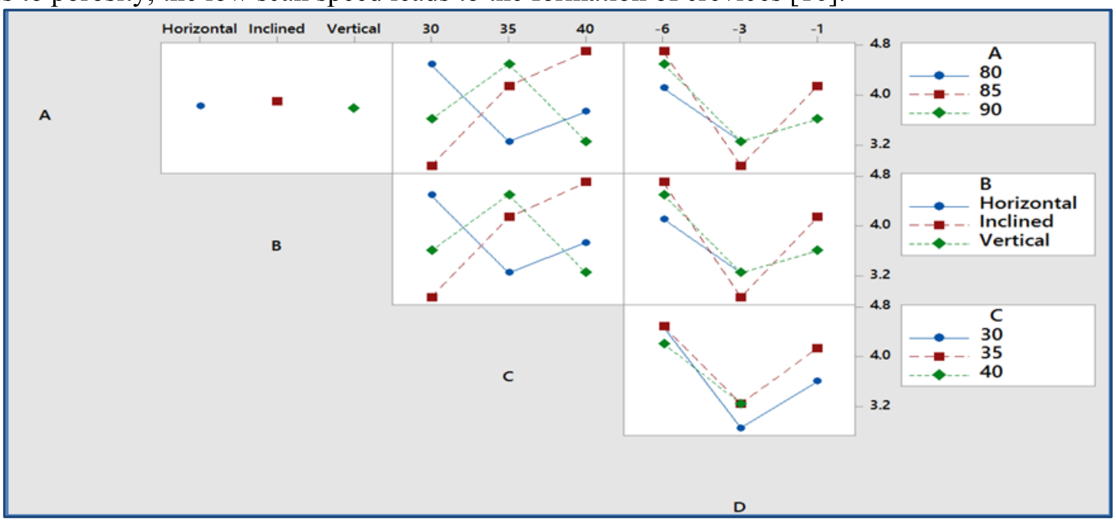

Figure 3. Interaction Plots for Porosity.

The least porosity among the built parts was found to be 2.8%, which is higher than the wrought sample porosity of 1.2%. The least noise or SN ratio has been noted at 35 µm layer thickness. When the layer thickness increases, porosity also increases, which would lead to crack formation associated with decrease in ductility and strength. Also, it is evident that density decreases with a larger layer thickness. The larger particles get entrapped in the thicker layer of powder, leading to porosity and causing gas bubbles to form around the pores. In addition, larger particles lead to shrinkage after solidification, and voids, cracks and layer separations can occur at grain boundaries. Therefore, it is advisable to use smaller particles, which would produce dense layers with better compaction. Larger particles could be excluded by the use of a recoater blade [17].

4. Conclusions

The effects of laser power, build orientation, layer thickness and defocus distance of fibre laser used in ProX200 SLM machine on the porosity of 17-4PH stainless steel parts have been investigated based on the orthogonal arrays arrived at using the Taguchi method. Using statistical methods, the following combination was found to be the optimum: the porosity and the surface roughness were measured at a defocus distance of -4 mm, laser power of 80% of 300 W, a layer thickness at 30 µm, and with a vertical build orientation. These process parameters have been validated by manufacturing samples using SLM, and the optimised results were obtained for the porosity.At the lowest level of porosity, the part built would have the highest relative density of all parts built. The experiment correspond tothe sample that had the highest density at 97.2%. The porosity of 2.8% could be due to the thermal history during manufacturing in the SLM. These pores can also affect the mechanical properties of parts built by SLM. In particular, the cracks can be initiated at these sites. Compared with a wrought sample of porosity 1.2%, the porosity of the wrought part was found to be less than for the SLM built part. As these parameters are not universally suitable for all SLM machines, it is advisable to perform more tests for the defocus distance. Other parameters could be deployed with the same values namely laser power, layer thickness and orientation as mentioned above for the 17-4PH material.

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