Experiment and Optimization of Surface Roughness and Hardness of Inconel718 in Selective Laser Melting Using Taguchi Method

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Abstract

The primary objective of this research was to produce fully dense part of Inconel718 processed with selective laser melting with better mechanical and surface properties. Out of several factors, four substantial process parameters laser power, scan speed, layer thickness and orientation are selected with vii four levels of variations. Taguchi is one of the popular methods for design of experimental plan. Taguchi orthogonal array L16 was implemented for experimental runs. Here, experimental study is carried out for selective laser melting process with Inconel718 powder to explore the influence of process parameters on quality responses like surface roughness, porosity and hardness of built part. Scanning electron microscopy (SEM) and optical microscopy (OM) used for microstructural characterization of as fabricated SLM specimens. The ANOVA (Analysis of Variance) is well-known statistical tool, based on variation between the set of observations to determine the statistical significance of effects of factors on output responses. The study on effects of volumetric energy density on evolution of microstructure and defect formation was extended in second part. Nearly fully dense part with relative density at the level of 98.6% was obtained with applied energy density 101.5 J/mm3. Average surface roughness was obtained between 6.1 to 10.7µm average hardness 207 HV. Post process aging heat treatment upgraded the average hardness to 350 HV.

Keywords: ANOVA, Inconel718, Microstructure, Selective Laser Melting, Taguchi, Porosity, Hardness

1. Introduction

Additive manufacturing (AM) has sustained and advanced as a manufacturing process from rapid prototyping (RP). Earlier, AM was mainly used for prototyping, but with due time and thanks to the contributions of many researchers, now, it can be employed in the commercial manufacturing of aircraft parts, prosthesis, spacecraft parts, high strength military equipment, automobile parts, etc. Against the conventional machining principle where the product is manufactured by removing unwanted materials from the blank, AM manufactures the components from scratch by adding materials in a layer-by-layer order directly from the sliced CAD model. AM offers various advantages such as printing multi-material parts, manufacturing of functionally graded materials, the ability to print highly customized biomedical parts, a little change in tools and machine layout for new designs, etc. The ability to manufacture complex shapes using lightweight materials by AM is another leverage that AM has over the conventional machining processes in the aerospace industry, as lightweight materials can be manufactured into complex shapes without losing strength using AM. Wenquan Wang et.al. The Inconel 718 superalloy (IN718) was fabricated by selective laser melting (SLM) successfully in this work. The optimization of process parameters and effects of three heat treatment processes on the microstructures and mechanical properties of samples were also systematically investigated. The relationship equation between relative density (RD) of SL Med samples and energy density (ED) coupled by laser parameters was determined. After the solution aging (SA) heat treatment, a large amount of needle-like δ phases precipitated and the precipitation of ultrafine spherical γ'/γ" strengthening phases as well as complete recrystallization appeared after homogenization + solution aging (HSA) heat treatment. The overall performances of SL Med IN718 samples were improved significantly using the HSA treatment, with the increase of tensile strength from 946 MPa to 1570 MPa.[1]. Jiun-Ren Hwang et.al. The study investigated the optimization of the LPBF Inconel 718 alloy with the Taguchi method and principal component analysis (PCA), covering four control factors at three levels in the manufacturing process. The results show that the highest tensile strength is obtainable at a laser power of 140 W, scanning speed of 800 mm/s, scanning pitch of 70 μm, and interlayer angle of 45 degrees. The optimal combination of process parameters for multi objective optimization is just the same as that for single-objective optimization for tensile strength. The difference between the predicted and experimental average tensile strength is 1.2%, and the error of the predicted optimal strength index is 12.6%. The most important control factor for tensile strength and multiple responses is the angle between layers, with a contribution rate exceeding 90%. With a given volume energy density of the LPBF process, the higher the power and scanning speed, the higher the accumulated energy and the larger the amount of dendritic or cellular crystals formed.[2]. Eslam M Fayad In the present study, multi-objective optimization is employed to develop the optimum heat treatments that can achieve both high-mechanical performance and non-distinctive crystallographic texture of 3D printed Inconel 718 (IN718) fabricated by laser powder bed fusion (LPBF). Heat treatments including homogenization at different soaking times (2, 2.5, 3, 3.5 and 4 h) at 1080 °C, followed by a 1 h solution treatment at 980 °C and the standard aging have been employed. 2.5 h is found to be the homogenization treatment threshold after which there is a depletion of hardening precipitate constituents (Nb and Ti) from the γ-matrix. However, a significant number of columnar grains with a high fraction (37.8%) of low-angle grain boundaries (LAGBs) have still been retained after the 2.5 h homogenization treatment. After a 4 h homogenization treatment, a fully recrystallized IN718 with a high fraction of annealing twins (87.1%) is obtained. 2.5 and 4 h homogenization treatments result in tensile properties exceeding those of the wrought IN718 at both RT and 650 °C. However, considering the texture requirements, it is found that the 4 h homogenization treatment offers the optimum treatment, which can be used to produce IN718 components offering a balanced combination of high mechanical properties and adequate microstructural isotropy.[3]. Cho-Pei Jiang et. al. (2023) The optimal printing and HT parameter values are used to manufacture a die and a punch to verify the suitability of the manufactured tool for deep drawing applications. The experimental results show that the greatest UTS is 1091.33 MPa. The optimal printing parameters include a laser power of 190 W, a scanning speed of 600 mm/s, a hatch space of 0.105 mm and a layer thickness of 40 μm, which give a UTS of 1122.88 MPa. The UTS for the post-processed specimen increases to 1511.9 MPa. The optimal parameter values for HT are heating to 720 °C and maintaining this temperature for 8 h, decreasing the temperature to 620 °C and maintaining this temperature for 8 h, and cooling to room temperature in the furnace. Surface finishing increases the hardness to HRC 55. The parameter values that are defined can be used to manufacture IN 718 tools with a UTS of more than 1500 MPa and a hardness of more than 50 HRC [4]. Karia M.C et. al. 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 [5]**.** D.A. Lesyk The turbine blade test parts were manufactured by the selective laser melting (SLM) process using a nickel-based pre-alloyed Inconel (IN) 718 powder. Various mechanical post-processing techniques, such as barrel finishing (BF), shot peening (SP), ultrasonic shot peening (USP), and ultrasonic impact treatment (UIT), were applied to improve the surface layer properties of the SLM-built specimens. Effects of mechanical surface treatments on surface topography, porosity, hardness, and residual stress were studied. In comparison with the SLM-built state the surface roughness (*Sa* = 5.27 μm) of the post-processed specimens were respectively decreased by 20.6%, 26.2%, and 57.4% after the BF, USP, and UIT processes except for the SP-treated ones. The *Sz* parameter was reduced in all treated SLM-built specimens except for the SP-treated ones. The surface microhardness of the SLM-built specimen (~390 $HV_{0.025}$) was increased after the BF (by 14.2%), USP (by 23.8%), UIT (by 50%), and SP (by 66.5%) processes. Wenquan Wang The Inconel 718 superalloy (IN718) was fabricated by selective laser melting (SLM) successfully in this work. The optimization of process parameters and effects of three heat treatment processes on the microstructures and mechanical properties of samples were also systematically investigated. The relationship equation between relative density (RD) of SLMed samples and energy density (ED) coupled by laser parameters was determined. After the solution aging (SA) heat treatment, a large amount of needle-like δ phases precipitated and the precipitation of ultrafine spherical γ'/γ" strengthening phases as well as complete recrystallization appeared after homogenization + solution aging (HSA) heat treatment. The overall performances of SLMed IN718 samples were improved significantly using the HSA treatment, with the increase of tensile strength from 946 MPa to 1570 MPa.[7]

2. Experimental Setup and Procedure

2.1 Specimen Material Details

A gas atomized preprocessed Inconel718 powder (CL 100 Nb) is used for processing. The average size of powder particles was 38 μm. The morphology and particleshape and size are important factors as they determine ability to flow, capacity to absorb laser energy and thermal conduction through powder bed. Spherical particle morphology helps to obtain high packing density during the process that helps to obtain high relative density of SLM built component. The chemical composition of alloy powder is presented in table 1.

Table 1: Chemical composition of metal powder

Element	Ni	Cr	Fe	Mn	Co	Ti	Al	Hg
Weight %	54.33	19.9	17.44	1.46	1.76	1.26	0.76	3.11

2.2 Machine

The machine was interfaced with a computer system for process control. Samples were built with varying four process parameters: laser power, scan speed, layer thickness and build orientation. The beam diameter 0.15 mm and hatch spacing 0.105 mm were kept constant. 5 mm X 5 mm island scanning strategy was used for building samples.

Figure 1: SLM Machine

3. Design of Experiment

For Taguchi DOE (4-parameters and 4-level) L16 orthogonal array has been prepared with software Minitab16.

Table 2: Control Factor and their Factors

Sr. no.	**Parameter**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
1	Power (Watt)	160	170	180	190
2	Scan Speed (mm/s)	500	600	700	800
3	Orientation Ɵ (degree)	0	10	20	30
4	Layer Thickness (mm)	0.03	0.04	0.05	0.06

Table 3: L16 Orthogonal array for experimental runs

Laser PowerW	**Scanspeedmm/s**	**Layer thickness µm**	**Orientation degree**
160	500	30	0
160	600	40	10
160	700	50	20
160	800	60	30
170	500	40	20
170	600	30	30
170	700	60	0
170	800	50	10
180	500	50	30
180	600	60	20
180	700	30	10
180	800	40	0
190	500	60	10
190	600	50	0
190	700	40	30
190	800	30	20

4. Result and Discussions

The experiments are conducted to study the effect of process parameters over the output response features with the process parameters. The S/N ratio results for the surface roughness, material removal rate and machining force are given. In the present study all the designs, plots and analysis have been carried out using Minitab 14 statistical software. The effect of different process parameters on MRR, surface roughness and machining force are calculated and plotted as the process parameters changes from one level to another. The use of ANOVA technique to analyze the results and hence, make it fast to reach on the conclusion.

4.1 Analysis of Variance for Surface Roughness

Table 4, laser power is ranked third level for statistical significance with p value 0.132. Higher p value stipulates that there is weak evidence to reject the null hypothesis. It can be deduced that highest significant parameter is layer thickness for surface roughness with significance level of 48.88%, followed by build orientation 25.18 %, laser power 13.26 % and scan speed 9.56% respectively shown in table 5.3. It can be observed significance level of error term is 3.09%, so that the linear model is in good agreement

Table 4: ANOVA for Ra

Source	**DF**	**Seq SS**	**Adj**	**F**	**P**	**Contribution %**
P	3	14.091	4.697	4.28	0.132	13.26
v	3	10.165	3.388	3.09	0.189	9.569
t	3	51.917	17.306	15.78	0.024	48.887
ɵ	3	26.756	8.919	8.19	0.059	25.18
Error	3	3.290	1.097			3.09
Total	15	106.219				96.90

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

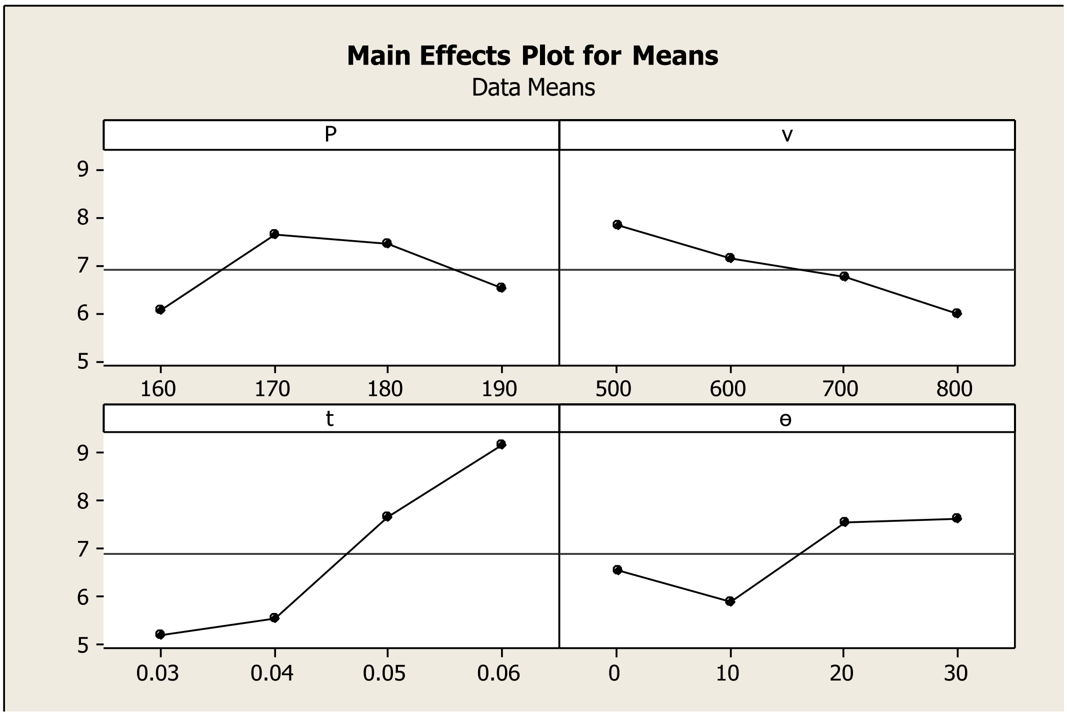

Figure 2: Main affects plots for surface roughness Ra

Figure 2 shows the S/N ratio plot for surface roughness for selected set of control parameters. It can be observed that scan speed is the least significant parameter as negligible main effect. The mean is almost similar about both side of mean value for different levels of scan speed. Figure 5.2 shows the main effect plot for surface roughness.

4.2 Analysis of Variance for Hardness

Table 5 From table 5.8, p values observed higher than critical value of 0.05 except power P, which indicates weak evidence to reject null hypothesis, it can be observed that the highest significant parameter for hardness is power 61.35% followed by orientation 22.77%, layer thickness 8.4% and scan speed by 0.98% respectively. Hardness predictions are obtained using equation 5.6. The significance level for error terms found 6.39%. Hence the linear curve fit for model is in agreement with observed values reasonably.

Table 5: ANOVA for Hardness

Source	**DF**	**Seq SS**	**Adj**	**F**	**P**	**Contribution %**
P	3	1864.42	621.47	9.59	0.048	61.35
v	3	29.80	9.93	0.15	0.921	0.98
t	3	258.05	86.02	1.33	0.411	8.4
θ	3	691.92	230.64	3.56	0.162	22.77
Error	3	194.42	64.81			6.39
Total	15	3038.61				99.89

S = 12.3609 R-Sq = 99.89% R-Sq(adj) = 86.58%

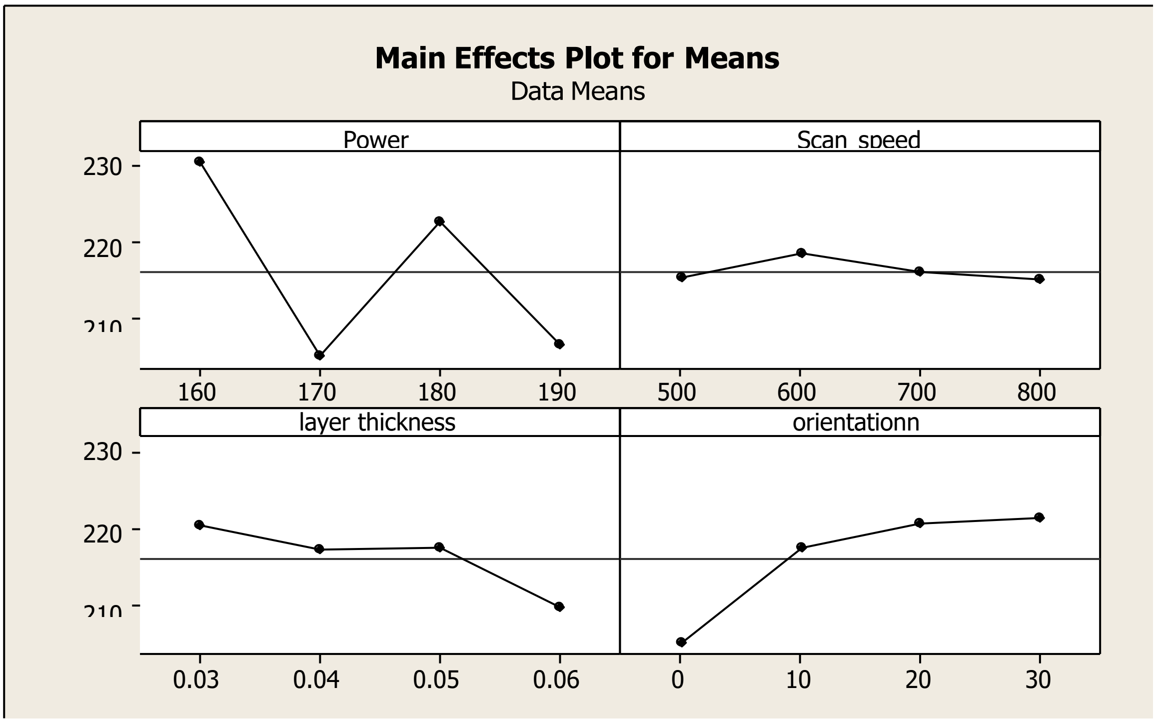

Figure 3: Main effect plots for hardness

To confirm this relationship experimentally, parameters are selected on basis of above analysis, experimental work carried out for same specimen with following set of parameters. Table 5.10 represents the parameter levels for confirmation experimental runs. Table 5.11, 5.12 and 5.13 represent the observed responses for confirmation trial.

Table 5.14, 5.15 and 5.16 demonstrate the deviation between observed value and predicted values of response variables.

Table 6: Measurement of surface roughness for confirmation experiments

SpecimenName	**Surface Roughness Ra**	**Surface Roughness Rz**	**Surface Roughness Rq**
1	5.7	32.6	7
2	5.8	32.1	7.1
3	5.9	45.1	7.1

Table 7: Measurement of hardness before and after aging heat treatment for confirmationexperiments

Specimen Name	**Hardness HRC1**	**Hardness HRC2**	**BHN 1**	**Hardened BHN2**	**HV1**	**HV2**
1	98	32	228	298	234	309
2	98	37	228	337.5	234	353
3	97	39	221.5	354.5	227	372

5. Conclusion

The ANOVA revealed that the layer thickness is the most dominant parameter is layer thickness for surface roughness with significance level of 48.88%, followed by build orientation 25.18 %, laser power 13.26 % and scan speed 9.56% respectively. Surface roughness values were obtained in the range of 3.87 - 11.6 µm with average value of 7.96 µm. It has been observed that highest 43.5 % deviation and lowest deviation for surface roughness is 1.5% . The optimal combination of process parameters for obtaining minimum surface roughness and minimum porosity at layer thickness 0.03 mm, build orientation 0, scan velocity 500 mm/s, power 160 W.

Hardness for as fabricated samples obtained between HV193 to HV228 with average value of 207HV.Parametric analysis revealed that highest dominant parameter on hardness is power 61.35% followed by orientation 22.77%, layer thickness 8.4% and scan speed by 0.98% respectively. The optimal combination of parameters considered for maximum hardness are: layer thickness 0.03 mm, build orientation 0, scan velocity 600 mm/s and laser power 160 W for confirmation experimental run.

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