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Optimization Of Selective Laser Melting Forming Process Parameters For IN718 Powder

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Abstract: *By using DEM-CFD numerical simulation method, a powder bed model and a laser melting model were established to simulate the SLM forming process. Based on this model, the evolution of the melt pool, the formation of defects and the influence of process parameters on the morphology of the melt channel during the SLM forming process are studied, and the process parameter optimization was carried out with the goal of minimizing surface roughness. Surface roughness measurement method based on the numerical simulation method was proposed, and the effects of laser power, scanning speed and hatch spacing on surface roughness were studied, as well as the effects of connection rate and physical energy density. The research results show that the lap rate and physical energy density have the greatest influence on the surface roughness. The optimal set of process parameters is P=270W, v=1000mm/s, s=70μm, and h=60μm. Under this process parameter, the surface roughness is the smallest at 3.8484μm. When the lap rate is 20%~30%, and the physical energy density is 60J/mm^3~70J/mm^3, the surface roughness is the smallest.*

***Keywords*:** *selective laser melting; numerical simulation; forming analysis; surface roughness; process parameter optimization*

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I. Introduction

IN718 alloy is a precipitation-reinforced nickel-based superalloy with an operating temperature of about 700℃. The alloy has excellent high temperature creep properties and heat-resistant corrosion properties[1][2].

Selective laser melting is a representative technology of AM, which can achieve rapid and near-net forming of parts with complex structures, and has broad application prospects in aerospace, medicine and other fields. The forming quality of the final formed parts of SLM will be significantly affected by the process parameters[3], and it is of great significance to study the influence of process parameters on the forming quality of SLM.

Zhang[4] studied the evolution of surface morphology and surface roughness under different durations of 3D contour instrumentation, and completed the improvement of the surface quality of the sample.

Wenquan Wang[5] et al. systematically studied the optimization of process parameters and the effects of the three heat treatment processes on the microstructure and mechanical properties of the sample. The relationship between the relative density (RD) of the sample and the energy density (ED) of the laser parameter coupling is determined.

Ilin et al. [6] Established a two-dimensional finite element model of SLM numerical simulation forming, analyzed the distribution law of the temperature around the melt pool, and mainly studied the influence of the local geometry of the parts, scanning speed and laser power on the morphology of the melt pool.

Yue et al. [7] used pure nickel as the research object and studied the effects of laser power and scanning speed on forming characteristics, densification behavior, and surface roughness.

Balbaa et al. [8] studied the influence of various process parameters on the characteristics of three parts: density, surface roughness, and surface residual stress. In addition to the study of the surface roughness and residual stress of IN718 laser selective melting, a process diagram has also been developed to select the best process parameters to achieve the required value of the combination of the three parameters.

Wang et al.[9] studied the influence of laser energy density (LED) on the density and surface roughness of AlSi10Mg samples treated by laser selective melting. Through solid density meters, industrial X-rays and CT inspection systems, the densification behavior of AlSi10Mg samples manufactured by SLM under different conditions is characterized. Surface roughness is measured using a field emission scanning electron microscope, an automatic optical measurement system, and a surface profiler.

From the above, it can be seen that the process parameters of SLM have a significant impact on the forming quality. In this paper, the numerical simulation and analysis method of DEM-CFD is used to simulate the dynamic process of single-layer dual-channel SLM forming, and the effects of laser power, scanning speed and hatch spacing on surface roughness are studied. The influence of lap rate and physical energy density is considered, and the minimum surface roughness is used as the goal to optimize the process parameters.

Numerical simulation method

Based on the discrete unit method and computational fluid dynamics method, this paper first generates a particle bed model through EDEM, imports the particle bed model into Flow-3D, and writes a laser heat source model program to simulate the dynamic process of SLM forming.

Establishment of particle bed model

Generate a particle bed with a density of 0.5 and a particle size distribution of 15~53μm to meet the normal distribution, as shown in Figure 1. The specific particle bed parameters are shown in Table 1.

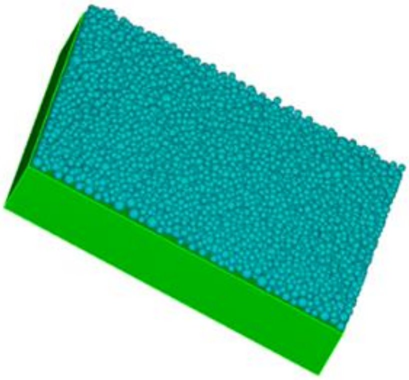


Figure 1 Particle bed model

Table 1 EDEM filling powder layer parameters

parameter	Particle size distribution (μm)	Space area (μm)	Powder layer thickness (μm)
Powder layer	15~53	1000×1000×60	60

SLM numerical simulation method

Selection of laser heat source

In order to reduce the amount of calculation, the volumetric heat source is simplified to a surface heat source. The mathematical formula of the Gaussian heat source is shown in (1).

$$S = q(x,y) = \frac{2AP}{\pi R^2}\exp(-2\times\frac{(x - x_{c0} - vt)^2 + (y - y_{c0})^2}{R^2}) \quad (1)$$

Where A is the absorption rate of the powder laser, P is the laser power, R is the radius of the Gaussian laser beam, and the initial position of the heat source model; is the scanning speed.

Melt pool flow control equation

The Volume of Fluid method is used to track and simulate the liquid levels of the two fluids and define the boundary conditions to express the movement of the free liquid level. The expression is shown in equation (2).

$$\frac{\partial F}{\partial t} + \nabla F\vec{v} = 0 \quad (2)$$

Boundary conditions and process conditions

Boundary conditions

The boundary conditions of the model can control the loss of heat.The heat loss in the SLM forming process is mainly divided into three parts: thermal convection, thermal radiation and evaporative heat dissipation. The expression for the heat of evaporation is expressed as equation (3).

$$q_{ev} = 0.82\frac{\Delta H^*}{\sqrt{2\pi MRT}}p_0\exp(\Delta H^*\frac{T - T_{1v}}{RTT_{1v}}) \quad (3)$$

Where R is the ideal gas constant; p_0 is the ambient pressure; M is the molar mass; $\Delta H*$ is the enthalpy of evaporation and escape; T_{lv} is the boiling point of the material.

The metal steam will gather above the laser area to form a thin layer of steam, forming a vertical downward pressure, called the steam recoil pressure, as shown in equation (4).

$$p_r = 0.54 p_0 \exp(\Delta H_v \frac{T - T_{1v}}{RTT_{1v}}) \quad (4)$$

Where ΔH_v is the latent heat of evaporation of the metal.

Process conditions

The research object of this paper is IN718 material, and the laser absorption rate of the material is set to 30%; the calculated domain size parameter is 1000×1000×100μm, and the specific material and process parameters are shown in Table 2.

Table 2 Numerical simulation of materials and process parameters of SLM forming process

parameter	value
Ambient temperature, T_0	300K
Spot radius, *R*	40μm
Powder thickness, *h*	60
Powder particle size	15-53μm
Material solid phase temperature, T_S	1523.15K
Material liquid phase temperature, T_L	1608.15K
Boiling point of the material, T_{1v}	3188K
Latent heat of melting, L_m	250000J/kg
Latent heat of evaporation, L_v	7340000J/kg
Metal molar mass	59.75g/mol
Specific heat capacity of solidified state	420J/(kg·K)

Surface roughness measurement

Surface roughness is an indicator that describes the degree of unevenness of tiny peaks and valleys on the surface. The Ra calculation formula is shown in (5).

$$Ra = \frac{\int_0^{l_\tau} |Z(x)| dx}{l_\tau} \quad (5)$$

Where $Z(x)$ is the difference between the points on the surface contour to the ordinate of the least squares midline, l_τ is the sampling length.

The surface roughness is measured by numerical simulation, and the method of calculating the surface roughness is as follows：

（1）Flow-3D exports the model after laser scanning, as shown in Figure 2.

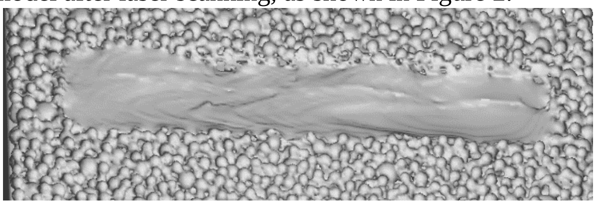


Figure 2 Model after laser scanning

（2）Import this STL model into the software Geomagic Studio software and extract the melt channel surface, as shown in Figure 3.

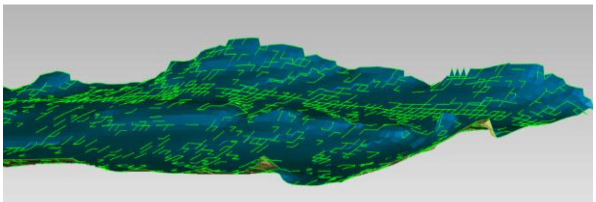


Figure 3 Extracted melt channel surface

（3）Load the model shown in Figure 3 into MATLAB, write the MATLAB program code for roughness calculation based on the least squares method, and obtain the corresponding roughness value. In order to reduce the error, take the cross-section characteristic curve corresponding to the different values of y five times, and take the average value to obtain the surface roughness value of the plane.

Verification of correctness of numerical simulation method

In this paper, the same process parameters and material parameters as Wang Wenwu et al**Error! Reference source not found.** are used to simulate the SLM forming process, and the melt pool width obtained in the experiment is compared with the melt pool width value obtained through simulation. See Table 3 and Figure 4.It can be obtained from Figures 4 and 3. The average relative error between the width of the melt pool in the experimental results and the simulation results in this paper is 3.4%, which has a good correlation. Therefore, the numerical simulation method used in this paper is correct.

Table 3 Comparison of melting width under P=200W

Scanning speed (mm/s)	Simulation melting width (μm)	Experimental melting width (μm)	Fitting melting width (μm)	Relative error (%)
1000	73	70.01	71.49	4.3
1300	67	69.81	65.54	4.0
1500	60	58.81	61.58	2.0

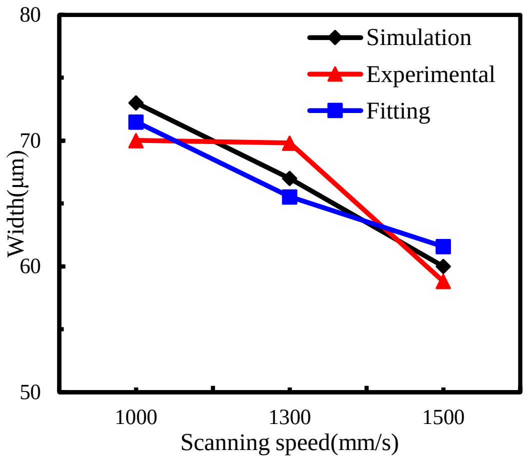


Figure 4 Comparison of simulated melting width and experimental fitting melting width

II. Calculation results and discussion

Effect of process parameters on surface roughness

Design a single-factor test scheme, analyze the laser power, scanning speed and hatch spacing that have a greater impact, and study the influence law on surface roughness. Simulate the SLM forming melt channel according to the parameters of the test scheme, and measure each melt channel according to the roughness measurement method described in the previous section. The scheme and measurement results are shown in Table 4.

Table 4 Test plan and measurement results

number	Scanning speed (mm/s)	Hatch spacing (μm)	Laser power (W)	Physical energy density (J/mm^3)	Surface roughness value (μm)
1	1000	70	210	50	5.4789
2			240	57	5.1730
3			270	64	3.8484
4			300	71	4.0494
5	800	70	270	80	4.8191
6	900			71	3.8993
7	1000			64	3.8484
8	1100			58	5.3848
9	1000	50	270	90	4.4819
10		60		75	4.3014
11		70		64	3.8484
12		80		56	4.5872

Effect of laser power on surface roughness

For the single-factor simulation test of laser power setting, this section uses a scanning speed of 1100mm/s, a hatch spacing of 70μm, and a laser power of 210W, 240W, 270W, and 300W for SLM single-layer dual-channel forming simulation. According to the simulation results and the measured roughness value, a trend chart of the influence of laser power on the surface roughness of the SLM forming melt channel is drawn, as shown in Figure 5.

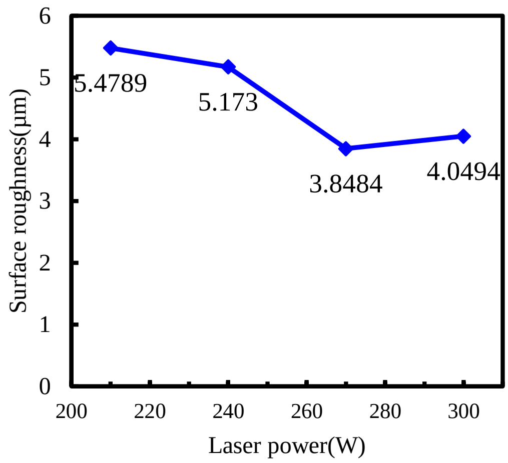
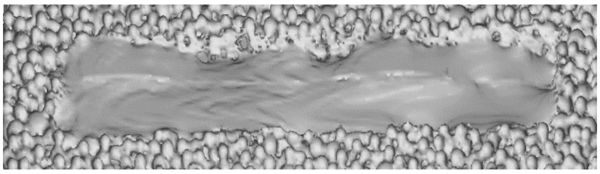


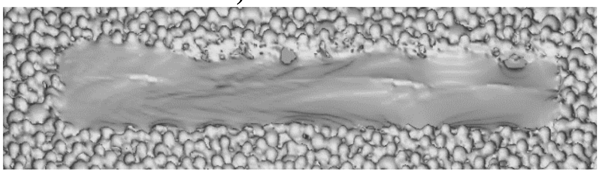
Figure 5 Surface roughness change diagram

As can be seen from Figure 5, the surface roughness decreases first and then increases as the laser power increases. When the laser power is 270W, the surface roughness is the smallest.When the laser power is less than 270W, the surface roughness is negatively correlated with the laser power; when the laser power is greater than 270W, the surface roughness is positively correlated with the laser power.

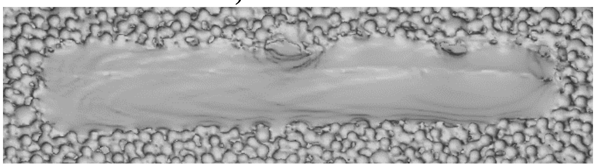
In order to explore the reason, the morphology of the simulated melt channel is shown in Figure 6.



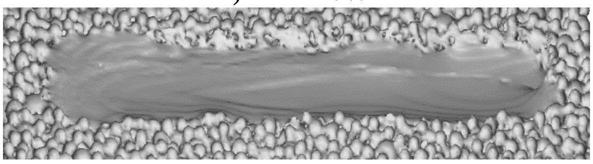
a) $P = 210\text{W}$



b) $P = 240\text{W}$



c) $P = 270\text{W}$



d) $P = 300\text{W}$

Figure 6 Topography of the melt channel under different laser powers

As can be seen from Figure 6, when the laser power is 210W, the laser energy is low and the matrix is not completely melted, resulting in poor wetting effect of the melted metal powder and the matrix forming parts, and poor fluidity of the melt pool, so the surface of the melt channel is uneven and the ripples are obvious, resulting in a more obvious spheroidization phenomenon, and the surface roughness of the parts is large; when the laser power is 270W, it can be seen that the surface morphology is the smoothest, the spheroidization phenomenon is almost absent, and the surface roughness is minimal; when the laser power is 300W, the laser energy is higher, although the melt channel is smoother, but The lap is too tight, resulting in a slight over-melting phenomenon.On the one hand, excessive laser power will increase the width of the melt pool, make the cooling and solidification time of the melt pool longer, and produce a serious sticky powder phenomenon, which is not conducive to the improvement of surface roughness; on the other hand, excessive laser power will increase the flow speed of the melt pool, which may produce splashing phenomenon, and a very irregular rough surface will be formed when it falls on the melt pool.Therefore, the suitable laser power can reduce the surface roughness of the melt channel. Under this simulation parameter, the surface forming quality of the melt channel is the best when the laser power is 270W.

Effect of scanning speed on surface roughness

The laser scanning speed also affects the laser energy input and has a significant impact on the surface roughness of the formed parts. A single-factor test is set for the scanning speed. It can be seen from the previous section that when the laser power is used, the surface roughness of the melt channel is the smallest, so the laser power is set to 270W.Based on the simulation results and measurement data, a trend chart of the influence of scanning speed on the surface roughness of the melt channel is drawn, as shown in Figure 7.

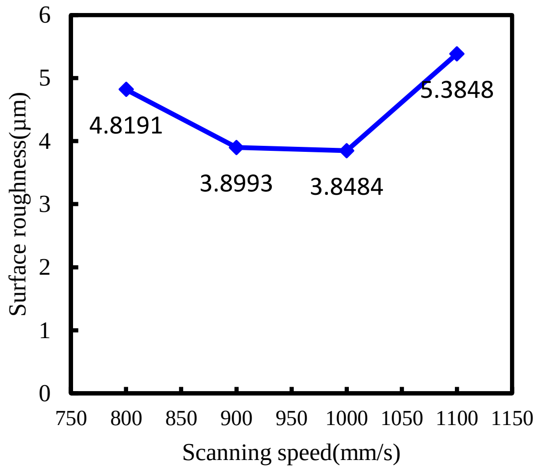
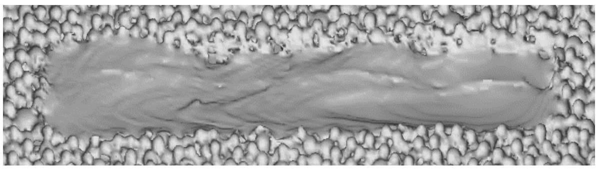


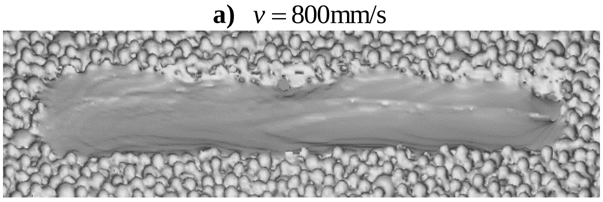
Figure 7 Trend chart of the influence of scanning speed on surface roughness

As can be seen from Figure 7, as the scanning speed increases, the value of the surface roughness decreases first and then increases. When the scanning speed is less than 1000mm/s, the surface roughness of the melt channel decreases with the increase of the scanning speed; when the scanning speed is greater than 1000mm/s, the surface roughness of the melt channel increases with the increase of the scanning speed, and when the scanning speed is 1000mm/s, the minimum surface roughness $Ra = 3.8484\mu m$ 。

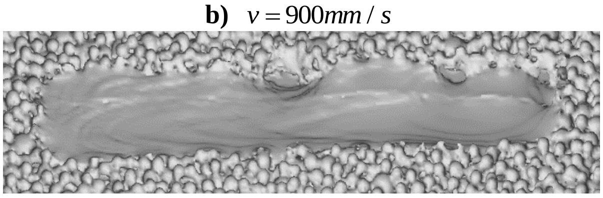
In order to explore the reason, the morphology of the simulated melt channel is shown in Figure 8.：



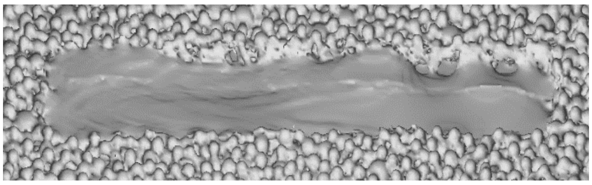
a) $v = 800mm/s$



b) $v = 900mm/s$



c) $v = 1000mm/s$



d) $v = 1100$mm/s

Figure 8 The morphology of the melt channel corresponding to different scanning speeds

As can be seen from Figure 8, the surface of the melt channel is relatively flat when the scanning speed is 900mm/s and 1000mm/s, especially when v=1000mm/s, the surface of the melt channel is the smoothest, and the surface roughness under this process parameter is the smallest, which is 3.5351μm.When the scanning speed is 800mm/s, the energy input is higher, the melted part of the metal powder increases, the melt channel widens and the solidification time is longer, resulting in a slight over-melting reaction and adhesion phenomenon, the surface quality of the melt channel is poor, and there are even bumps where the melt pool splashes and falls on the melt channel. When the scanning speed is 1100mm/s, due to the faster scanning speed, the powder absorbs less energy, the metal powder and the substrate are not melted sufficiently, and the wettability is not good, resulting in a serious spheroidization phenomenon. Therefore, the appropriate scanning speed should be selected. Too high or too low scanning speed will increase the surface roughness of the melt channel. Under this process parameter, the melt channel is the flattest when the scanning speed is 1000mm/s.

Effect of hatch spacing on surface roughness

针对扫描间距设置单因素试验，采取上两节得到的最优工艺参数 $P = 270$W 、$v = 1000$mm/s，扫描间距取 50μm、60μm、70μm 和 80μm 进行仿真，对仿真结果进行粗糙度测量，如图 9 所示。

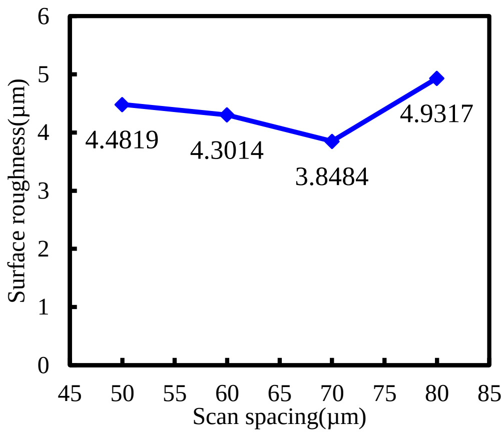
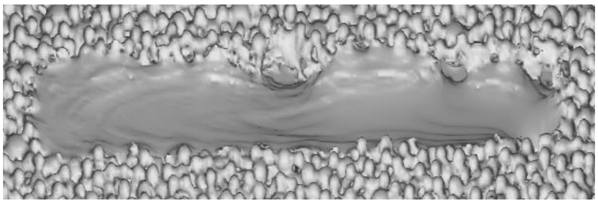


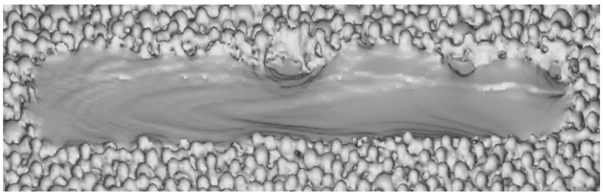
Figure 9 Trend chart of the influence of hatch spacing on surface roughness

As can be seen from Figure 9, as the hatch spacing s increases, the surface roughness tends to decrease first and then increase, and the minimum value is obtained at s=70μm.

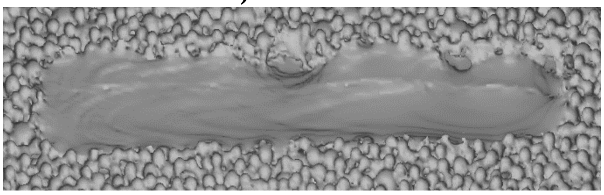
In order to explore the reason, a topographic map of the surface of the simulated melt channel was intercepted, as shown in Figure 10.



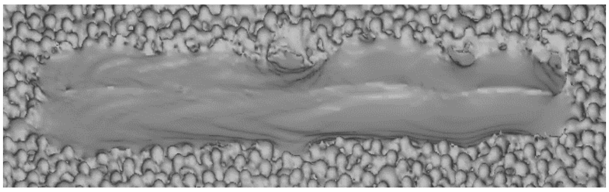
a) $s = 50$μm



b) $s = 60\text{mm}$



c) $s = 70\mu\text{m}$



d) $s = 80\mu\text{m}$

Figure 10 The morphology of the melt channel corresponding to different hatch spacing

As can be seen from Figure 10, when the hatch spacing is 50µm, the spacing of the melt channels is very small at this time, making the adjacent melt channels overlap in a large area and the heat accumulates a lot, resulting in a more serious over-melting phenomenon.When the hatch spacing is 60 µm and 70 µm, the lap between the melt channel and the melt channel is good, especially when s=70 µm, the surface of the melt channel is straight and smooth.When the hatch spacing is 80µm, it can be clearly seen from the figure that the lap is not tight, and there are obvious ups and downs at the lap. This is because the hatch spacing is too large, resulting in a decrease in the lap area between adjacent melt channels, which greatly increases the surface roughness of the melt channel.Under this process parameter, the optimal hatch spacing is 70µm.

According to the above analysis, it can be seen that the influence of hatch spacing on roughness is essentially mainly the influence of the lap rate between the melt channels on the surface roughness, so it is necessary to further study the influence of the lap rate on the roughness.The lap rate can be obtained from equation (6)：

$$\delta = (a - s) / a \qquad (6)$$

Where, δ is the lap rate; s is the hatch spacing; a is the melting width of a single melt channel.

Measure the melting width of a single melt channel at different scanning intervals, calculate the lap rate of the melt channel, and draw a diagram of the influence between the lap rate of the melt channel and the surface roughness, as shown in Figure 11.

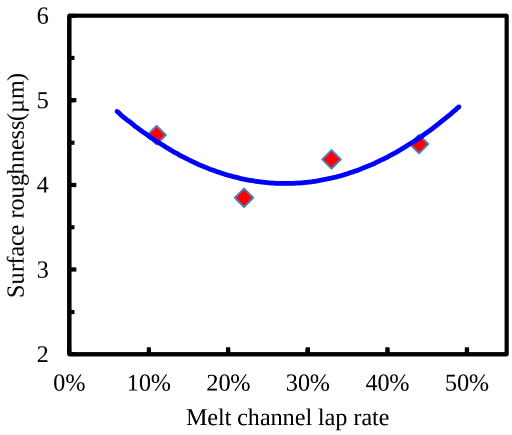


Figure 11 The influence curve of the lap rate of the melt channel on the surface roughness

As can be seen from Figure 11, as the lap rate of the melt channel increases, the surface roughness decreases first and then increases. The lap rate of the melt channel is too high or too low. It is not conducive to the improvement of the surface roughness of the melt channel. When the lap rate is between 20% and 30%, the surface roughness is the smallest. When the lap rate is 22.2%, the minimum surface roughness is 3.8484μm.Therefore, when choosing the hatch spacing, the appropriate laser power and scanning speed and other process parameters that affect the width of the melt channel should be selected, so that the melt channel lap rate is between 20% and 30%, and the smallest surface roughness can be obtained in this interval.

Effect of physical energy density on surface roughness

In the SLM forming process, multiple process parameters are involved, and the surface roughness is the result of the interrelationship and mutual influence of each process parameter.This paper introduces the physical parameter of physical energy density, the meaning of which is the size of energy input per unit volume per unit time.The formula for calculating the energy density of the body is shown in (7).

$$\omega = P/(vsh) \qquad (7)$$

Where, P is the laser power, v is the scanning speed, s is the hatch spacing, and h is the thickness of the powder

According to the test results and measurement data in Table 4, calculate the physical energy density corresponding to each set of parameters, and draw a trend chart of the influence of physical energy density on surface roughness and a comparison chart of the influence of various factors on physical energy density, as shown in Figures 12 and 13.

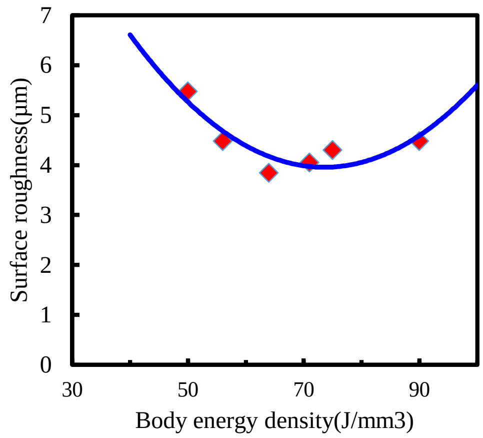


Figure 12 The trend of the influence of physical energy density on roughness

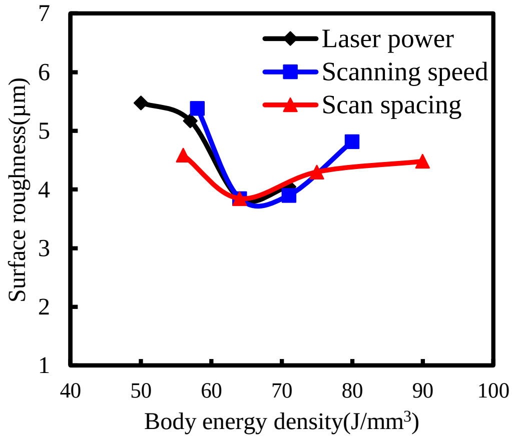


Figure 13 Comparison of the influence trend of energy density of various factors

As can be seen from Figures 12 and 13, the surface roughness decreases first and then increases with the increase of the body's energy density. The body's energy density is too large or too small to be conducive to the improvement of the surface roughness, and under the same body's energy density, the influence of different process parameters on the surface roughness tends to be approximately the same. Therefore, in the SLM forming process, it is necessary to ensure that the body's energy density is within a reasonable range. When ω=60J/mm^3, the minimum surface roughness is obtained, and the minimum value is 3.8484μm.

Comparison of simulation results and experiments on surface roughness of single-layer forming

According to the process parameters used in the experiment of Balbaa et al.[8], a single-layer two-channel SLM forming simulation was carried out, and the surface roughness obtained by the simulation was compared and analyzed with the data obtained by the experiment to verify the feasibility of single-layer forming analysis of surface roughness.

The roughness of the simulated forming melt channel is measured and compared with the experimental surface roughness, as shown in Table 6, and a comparison chart of the influence of simulation and experimental scanning speed on the surface roughness is drawn, as shown in Figure 14.

Table 5 Comparison of simulation and experimental surface roughness results

Scanning speed (mm/s)	Simulation (μm)	Experiment (μm)	Relative error (%)
500	4.3	4.2	2.4
600	3.1	3.7	16.2
700	2.4	3.0	20.0
800	3.9	4.2	7.1
1000	4.3	5.5	21.8
1200	8.6	9.0	4.4

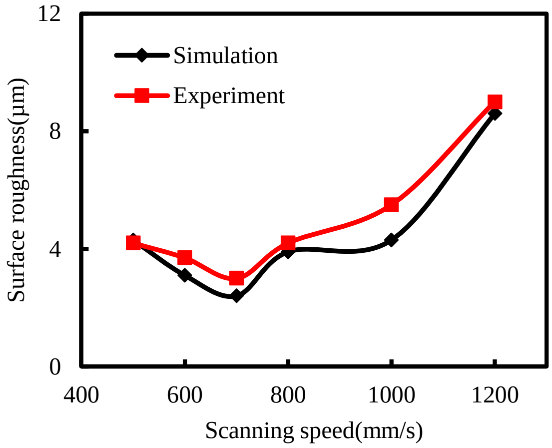


Figure 14 Comparison of simulation results and experimental results

Observe Figure 14 and compare the surface roughness simulated in this paper with the results of the experiment. The average relative error is 12.0%, less than 15%, and it has approximately the same regularity and good correlation.Therefore, it is feasible to study the surface roughness of the formed parts through a single-layer melt channel.

III. Conclusion

(1) The influence trends of laser power, scanning speed and hatch spacing on surface roughness were studied, and the optimal set of process parameters was obtained: P=270W, v=1000mm/s, s=70μm. Under this process parameter, the melt channel is straight, there is no obvious spheroidization phenomenon, and the lap is good, with a minimum roughness.

(2) Considering the influence of laser power, scanning speed and hatch spacing on surface roughness, the lap rate is between 20% and 30%, and the surface roughness is the lowest when the physical energy density is between 60J/mm^3 and 70J/mm^3.

(3) By comparing the single-layer forming simulation with the experimental forming, the average relative error between the surface roughness of the single-layer simulation and the surface roughness of the experimental complete body forming is 12.0%, and it has a good correlation, proving that it is feasible to study the surface roughness of the formed body through the single-layer forming surface roughness.

References

[1] Amato K N, Gaytan S M, Murr L E, et al. Microstructures and mechanical behavior of Inconel 718 fabricated by selective laser melting. Acta Materialia, 2012, 60(5): 2229-2239.

[2] Popovich V A, Borisov E V, Popovich A A, et al. Impact of heat treatment on mechanical behaviour of Inconel 718 processed with tailored microstructure by selective laser melting. Materials & Design, 2017, 131: 12-22.

[3] Li Y, Založnik M, Zollinger J, et al. Effects of the powder, laser parameters and surface conditions on the molten pool formation in the selective laser melting of IN718. Journal of Materials Processing Technology, 2021, 289: 116930.

[4] Baicheng Z, Xiaohua L, Jiaming B, et al. Study of selective laser melting (SLM) Inconel 718 part surface improvement by electrochemical polishing. Materials & Design. 2017, 116: 531-537.

[5] Wang W, Wang S, Zhang X, et al. Process parameter optimization for selective laser melting of Inconel 718 superalloy and the effects of subsequent heat treatment on the microstructural evolution and mechanical properties. Journal of Manufacturing Processes, 2021, 64: 530-543.

[6] Alexander Ilin, Ruslan Logvinov, Alexander Kulikov,et al. Computer Aided Optimisation of the Thermal Management During Laser Beam Melting Process. Physics Procedia, 2014, 56.

[7] YUE T, ZHANG S, WANG C, et al. Effects of selective laser melting parameters on surface quality and densification behaviours of pure nickel. Transactions of Nonferrous Metals Society of China, 2020, 32(8): 2634-2647.

[8] Balbaa M, Mekhiel S, Elbestawi M, et al. On selective laser melting of Inconel 718: Densification, surface roughness, and residual stresses. Materials & Design, 2020, 193: 108818.

[9] Wang L, Wang S, Wu J. Experimental investigation on densification behavior and surface roughness of AlSi10Mg powders produced by selective laser melting. Optics & Laser Technology, 2017, 96: 88-96.

[10] Wen W. Research on the surface and pore control of laser selective melting and forming of stainless steel metal powder. Yanshan University, 2022.