Effect of processing parameters on the size of molten pool in GH3536 alloy during selective laser melting

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Abstract. A combination of the finite element simulation and experimental measurement is proposed to study the influence of laser power and scanning velocity on the molten pool size in the selective laser melting (SLM) of GH3536 alloy. The results show that line energy density and molten pool size exhibit linear growth relationship within the scope of the study parameters. In addition, several GH3536 alloy samples are fabricated by SLM technology with different parameters. All SLM samples are used for metallographic experiment to measure the molten pool size. The result shows that experimental measurements are in good agreement with the simulation predictions.

1. Introduction

Nowadays, GH3536 alloy attracts increasing attention due to its high temperature strength, high oxidation resistance and hot corrosion resistance. Due to these excellent performances, GH3536 alloy becomes one of the most important high-temperature alloys and is widely used in the aviation and aerospace industry such as turbine of engine, fastener and blade. However, with the continuous development of industrial technology, traditional processing method such as forging and casting not only need more costing and time consuming, but also are getting harder to meet the demand for complex construction design and process.

SLM is one of additive manufacturing (AM) technologies used for directly fabricating 3D metal components with complex shapes.1, 2 Owing to incremental manufacturing mechanism, SLM technique has several advantages such as complete fusion, near-net forming, small heat affected region and complex structural design flexibility.3-5

It is well known that the process parameters take significant influence on the stability, microstructural and microdefects in SLM.6 Therefore, a better understanding of the process parameters is necessary for understanding the evolution mechanism of thermal behavior and temperature distribution during SLM.7 However, SLM is a complicated physicochemical metallurgy process which involves with phase transformation, the radiation effect on the melt surface, thermal stress, local shrinkage of metal materials and heat transfer in a short-period time. These physicochemical phenomena cannot be investigated by traditional experimental method, but finite...
Finite element method is a reasonable choice.8, 9

In the present work, a 3D finite element model is developed to study the effect of process parameters on temperature distribution and melting pool behavior during SLM. In addition, several GH3536 alloy samples are fabricated using SLM technology with different thermal input parameters and the thermal behavior is analyzed by experiments as well.

2. Finite element modeling method

Numerical simulation is performed using finite element modelling in this research. Figure 1 shows the geometry of the model with defined laser scanning path. The model consists of a stainless-steel substrate with a dimension of 1.40×0.80×0.20 mm, a powder bed of GH3536 with a dimension of 0.80×0.40×0.08 mm. The powder bed is divided into two layers. Each layer is 40 μm thickness.

To reduce simulate time and maintain sufficient calculation accuracy, a finer mesh is used in the powder layer while coarser mesh is used in the stainless-steel substrate. The fine mesh size is 0.0125×0.0125×0.0125 mm and the coarser mesh size is gradual increase with the distance away from the GH3536 powder bed.10 Consequently, the three-dimensional simulation model is meshed into 34881 nodes and 30296 elements in total.

Considering the laser penetration and the transient thermal transportation phenomenon in the SLM process, the continuous heat source is modelled as a moving Gaussian heat source distribution,11

\[
q(x, y, z) = \frac{\eta \cdot 6\sqrt{3}Q}{hr^2\pi \sqrt{\pi}} \exp \left( -\frac{3x^2}{r^2} - \frac{3y^2}{r^2} - \frac{3z^2}{h^2} \right)
\]

where, the \(q(x, y, z)\) is the heat flux density of point \((x, y, z)\) in the coordinate system, \(Q\) is the laser absorption power of powder, \(\eta\) is the laser power, \(r\) is radius of surface circle of Gaussian heat source and \(h\) is the depth of Gaussian heat source.

Temperature-dependent material properties used in the model are presented in table 1. To imitate the intense convective heat transfer effect in the melting pool, the conductivity in the molten metal is artificially regard as three times as thermal conductivity in the solid stage. The process of powder-to-solid transition and convection effect and heat radiation of material surface are all considered in the model and realized through several user written programs. For the simulation process, the hatch spacing is fixed at 100 μm. The different scanning velocities are 860, 960 and 1060 mm/s, and the different laser powers are 255, 285 and 315 W, respectively.

Table 1. Thermal physical properties of GH3536 alloy.

| Temperature (°C) | Density (g • cm⁻³) | Specific heat (J/(g • K)) | Conductivity (W/(m • K)) |
|------------------|----------------------|---------------------------|--------------------------|
| 25               | 8.34                 | 0.422                     | 12.61                    |
3. Experimental procedure
Experimental study is carried out via an EOS M290 SLM equipment. The installation is equipped with a fiber laser whose maximum power and spot diameter are 400 W and 80 μm, respectively. The GH3536 powder is placed in a vacuum chamber which is filled with argon gas so as to afford an inert atmosphere for SLM and then the powder bed is melt by a computer-controlled laser selectively with a scanning velocity of 960 mm/s. The other specific experimental parameters are the same with the data used in the model. The chemical composition of GH3536 powder is listed as follows (mass fraction. %): 0.45 Si, 21.45 Cr, 18.99 Fe, 4.03 V, 8.73 Mo, 0.45 Mn, 0.99 Co, 0.52 W and balance Ni.

All SLM samples are slightly eroded with an aqua regia (nitric acid: hydrochloric acid=1:3). The cross-sectional microstructure of the eroded part is examined by an optical microscope (OM). In the metallographic microanalysis, the sizes of 20 clear molten pools are measured and then average them as molten pool size.

4. Results and discussion

4.1. Effect of scanning velocity and laser power on molten pool dimensions
The molten pool size plays an important role in the SLM technique because it significantly affects the metallurgical bonding between the adjoining trajectories and layers in the process of SLM. If the molten pool size is appropriate, the defects caused by improper thermal input parameter can be averted. Thus, prediction of molten pool size will provide crucial guidance for optimizing the thermal input parameters of SLM technology.

It is well known that scanning velocity and laser power are two important parameters that significantly affect molten pool size. Figure 2 shows the effect of thermal input parameters on simulated molten pool size. It is clearly shown that, on the one hand, with the certain scanning velocity, the width and the depth of molten pool increase with the laser power increasing. On the other hand, the increase of scanning velocity will lead to a reduction in molten pool size.

To further understand the actual influence of thermal input parameters on the molten pool size, the laser power and scanning velocity are combined to the line energy density which is a ratio of laser

| Speed/mm s⁻¹ | 850 | 900 | 950 | 1000 | 1050 |
|---------------|-----|-----|-----|------|------|
| Width/μm     | 75  | 70  | 65  | 60   | 55   |
| Depth/μm     | 120 | 110 | 100 | 90   | 80   |

(a) Melting pool depth
(b) Melting pool width

Figure 2. Effect of thermal input parameters on simulated molten pool:(a) molten pool width and (b) molten pool depth.
power to scanning velocity. In this study, the different line energy densities are 0.241, 0.266, 0.269, 0.297, 0.328, 0.331 and 0.366 J/mm, respectively. From Figure 3, it is obvious that within the scope of the study parameters, the molten pool size increases linearly with the increase of the line energy density. And under the identical line energy density, different scanning velocity and laser power will also produce similar molten pool size.

![Figure 3. Effect of laser line energy on simulated melting pool](image)

4.2. Metallographic analysis and experimental validation

Figure 4 shows the OM cross-sectional micrographs of SLM parts after etching at a scanning velocity of 960 mm/s and a laser power of 255, 285 and 315 W, respectively. It is obvious that, with the increase of the laser power, both the molten pool width and depth become larger and larger. This conclusion is quite consistent with the simulation result. To quantitative analysis of the molten pool, its size is measured by metallographic observation. The molten pool size from experimental measurement and numerical simulation are summarized in table 2. It is concluded that the simulated molten pool width and depth are in good agreement with experimental values with maximum percentage errors at 5.01% and 8.42%, respectively. It is convinced that the model used in this research can be used to predict the molten pool size in the SLM correctly and the numerical simulation is a useful method for guiding the process optimization in SLM.

![Figure 4. Optical micrograph of eroded parts with 100 μm hatch spacing at scanning velocity of 960 mm/s and laser power of 255 W (a), 285 W (b) and 315 W(c).](image)

| Laser power | Experiment | Simulation | Percentage |
|-------------|------------|------------|------------|
|             |            |            |            |
(W) | (μm) | (μm) | error
---|---|---|---
255 | 86.32 | 90.64 | 5.01%
285 | 102.56 | 100.65 | 1.86%
315 | 112.55 | 109.23 | 2.95%

(b) | Laser power | Experiment (μm) | Simulation (μm) | Percentage error
---|---|---|---|---
255 | 59.21 | 64.19 | 8.42%
285 | 63.42 | 66.76 | 5.27%
315 | 75.16 | 72.62 | 3.38%

5. Conclusion
In this study, the influence of laser power and scanning velocity on the molten pool size in the selective laser melting of GH3536 alloy are systematically investigated by a combination of simulation and experiment. The important results are summarized as follows,

1. The increase of laser power and the decrease of scanning velocity will increase the size of molten pool.
2. There is a positive linear relationship between the line energy density and molten pool size.
3. The simulated molten pool width and depth are in good agreement with experimental values with maximum percentage errors at 5.01% and 8.42%, respectively.

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