Research on Directional Forming Process of 316L Alloy Laser

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Abstract. This paper uses 316L stainless steel as the powder and matrix material for laser cladding. The scanning speed is 8.18mm/s, the powder feeding rate is 1.15r/min, and the laser melting is performed with a constant laser power (1002.74W) and a layer-by-layer reduction. The laser cladding experiment of single channel multilayer straight thin-walled parts is carried out under the above machining parameters. Lower power laser cladding layer by layer can effectively control the molten pool volume and improve the forming quality and precision of straight thin-walled parts. And it can be observed that the microstructure from bottom to top changes from columnar crystals to equiaxed crystals and then to columnar crystals.

1. Introduction

Laser cladding is a rapid prototyping technology produced by applying the principles of rapid prototyping technology (RP) to laser cladding technology [1-3]. This technology has a high degree of flexible manufacturing, which can shorten the product development cycle, increase the processing speed, and use multiple materials to mix and process the same part according to the designed ratio. It is less restricted by the size of the parts and the complexity of the structure, and the processed parts are outstanding in performance. Based on the above characteristics, laser cladding technology is widely used in aerospace, automotive industry, mold design and manufacture, medical research, parts repair and other industries [4-7].

ML Griffith et al. [8] introduced a new technology called Laser Engineered Net Shaping (LENS) and its latest development. The metal powder particles are sprayed into a laser beam to melt and deposit on the substrate, and stacked layer by layer to produce the desired dense metal parts. S. Kumar et al. [9] proposed a three-dimensional heat transfer model in the laser cladding process, and used the finite volume method to simulate the powder feeding laser cladding process in the non-orthogonal grid system. The developed model could predict the geometry of the accumulation layer above the substrate within the acceptable tolerance range. Razavi Seyed et al. [10] studied the fatigue behavior and fracture mechanism of Ti6Al4V sample processed by additive manufacturing. The non-porous laser near-net forming specimen showed similar fatigue performance as the forged specimen, but the fatigue strength of the porous specimen was greatly reduced. Johnson et al. [11] studied the microstructure and fatigue properties of Inconel 718 superalloy formed by laser near net. It was found that some dendritic structures were retained between cladding layers, and laser cladding specimens had lower fatigue resistance than forged Inconel 718. Huang Weidong [12] summarized the laser cladding technology from the aspect of mechanical properties, and found that the mechanical properties of most laser cladding parts have reached the standard of forgings. It is because the microstructure of laser three-dimensional forming parts is fine, dense and uniform, and the internal substructure of grains is fine. It indicates that the technology has a good development prospect in the
repair field of important metal parts. F. Y. Niu et al. [13] studied the direct fabrication of Al₂O₃ thin-walled structure by using laser near net forming (LENS) technology, and analyzed the influence of process parameters on the number of cracks through experiments. Finally they successfully manufactured the thin-walled sample without cracks by optimizing the process. Guohui Zhang et al. [14] manufactured bulk Inconel 718-NiCrAlY composite with almost no defects by laser near net forming, and analyzed the phase composition and microstructure characteristics. When the content of NiCrAlY was high, the wear mechanism changed from adhesive wear and abrasive wear to main abrasive wear and micro-brittle fracture. Xinlin Wang et al. [15] studied the effects of scanning mode (reciprocating and unidirectional scanning mode) and vertical increment (Z-axis lifting amount) on the overhang structure in laser near net forming. The result showed that the protrusion deposited by reciprocating mode has higher geometric accuracy than protrusion deposited by unidirectional method.

The laser three-dimensional forming is a process in which the powder melts and solidifies rapidly, and the two-dimensional contour is obtained according to the pre-planned path, and then the structure is stacked layer by layer in the height direction, and finally three-dimensional solid parts are obtained. The laser three-dimensional forming technology involves the adjustment of process parameters and the planning of processing methods, which affect the accuracy and performance of formed parts. This article mainly explores the changing law of the cladding layer microstructure under different process parameters, and conducts laser cladding single-pass multilayer straight thin-walled parts experiments to observe the forming quality, forming accuracy and microstructures distribution of different regions.

2. Mathematical model for temperature field simulation of laser single-pass cladding

2.1. The temperature field control equation

The laser cladding process is a nonlinear transient heat transfer process, and its temperature distribution follows the transient energy conservation equation [16], which is shown as follows:

\[ \rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(k \frac{\partial T}{\partial z}) + q \]  

(1)

In the formula: \( \rho \) is the density in kg/m³; \( C \) is the specific heat capacity in J/kg·℃; \( k \) is the thermal conductivity in W/m·℃; \( q \) is the heat flux density of the light source in W/m²; \( T \) and \( t \) respectively refer to temperature and time variables.

2.2. Initial conditions and boundary conditions

The solution of the temperature field equation requires initial conditions, and the initial temperature is taken as the initial conditions [17-18]:

\[ T(x, y, z, t) |_{t=0} = T_0 \]  

(2)

In the formula, \( T_0 \) represents the initial temperature of the substrate, and \( T_0 = 20\text{℃} \).

In addition to the initial conditions, additional boundary conditions are required. Two types of boundary conditions are required to solve the temperature field. The first category is the heat flux function \( q(x, y, z, t) \) of the laser radiation area:

\[ \lambda \frac{\partial T}{\partial x} n_x + \lambda \frac{\partial T}{\partial y} n_y + \lambda \frac{\partial T}{\partial z} n_z = q(x, y, z, t) \]  

(3)

The second category is the convective heat transfer coefficient and ambient temperature between the fluid medium in contact with the object:

\[ \lambda \frac{\partial T}{\partial x} n_x + \lambda \frac{\partial T}{\partial y} n_y + \lambda \frac{\partial T}{\partial z} n_z = h(T_s - T_o) \]  

(4)

In which \( n_x, n_y, n_z \) represent the direction cosine of the normal outside the boundary, and \( T_s \) represents the temperature of the outer surface of the workpiece.
In the actual processing process, the convective heat transfer coefficient increases with the increase of temperature. Refer to literature [19] to define the convective heat transfer coefficient in the program.

3. Experiment

3.1. Experimental materials and equipment

The cladding material is 316L stainless steel powder (the brand is 00Cr17Ni14Mo3), the particle size is 100-200 mesh, the substrate material is 316L stainless steel, and the size is 100mm×100mm×10mm. Before the experiment, use 400-mesh coarse sandpaper to polish the surface to make the surface free of impurities and dirt.

The laser cladding processing system is the five-axis linkage increase and decrease material composite machining center SVW80C-3D produced by Dalian Third Base Group, equipped with HEIDENHAIN640 CNC system. The laser cladding head equipped with this processing system is an optical coaxial powder feeding laser head, as shown in Figure 1. Its maximum laser power is 2000W, the output spot diameter is 3mm, the cladding head collimation focal length is 150mm, and the focusing focal length is 300mm.

![Figure 1. Laser cladding head.](image1)

![Figure 2. Laser cladding powder feeding device.](image2)

![Figure 3. Protective gas device.](image3)

Figure 1 shows the double-material negative pressure powder feeder of the machining centre. The double-storage bins of the powder feeder are equipped with independent powder feeding pipelines. The powder feeder can convey two kinds of metal powder at most, and the maximum powder feed rate is 25g/min. In Figure 2, there are two powder cylinders, the left one contains 316L stainless steel powder, and the right one contains 718 high-temperature alloy powder. The system is equipped with an air compressor and a high-purity nitrogen generator to provide protective gas and powder feeding gas for laser cladding processing. Figure 3 shows the high-purity nitrogen generator.

3.2. Experimental program

The macroscopic morphology, microstructure morphology and performance of the laser cladding cladding layer are restricted by many factors, such as laser power, scanning speed and powder feeding rate. Therefore, it is necessary to comprehensively consider the influence of multiple factors on the quality of the cladding layer.

In this experiment, the central composite design method (CCD) of the response surface method is selected. The laser power $P$, the scanning speed $v$ and the powder feeding rate $f$ are input variables, while the ratio of width to height $\lambda$ and the dilution rate $\mu$ are responses. This experiment is a 3-factor 5-level experiment with 20 groups in total. There are 8 groups of full factor experiments, 6 groups of axial point experiments, and 6 groups of central point experiments. Table 1 shows the experimental factors and levels of CCD, and Table 2 shows the experimental scheme and measurement results.
Mintab software has a response optimizer. Multi-objective optimization is performed with dilution rate and aspect ratio as the response. The target value of aspect ratio is 3.2, the upper limit is 3.4, and the lower limit is 3; the target value of dilution rate is 0.18, the upper limit is 0.2, and the lower limit is 0.16. The optimal combination of process parameters is: $P=1002.74\, \text{W}$, $v=8.18\, \text{mm/s}$, $f=1.15\, \text{r/min}$.

Table 1. Process parameters and levels of composite test in single pass cladding center.

| -α level | Low level | Zero level | High level | + α level |
|----------|-----------|------------|------------|-----------|
| Laser power $P$ (W) | 932 | 1000 | 1100 | 1200 | 1268 |
| Scanning speed $v$ (mm/s) | 5.32 | 6 | 7 | 8 | 8.18 |
| Powder feeding rate $f$ (r/min) | 0.932 | 1 | 1.1 | 1.2 | 1.268 |

Table 2. Laser single pass cladding test plan and measurement results.

| Experiment number | Laser power $P$ (W) | Scanning speed $v$ (mm/s) | Powder feeding rate $f$ (r/min) | Aspect ratio λ | Dilution rate μ |
|-------------------|---------------------|---------------------------|-------------------------------|----------------|-----------------|
| 1                 | 1000                | 6                         | 1                             | 2.379382       | 0.243510        |
| 2                 | 1200                | 6                         | 1                             | 2.84333        | 0.268527        |
| 3                 | 1000                | 8                         | 1                             | 3.226832       | 0.164077        |
| 4                 | 1200                | 8                         | 1                             | 3.767165       | 0.401565        |
| 5                 | 1000                | 6                         | 1.2                           | 2.151647       | 0.119967        |
| 6                 | 1200                | 6                         | 1.2                           | 2.388439       | 0.255260        |
| 7                 | 1000                | 8                         | 1.2                           | 3.047752       | 0.183535        |
| 8                 | 1200                | 8                         | 1.2                           | 2.785305       | 0.268268        |
| 9                 | 932                 | 7                         | 1.1                           | 3.138388       | 0.230741        |
| 10                | 1268                | 7                         | 1.1                           | 2.796278       | 0.322274        |
| 11                | 1100                | 5.32                      | 1.1                           | 2.443411       | 0.245621        |
| 12                | 1100                | 8.68                      | 1.1                           | 3.553524       | 0.262443        |
| 13                | 1100                | 7                         | 0.932                         | 3.428098       | 0.370466        |
| 14                | 1100                | 7                         | 1.268                         | 2.973294       | 2.973294        |
| 15                | 1100                | 7                         | 1.1                           | 3.213383       | 0.282910        |
| 16                | 1100                | 7                         | 1.1                           | 3.080641       | 0.298159        |
| 17                | 1100                | 7                         | 1.1                           | 3.422088       | 0.302002        |
| 18                | 1100                | 7                         | 1.1                           | 3.318833       | 0.251425        |
| 19                | 1100                | 7                         | 1.1                           | 3.493526       | 0.290522        |
| 20                | 1100                | 7                         | 1.1                           | 3.21991        | 0.325213        |

Two methods are used to pile up and form thin-walled parts: 1. Constant power laser scans back and forth without interruption. Laser power is $1002.74\, \text{W}$, scanning speed is $8.18\, \text{mm/s}$, powder feeding rate is $1.15\, \text{r/min}$. 2. The power is reduced layer by layer, and the laser scans intermittently. The scanning speed is $8.18\, \text{mm/s}$, and the powder feeding rate is $1.15\, \text{r/min}$. The scanning paths of the two methods are shown in Figure 4. Figure a represents the constant power uninterrupted reciprocating scanning method. During this process, the laser is always on. Figure b represents the method of reducing the power layer by layer and the laser intermittently reciprocating scanning. In this process, the dotted line represents the path of the laser head when the laser is turned off, and the solid line represents the path of the laser head when the laser is turned on.
Firstly, obtain the average temperature and size of the molten pool center of each layer under the constant power laser continuous scanning mode. And then adjust the laser power reduction range according to the expected molten pool center temperature and molten pool size. Through continuous adjustment of the laser power, the specific change value of the laser power is finally obtained, as shown in Table 3.

Table 3. Laser power change value in 20 layers.

| Number of layers | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Laser power P (W)| 1002.74 | 975  | 950  | 925  | 900  | 890  | 880  | 870  | 860  | 850  |
| Number of layers | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20   |
| Laser power P (W)| 845  | 840  | 835  | 830  | 825  | 820  | 820  | 820  | 820  | 820  |

The reason for adjusting the laser power is that in the first few layers of thin-walled parts forming, the heat is mostly emitted into the air through the substrate, but the volume of the substrate is large, and the heat dissipation is slow, so the cladding layer is easy to accumulate more heat in a short time. Therefore, in the first few layers, the power reduction is large. With the increase of the number of stacking layers, the cladding layer gradually increases, and most of the heat firstly dissipates into the air through the formed thin-walled cladding layer. However, the volume of the thin-walled cladding layer is smaller and the heat dissipation is faster. The accumulated heat of the cladding layer reduces in a short time, so the speed of power reduction decreases. The heat input and output on the cladding layer is basically maintained in a balance state when it is accumulated to more than ten layers, so the power remains unchanged. The reason for setting the laser intermittent reciprocating scanning path is that when the laser is turned off, the cladding layer can also have a cooling time, and the heat is no longer input all the time, which also helps to reduce the accumulated heat on the cladding layer.

4. Results and analysis

4.1. Comparison of center temperature and penetration depth of molten pool

Compare the average temperature and penetration depth of the center of each layer of the molten pool in the two modes of constant power laser uninterrupted scanning and layer-by-layer reduced power laser intermittent scanning. The length of the cladding layer along the scanning direction is 35mm, and each layer is divided into 35 load steps. Add the temperature at the center of the molten pool at the 5th, 10th, 15th, 20th, 25th, and 30th load steps of each layer, find the average value, and then obtain the molten pool depth at the middle load step of each cladding layer. The comparison of the average temperature and penetration depth of the center of the molten pool under the two methods is shown in Figure 5 and Figure 6.
It can be seen from Figure 5 that under the constant power laser scanning mode, the average temperature in the center of the molten pool rapidly increases from about 1500°C to about 2200°C in the first few layers, and is maintained at about 2200°C. The penetration depth increases rapidly from about 0.1mm to about 1.1mm in the first few layers, and remains at about 1.1mm. The penetration
depth is almost twice the height of the cladding layer, and the molten pool has a larger volume. In the mode of reducing the power of the laser intermittent scanning layer by layer, the average temperature of the molten pool center and the growth rate of the molten pool depth are slowed down, and the average temperature of the molten pool center is finally maintained at about 1900℃, which is 300℃ lower than the first method. The penetration depth is finally maintained below 0.6mm, which effectively reduces the volume of the molten pool. Figure 7 more intuitively shows the changes in the volume of the molten pool from 15th to 20th in the two scanning modes.

![Figure 7. Comparison of the size of the 15-20 layer molten pool in the two scanning methods.](image)

The reduction in the volume of the molten pool means that when the current layer is cladding, the next layer will be repeatedly melted less material, which can effectively avoid the collapse of the cladding layer caused by excessive remelting of the lower cladding layer. Thereby, it can ensure that the parts are successfully formed, and have higher precision and quality.

From 15th to 20th layers, the size of the molten pool is basically stable, but the size of the molten pool under the intermittent scanning mode of decreasing power laser layer by layer is almost half of that under the continuous scanning mode of constant power laser, which intuitively shows that the intermittent scanning mode of decreasing power laser layer by layer can effectively reduce the size of molten pool.

4.2. Comparison of experimental results under the two processing methods

A set of experiments is compared. 1. Use constant power laser scanning continuously to stack up 50 layers, while laser power $P$ is 1002.74W, scanning speed $v$ is 8.18mm/s, powder feeding rate $f$ is 1.15r/min. 2. Reduce the power laser intermittently scanning layer by layer to stack up 50 layers, while the laser power $P$ in the first 20 layers is shown in Table 3, and the next 30 layers laser power is maintained at 820W. The scanning speed $v$ and the powder feeding rate $f$ are consistent with the constant power laser continuous scanning. Compare the straight thin-walled parts formed by the two methods, as shown in Figure 8, in which Figure a shows uninterrupted scanning with constant power laser, and Figure b shows intermittent scanning with reduced power laser layer by layer.

It can be seen from the Figure 8 that in the vertical direction, the thickness of the straight thin-walled parts formed in the method a is not uniform, reflecting the characteristics of thin bottom and thick top, while the straight thin-walled parts formed in the method b have uniform thickness. In the laser scanning direction, the height of the straight thin-walled parts formed in the method a is not consistent, reflecting the characteristics of high at both ends and low in the middle, while the height of the straight thin-walled parts formed in the method b is more consistent.
Figure 8. Comparison of experimental results in two scanning methods.

The reasons for this phenomenon are shown as follows. In the continuous scanning mode with constant power laser, heat is constantly input and accumulates with the height, so the output and input cannot reach the balance, which results in the uneven thickness of the straight thin-walled parts. In constant power laser continuous scanning mode, the laser head has the process of slowing down, accelerating and lifting up at both ends. In this process, the laser is always in the open state, the laser stays at both ends for too long, and the heat input is too much, so both ends of the molten pool volume is large, and more powder is put into the molten pool, resulting in the straight thin-walled pieces at both ends of the height higher than the middle height. The intermittent laser scanning with reduced power layer by layer can avoid this phenomenon.

4.3. Analysis of the microstructure of different areas of straight thin-walled parts

The straight thin-walled parts obtained by the laser intermittent scanning method of layer-by-layer reduction in power were cut along the scanning direction and processed to obtain the metallographic structure pictures of the straight thin-walled parts in different areas at the same multiple, as shown in Figure 9.

It can be seen from Figure 9 that there are fine equiaxed crystals and a few fine columnar crystals at the bottom of the straight thin-walled pieces. There are large columnar crystals in the middle which have small secondary dendrite arms. At the top, the structure changes from large columnar crystals to equiaxed crystals because the cooling rate increases as the temperature gradient at the top decreases, as happens at virtually every layer. However, as long as the remelting depth of the next cladding exceeds the thickness of this transition layer, the transition layer will be remelted, so this transition layer can only be observed at the top of the straight thin-walled piece.

Grains also grow in different directions from bottom to top, as shown in Figure 10.
Figure 10. Grain growth direction in different regions of straight thin-walled parts: 
   a - bottom; b - middle; c – top.

It can be seen from the Figure 10 that at the bottom of the straight thin-walled part, the dendrite grows obviously off the laser scanning direction. With the increase in the number of cladding layers, the dendrite does not deviate to the scanning direction, but grows vertically upwards, and most of the dendrites grow continuously in multiple layers in the vertical direction. At the top of the cladding layer, the growth direction has changed significantly, and the grains grow in the X direction.

5. Conclusion
In laser single-pass multilayer cladding, the processing method of reducing the power of laser intermittent scanning layer by layer can effectively maintain the size and temperature of the molten pool. In the experiment of forming straight thin-walled parts, it is found that the height and thickness of the straight thin-walled parts processed are relatively uniform, and the forming accuracy and quality are higher.

Observing the microstructure of the straight thin-walled part, it is found that the bottom of the straight thin-walled part contains small equiaxed crystals and a few small columnar crystals. The middle are developed columnar crystals, and these developed columnar crystals also have some small secondary dendritic arms. A significant transformation occurs at the top, and the organization changes from a developed columnar crystal to an equiaxed crystal.

At the bottom of the straight thin-walled part, dendrites grow obviously off the laser scanning direction. With the increase of the number of cladding layers, the dendrite does not deviate to the scanning direction, but grows vertically upwards, and most of the dendrites grow continuously in multiple layers in the vertical direction, which conforms to the characteristics of directional forming.

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