Simulation Research on Temperature Field of IN 625 Alloy by Micro-arc Plasma Additive Manufacturing Using Gaussian Heat Source

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Abstract. As a rising star in the field of additive manufacturing, micro plasma additive manufacturing technology has attracted more and more attention because of its unique heat source advantages. However, the simulation method based on micro plasma additive manufacturing technology is not mature enough to reveal the law and guide the experiment. In this paper, the single pass single-layer cladding process of in625 alloy manufactured by micro arc plasma additive is simulated by computer simulation method. The temperature field distribution in the manufacturing process of micro arc plasma additive is studied and the thermal process of characteristic points is output. The results show that: the finite element simulation method can better restore the heat source moving process of micro arc plasma additive manufacturing, and the Gaussian surface heat source has good applicability in the micro arc plasma additive manufacturing. The simulation results can provide theoretical basis and data support for the organizational evolution in the manufacturing process of micro arc plasma additive.

1. Introduction
Additive manufacturing (AM), also known as 3D printing, has the advantages of superior performance and low cost for the manufacturing of complex structural parts compared with the traditional reduction manufacturing method [1]. Figure 1 (a) shows the micro-arc plasma additive manufacturing (MPAM) technology belongs to a kind of plasma additive manufacturing technology. Due to the characteristics of small beam spot, large change of heat input and high production efficiency, it can realize low-cost rapid manufacturing under the premise of good manufacturing accuracy, which is a technical advantage that other additive manufacturing technologies cannot compare [2]. It is found that micro arc plasma additive manufacturing is the result of layered forming of molten materials. Due to heat accumulation, there will be thermal stress concentration and side gradient effect as shown in Fig. 1 (b). The edge droplet is easy to expand and cause collapse, which eventually leads to the decline of precision and surface quality of the parts.

In order to improve the process and improve the quality of components purposefully, numerical simulation method has been widely used in the research of additive manufacturing to improve the optimization speed. Many scholars based on laser and plasma rapid prototyping method study the forming process and control the forming process from the perspective of macro temperature field and stress field. Beijing University of technology and Beijing University of technology have simulated the process of powder falling and condensation and temperature field in the process of laser cladding...
additive [2-4]. It is found that the heat source model and parameter setting are the main decisive factors. Wu Ri [5, 6] and others used the finite element model of plasma cladding forming 304 stainless steel thin-walled parts. Through experiments, the simulation results of Gaussian surface heat source and double ellipsoid heat source were compared and analyzed. It was considered that the "pool depth" of Gaussian heat source was too small. Mayur S. et al. [7] simulated the micro arc plasma transfer arc additive manufacturing (MPTAAM) process with the finite element simulation method of diffusion, and verified the model. It was found that the micro arc heat source is different from the conventional plasma heat source, and its lower heat input can meet the Gaussian heat source distribution characteristics. Keller, T [8] simulated the molten pool through finite element analysis. After adjusting the parameters, the simulated surface temperature was in good agreement with the in-situ thermal image measurement results of Inconel625.

Figure 1. Micro-arc plasma additive manufacturing system (a) [9] and collapse in conventional plasma deposition (b) [10]

The analysis and research results show that there is no simulation example of temperature field in the manufacturing process of micro arc plasma, and the accuracy of heat source model is not verified. Therefore, this paper proposes the simulation of single layer cladding process by using the method of life and death element and Gaussian surface heat source to simulate the single layer cladding process of micro arc plasma material addition. The temperature field distribution and characteristic node heat history are output. The temperature value of characteristic points in actual working condition is compared to verify the accuracy of heat source model, so as to provide theoretical and data support for the later research on process regulation and organization evolution.

2. Simulation method
The finite element method uses Newton's calculus thought to divide the difficult continuum into finite micro elements, so as to simplify the calculation. Since the early 1940s, it has been applied in engineering practice. With the vigorous development of the computer industry, the finite element analysis method has been continuously promoted and has become an important tool for contemporary computer simulation and engineering practice guidance [11, 12]. Because of many influencing factors and difficult measurement, many parameters in the manufacturing process of micro arc plasma cladding additive cannot be measured (such as the temperature field in the molten pool, the stress field of cladding material and substrate, etc.), which can be described by computer numerical simulation method is more efficient. On the basis of previous experiments, finite element software ABAQUS was used to simulate and verify the process of single pass cladding IN 625 alloy.

2.1. Model Building
The manufacturing process of cladding additive is a continuous process of gradual accumulation of materials. The finite element modeling takes discrete points as the research object. If the cladding material is expressed in a fixed form, the cumulative effect of the material cannot be characterized. The
representative volume element is used in the research. Element (RVE) is used to simulate the material accumulation process in the heat source region, which is convenient for simulation modeling and boundary condition change. This kind of “life and death element” has an important application in the simulation process of finite element software ABAQUS. At the beginning of the cladding process, all the RVE elements in the cladding layer are “step killed”, which is not activated with the advancement of heat source calculation process, when the advancing heat source scans a certain cladding unit, the element will be activated. Under the action of high-energy heat source, heat transfer process will be carried out together with the substrate, while those not scanned are still in inactive state. According to this method, with the process of cladding, the units are activated one by one (as shown in Fig. 2), and the dynamic deposition of cladding layer increases, which simulates the real cladding process.

According to the simulation of the temperature field distribution of the molten pool and the base part during the cladding process, combined with the actual working conditions and research progress, the simulation model is simplified appropriately. The base material uses the rectangular plate model, and the cladding layer adopts the “weld bead” model with arc surface on the upper surface, as shown in Fig. 3 (a and b), the size of the substrate is 50mm × 50mm × 5mm (length × width × thickness). The cross section of the single layer cladding layer is cross-section. The chord length is 3mm, the height is 1mm, and the whole cladding layer is 50mm long. The model is divided into cladding layer and substrate by creating cross section, and the cladding layer is divided into 20 RVE units.

According to the research results of Lu Xin [13], for the micro arc plasma additive manufacturing (MPAM) process, the actual cross-sectional area of single pass cladding layer can be expressed as follows:

\[ A_{\text{scan}} = \frac{v_{\text{powder}} \cdot \lambda}{4v_{\text{scan}} \cdot \rho} \]  

(1)

- \( v_{\text{powder}} \) —— Powder feeding speed, powder feeding mass per unit time (kg/min),
- \( \rho \) —— Density of cladding material (kg/m³),
- \( v_{\text{scan}} \) —— Scanning speed of cladding (m/min),
- \( \lambda \) —— Powder utilization.

According to the previous experimental research, the scanning speed is 0.26 m/min, the cladding material density is 4.52 g/cm³, that is 4520 kg/m³, the powder supply is 12 g/min, that is \( 1.2 \times 10^{-2} \) kg/min, and the powder utilization rate is 0.75. The actual cross-sectional area of single pass cladding is about 2.39 mm² by substituting the above data into equation (1). The cross-sectional area of cladding layer in simulation modeling can be obtained by geometric calculation, which is about 2.43. The error is less than 2%. It is considered that the accuracy and feasibility of simulation modeling are better.
In order to compare modeling and calculation, the density of mesh generation was studied. The conventional method of mesh generation is that hexahedron is evenly distributed, but in general, the heat affected zone of single cladding layer is small, and the heat affected zone is concentrated around the cladding layer. In view of this situation, the mesh generation is adjusted. As shown in Fig. 3 (d), tetrahedral and wedge-shaped elements are used instead of hexahedron with the total number of elements unchanged, the mesh of the model is refined again, which makes the middle grid denser and the edge grid sparse, so as to achieve better heat transfer at the cladding layer.

2.2. Material property configuration

relevant assumptions: the substrate used in the simulation is 45# steel, and the cladding layer is IN 625 alloy. In order to simplify the calculation, the material density is approximately constant values of 7850 kg/m$^3$ and 8440 kg/m$^3$ respectively. The specific heat capacity is related to the specific heat capacity and specific heat capacity in reference table 1. ABAQUS software cannot directly define the material properties of the selected module, but first define the section of the assembly section, and then indirectly assign the material properties to the geometric components (property module).

According to the mapping of material property configuration (Fig. 4), it can be seen that whether it is thermal conductivity or specific heat capacity, the parameters of cladding layer and substrate are quite different. Especially for the thermal conductivity parameters below 1000°C, the thermal conductivity of 45# steel is negatively correlated with temperature, while IN 625 alloy is significantly positive correlated, which can be reflected in the heat affected zone during heat transfer.

| Temperature $T$/°C | Density $\rho$/kg/m$^3$ | Specific heat capacity $C_p$/J/kg °C | Thermal conductivity $\lambda$/W/m °C |
|-------------------|-------------------------|-------------------------------------|-------------------------------------|
| 100               | 7850                    | 480                                 | 43.53                               |
| 200               | 7850                    | 498                                 | 40.44                               |
| 300               | 7850                    | 524                                 | 38.13                               |
| 400               | 7850                    | 560                                 | 36.02                               |
| 500               | 7850                    | 615                                 | 34.16                               |
| 600               | 7850                    | 700                                 | 31.97                               |
| 700               | 7850                    | 854                                 | 28.66                               |
| 755               | 7850                    | 1064                                | 25.14                               |
| 800               | 7850                    | 806                                 | 26.49                               |
| 900               | 7850                    | 637                                 | 25.92                               |
| 1000              | 7850                    | 602                                 | 24.02                               |
| 1200              | 7850                    | 655                                 | 29.5                                |
| 1500              | 7850                    | 718                                 | 31.4                                |
Table 2. Thermophysical parameters of IN 625 [16]

| Temperature $T$/℃ | Density $\rho$/($\text{kg/m}^3$) | Specific heat capacity $C_p$/($\text{J/kg} \cdot \text{℃}$) | Thermal conductivity $\lambda$/($\text{W/m} \cdot \text{℃}$) |
|------------------|-----------------|-----------------|-----------------|
| 21               | 8440            | 410             | 9.8             |
| 93               | 8440            | 427             | 10.8            |
| 204              | 8440            | 456             | 12.5            |
| 316              | 8440            | 481             | 14.1            |
| 427              | 8440            | 511             | 15.7            |
| 538              | 8440            | 536             | 17.5            |
| 649              | 8440            | 565             | 19              |
| 760              | 8440            | 590             | 20.8            |
| 871              | 8440            | 620             | 22.8            |
| 982              | 8440            | 645             | 25.2            |
| 1093             | 8440            | 670             | 27.5            |

Figure 4. The temperature dependence of (a) specific heat capacity and (b) thermal conductivity of 45# Steel and IN 625

2.3. Heat source model configuration

The heat transfer process in MPAM process can be simplified as follows: the heat of plasma torch acts on the substrate and cladding layer, through the heat transfer between the cladding layer and the substrate, part of the heat is lost through the surface of the cladding layer and the substrate, and the other part is transferred through the heat transfer between the cladding layer and the substrate, and then through the lower surface of the substrate. Combined with the optimal process parameters obtained from previous experiments, the Gaussian surface heat source model is selected as the heat source model, and the user subroutine file is written in FORTRAN language to realize the description and moving loading of heat source model in ABAQUS.

Based on the characteristics of plasma arc welding and heat transfer mode, Gauss surface heat source model is widely used to simulate the temperature field of cladding process [17, 18]. The surface heat source distribution function of Gaussian model can be expressed as

$$q(r) = q_{\text{max}} \exp \left(-\frac{3r^2}{R_0^2}\right) = q(x, y, t) = q_{\text{max}} \exp \left[-\frac{3(z^2 + y^2)}{R_0^2}\right]$$

(2)
\[ q_{\text{max}} = \frac{3Q}{\pi R_0^2}, \quad Q = \eta UI \]  

\( q_{\text{max}} \) — Maximum heat flux density,

\( Q \) — Effective power of heat source,

\( R_0 \) — Heating surface radius of heat source,

\( \xi \) — The heat source center is at the position of the shaft,

\( U \) — Input voltage,

\( I \) — Input current,

\( \eta \) — Conversion efficiency.

**Figure 5.** Gauss surface heat source model [17, 18]

**Table 3.** Parameter setting of Gaussian surface heat source

| \( \eta \) | U/V | I/A | R_0/mm | \( \pi \) |
|---|---|---|---|---|
| 0.75 | 30 | 90 | 3 | 3.1416 |

2.4. Configuration analysis steps and interactions

Additive manufacturing process is the process of material accumulation from nothing to existence, from less to more. In order to meet the actual working conditions, the life and death unit technology is used to simulate the accumulation process of materials. Set Initial, step kill, step1 There are 22 analysis steps in step 20 to control the material accumulation of single-layer cladding Step10 control unit “born”. The analysis step is set as heat conduction analysis, and data output is set as temperature field output. When setting the analysis step, the kill time should be set short enough, while the birth step should be set to the actual scanning time of each RVE unit. When setting the step size, the step size should be set smaller to facilitate the convergence of calculation, but too small will increase the amount of calculation, and the parameter selection should be controlled within a certain range. In this study, the time of step kill is set as \( 1 \times 10^{-8} \)s, and the time from step 1 to 20 is set as 0.625s. The step size is set according to the total time of a single analysis step. The maximum and minimum increment determine the quality of the final calculation results. The specific settings are shown in Table 5.

**Table 4.** Heat exchange film setting conditions

| Temperature (°C) | 20 | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Membrane coefficient (W/m²·°C) | 360 | 1800 | 3600 | 5400 | 7200 | 9000 | 10800 | 12600 | 14400 | 16200 | 18000 |

Before loading the heat source model, the ambient temperature of the whole model is set at room temperature of 20 °C, and the boundary conditions are determined according to the actual situation of the substrate. Considering the particularity of single-layer cladding process, the simplified cladding layer mainly dissipates heat through heat transfer with the substrate, and the heat exchange type is set
as surface heat exchange condition, and the film coefficient setting in membrane interaction is shown in Table 6; since the heated cladding layer and substrate mainly exchange heat with the environment, the main form is thermal radiation, and the interaction is surface radiation and emissivity set to 0.85 and the radiation type is consistent.

Table 5. Analysis step settings

| Analysis step | Response | Time | Initial incremental step | Minimum increment step | Maximum increment step | Maximum temperature change | Maximum radiation variation |
|---------------|----------|------|--------------------------|------------------------|------------------------|----------------------------|-----------------------------|
| Step-kill     | Instant  | $1\times10^{-8}$ | $1\times10^{-8}$ | $1\times10^{-13}$ | $1\times10^{-8}$ | 200 | 0.1 |
| Step-1        | Instant  | 0.625 | 0.01 | $6.25\times10^{-6}$ | 0.05 | 200 | 0.1 |
| Step-2        | Instant  | 0.625 | 0.01 | $6.25\times10^{-6}$ | 0.05 | 200 | 0.1 |
| Step-3        | Instant  | 0.625 | 0.01 | $6.25\times10^{-6}$ | 0.05 | 200 | 0.1 |
| …            | …        | …   | …            | …                | …            | …            | …            |
| Step-20       | Instant  | 0.625 | 0.01 | $6.25\times10^{-6}$ | 0.05 | 200 | 0.1 |

Table 6. Interaction configuration

| Main parameter                          | Parameter value                          | Main parameter                          | Parameter value                          |
|-----------------------------------------|------------------------------------------|-----------------------------------------|------------------------------------------|
| Name                                    | Int-film                                 | Name                                    | Int-radiation                            |
| Type                                    | Surface heat exchange conditions          | Type                                    | Surface radiation                        |
| Analysis step                           | Step-1–Step-20                           | Analysis step                           | Step-1–Step-20                           |
| Surface                                 | Surf-2                                   | Surface                                 | Surf-2                                   |
| Definition                              | Attribute Reference                      | Radiation type                          | To the environment                       |
| Membrane interaction properties         | Film                                     | Emissivity distribution                 | Agreement                                |
| Definition of sink                      | Agreement                                | Emissivity                              | 0.85                                     |
| Ambient temperature                     | 20                                      | Ambient temperature                     | 20                                       |
| Ambient temperature amplitude           | Instant                                  | Ambient temperature amplitude           | Instant                                  |

3. Analysis of results

3.1. Verification method of simulation results
The simulation results are verified by qualitative analysis of temperature field and comparison of thermal history test data of characteristic nodes. The post-processing of data requires the final output of temperature field distribution and temperature history of special sampling points. In the analysis step, the output of temperature field should be set in advance, and the position to be measured should be determined according to the actual cladding situation. The temperature of characteristic points should be measured by using K-type thermocouple. The thermocouple should be fixed at the corresponding characteristic point position through tin paper tape the location of the measuring points is shown in Fig. 6. A total of 9 thermal history output nodes are set, among which 4 points are convenient for detection and installation as temperature measurement points.
3.2. Output results and analysis of temperature field

In Fig. 7 (a, b), the temperature field nephogram of the initial stage and the end stage in the single pass single-layer cladding process are given respectively. The cloud image type is banded, and the logarithmic cloud image interval type is output by tessellated method. It can be seen that in the initial stage of cladding, the diffusion of temperature field nephogram is small, indicating that the temperature is relatively low in the initial stage of cladding, the heat accumulation is not obvious, and the heat affected zone is small. Fig. 7 (c) shows the output results of local temperature field. It can be clearly seen that the high temperature position at the front end is the molten pool area. When the heat source moves forward, the molten pool part will drag, which is close to the actual cladding situation. Fig. 7 (d) shows the temperature field of local section, and the morphology of the molten pool is ellipsoid, which is scattered in the opposite direction of the moving direction. Degree gradually decreased.

3.3. Comparison of thermal history output results of temperature measurement points

The thermal history data is output to excel file through the plug ins module in ABAQUS, and the temperature time curve is drawn with the temperature history of test points, as shown in Fig. 8.
It can be seen from the figure that there is no significant difference between the simulation value and the measured value, and the overall consistency is good, especially in the peak position, that is, the peak arrival time. The time difference of A2 point measured value mainly lies in the fact that the plasma cladding gun has started to start the arc before reaching the substrate. After the arc ignition, the plasma arc directly acts on the substrate, and the heat increases rapidly. However, the peak position in the simulation only appears after the arc light reaches, which causes the lag of the peak position in the simulation. It can also be seen from the figure that the measured temperature values are slightly larger than the simulation values Temperature, which is caused by the error caused by simplifying the model and method in the temperature field simulation. The test temperature measurement value of A2 point in the cooling stage is obviously faster than the simulation result, because in the actual operation, the fixation of the fixture at the edge position makes the heat dissipation faster, and the heat transfer in the simulation does not consider the influence of the fixture on the heat dissipation, so it can be improved in the next step.

![Figure 8. Temperature verification of temperature measurement points at different positions (a-d)](image)

Fig. 3.9 shows the temperature curve of each test node. It can be seen from the figure that the whole process of heating in areas a, B, C and D is successively heated. In area a, since point A1 is closest to the cladding layer and heated the largest and earliest, the maximum temperature reaches nearly 300 °C, and the peak temperature is far higher than that of A2 and A3. Node 2 in area B, C and D is far away from the position of cladding layer than node 1. Compared with the peak position, the peak position of node 1 is ahead of node 2 and node 3. For area a, node 1 is close to the cladding layer. After the powder is melted by the heat source, the temperature in the cladding area will rise sharply, and even the node will be directly heated by the outside of the arc flame, resulting in the emergence of the peak value. However, nodes 2 and 3 are at the lower side, and the temperature rise is mainly due to the heat
conduction of the matrix as a result, the reason for the lag of peak position in B, C and D regions is similar.

4. Conclusion
In this paper, the single pass single-layer cladding process of IN 625 alloy manufactured by micro arc plasma additive is simulated by computer simulation method. The temperature field distribution in the manufacturing process of micro arc plasma additive is studied and the thermal process of characteristic points is output. The validity and accuracy of the temperature field simulation and heat source model are verified by comparing the simulation results with the verification test.

The conclusions are as follows:
1. The finite element simulation method can better reduce the heat source moving process of micro arc plasma additive manufacturing.
2. Through the comparison of verification tests, it is found that Gaussian surface heat source has good applicability in micro arc plasma additive manufacturing.
3. The results can provide theoretical basis for the simulation of microstructure evolution.

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