Numerical Simulation of Temperature Field of 12crni2 by Laser Melting Deposition

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Abstract. Based on the heat transfer theory, and the fact that thermal physical parameters, latent heat of phase change and heat transfer coefficient which vary with temperature is taken into considered, a three-dimensional transient temperature field model of 12CrNi2 by Laser Melting Deposition (LMD) is establish ed by using the parametric design language of ANSYS. Optimum process parameters were determined by single-layer and single-track experiments of LMD. Microstructure observation by optical microscope shows that the width of heat affected zone increased with the increase of laser power and decreased with the increase of printing speed. The top of the deposited layer is mainly composed of equiaxed dendrites, and the middle and bottom of the deposited layer are columnar crystals with epitaxial growth characteristics. At the same time, the accuracy and reliability of temperature field model are verified by comparing the morphology of molten pool. The simulation results show that in the process of LMD, the peak temperature of molten pool increases with the increase of layers; the peak temperature of the node increases with the increase of laser power and the decrease of printing speed. The research results in this paper would be reference for LMD of 12CrNi2 alloy steel.

1. Introduction
Camshaft is the core metal component of nuclear power emergency diesel engine. At present, it mainly depends on import and is forged from 12CrNi2 steel. Its structure is complex, and the traditional forging process is complicated and the cutting quantity is large. Laser Melting Deposition (LMD) technology is a new type of Laser Additive Manufacturing (LAM) technology, which has characteristics of unrestricted forming dimensions, multi-material compounding and preparation of functionally graded material parts, as well as parts repair and remanufacturing. It has been widely used in automobile manufacturing, household appliances production, and military industry, and biomedicine, aerospace and other fields. So it has a very wide application foreground [1-4].

Labudovic et al. [5] established a three-dimensional finite element model for direct deposition of laser metal powders. The model was used to calculate the transient temperature field distribution, and the high-contrast images of the molten pool were obtained synchronously by using ultra-high speed cameras. Costa et al. [6] established a thermodynamic numerical model of laser powder deposition on thin wall of multi-layered AISI420 steel. The combination of experiment and simulation showed that the thermal history and microstructure and properties of the final part during the forming process are
closely related to the relevant parameters. Lee [7] established a three-dimensional finite element model of LMD using Flow 3D finite element software, and studied the relationship between the simulated pool convection mode and solidification boundary shape, cooling rate distribution and primary dendrite arm spacing. Liu et al. [8] established a finite element model of coaxial laser direct metal deposition process, and simulated the geometry of Ti6Al4V single-track pass deposition. The results showed that the model predictions were in good agreement with the experimental results. Gan et al. [9] established a predictive three-dimensional numerical model to understand the thermal behavior of nickel-based cast iron alloys manufactured by multi-layer additives.

12CrNi2 alloy steel for camshaft of nuclear power emergency diesel engine is taken as the research object. The optimum process parameters are determined by single-layer and single-track LMD process experiment. The metallographic structure and morphology of molten pool are observed by optical microscope to verify the accuracy of the simulation. The effects of laser power and printing speed on temperature distribution during laser melting of 12CrNi2 thin wall are studied by numerical simulation.

2. Finite element analysis theory and model

2.1. Heat transfer model

LMD process is a nonlinear transient heat transfer process, which conforms to the Fourier heat conduction differential equation.

\[
\begin{align*}
\frac{\partial}{\partial x} (k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (k_z \frac{\partial T}{\partial z}) + Q &= \rho c \frac{\partial T}{\partial t} \\
\end{align*}
\]

(1)

Where \( k_x, k_y, k_z \) are the thermal conductivity of the material; \( \rho \) is the material density; \( c \) is the specific heat capacity of the material; \( T \) is the temperature field distribution function; \( t \) is the time; \( Q \) is the internal heat source density; \( x, y, z \) are the three coordinate directions of the Cartesian coordinate system.

In order to improve the calculation accuracy, three heat transfer modes of heat conduction, heat convection and heat radiation are considered in the simulation process. Referring to refs [10-12], the comprehensive convective heat transfer coefficient is used to consider convection and radiation. Meanwhile, the latent heat of phase change is treated by enthalpy method.

2.2. Heat source model

In the LMD process, the laser energy density follows the Gauss distribution and its mathematical expression is as follows.

\[
q(r) = \frac{3\eta P}{\pi R^2} \exp\left(-\frac{3r^2}{R^2}\right)
\]

(2)

Where \( q(r) \) is the laser heat flux density; \( R \) is the laser spot radius; \( \eta \) is the laser energy absorption rate; \( P \) is the laser power; \( r \) is the distance from the calculation point to the heat source center.

2.3. Material properties

In this paper, the substrate material is 45 steel and the deposited layer material is 12CrNi2 alloy steel. The thermal properties of 45 steel and 12CrNi2 alloy steel are obtained by refs [13-15].

2.4. Finite element model

The finite element model of LMD temperature field analysis is established by using ANSYS parametric design language. The size of the substrate is 120mm×120mm×15mm and the material is 45
steel. The size of the deposit layer is 120mm×3mm×30mm (10 layers), and the material is 12CrNi2 alloy steel. In order to improve the computational efficiency and convergence of the simulation, the mesh size of the deposit layer unit is set to 1mm×0.5mm×1mm, and the substrate grid is set to 1mm×1mm×2.5mm. The element type is Solid70 thermal analysis unit, and the mesh model is shown in Figure 1. The printing mode is single direction printing, as shown in Figure 2. Node1, Node2 and Node3 are all located on the central symmetrical plane of the deposited layer.

2.5. Experiment
The experimental deposition material is 12CrNi2 alloy steel powder, and the substrate material is 45 steel. The experimental equipment includes IPG YLS-4000 fiber laser, powder feeder, Faunc robot, PRECITEC YC52 cladding head and protective gas chamber with high purity argon. The laser has a wavelength of 1070nm, a power of 0~4000W continuously adjustable, and a spot diameter of 3mm. The laser is cooled by water. The experimental parameters are shown in Table 1. The experimental specimens are subjected to wire cutting, inlaying, grinding, polishing, corrosion, and then the microstructure of the deposited layer is observed by optical microscope.

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| Number | Power/W | Printing speed/mm·s⁻¹ | Powder feeding rate /g·min⁻¹ |
|--------|---------|------------------------|-----------------------------|
| 1      | 1800    | 5                      | 11                          |
| 2      | 2000    | 5                      | 11                          |
| 3      | 2200    | 5                      | 11                          |
| 4      | 2400    | 5                      | 11                          |
| 5      | 2000    | 3                      | 11                          |
| 6      | 2000    | 7                      | 11                          |
| 7      | 2000    | 9                      | 11                          |

3. Results analysis and discussion

3.1. Experimental results and model validation
3.1.1. Experimental results. Figure 3 shows the single-layer single-track morphology of laser melting deposition under different process parameters. The process parameters are shown in Table 1. It can be seen that the deposition quality of samples 6 and 7 is poor and oxidation occurs because of their too fast speed. The surface of sample 5 has sticky powder phenomenon; the surfaces of samples 3 and 4 also show oxidation, and the surface roughness is not good; the deposition lines of samples 1 and 2 are full and the forming quality is high. In summary, the optimum process parameters are laser power 1800W or 2000W, printing speed 5mm/s and powder feeding rate 11g/min.
Figure 3. Morphology of single-layer and single-track under different process parameters of LMD.

Figure 4 shows the morphology of single-layer and single-track deposited layer under different powers with a printing speed of 5 mm/s and a powder feeding rate of 11 g/min. As can be seen, as the laser power increases, the width of the heat affected zone (HAZ) becomes significantly larger. The top of the deposited layer is mainly composed of equiaxed crystal, and the middle and bottom are mainly columnar crystal. The columnar crystals exhibit epitaxial grows perpendicular to the upper boundary line of the HAZ. This is because the temperature gradient along the normal direction of the boundary line on HAZ is the largest. It can also be seen that there is no obvious boundary between columnar and equiaxed regions.

(a) 1800W  
(b) 2000W  
(c) 2200W  
(d) 2400W

Figure 4. Microstructure of the single-layer and single-track deposition layer under different powers.

Figure 5 shows the morphology of single-layer and single-track deposited layer under different printing speeds with a power of 2000W and a powder feeding rate of 11 g/min. According to the analysis of the images, with the increase of printing speed, the width of HAZ decreases, and the height
of deposit decreases. This is because the increase of printing speed results in the decrease of energy input of molten pool per unit time, which leads to the width of HAZ decreases. The equiaxed crystals and columnar crystals are mainly distributed in the top, middle and bottom of the deposits, and also exhibit epitaxial grows perpendicular to the upper boundary line of the HAZ. The boundary line between the two regions is also not obvious.

![Figure 5. Microstructure of the single-layer and single-pass deposition layer at different printing speed.](image)

### 3.1.2. Model validation

In order to verify the accuracy of finite element numerical simulation, a single-layer and single-track temperature field numerical analysis model is established in this section. As shown in Figure 6, the size of substrate is 20mm×20mm×10mm; the size of deposit layer is 20mm×3mm×0.5mm. The type of element is Solid70 thermal analysis unit; the printing speed is 5mm/s; the laser power is 2000W, and the diameter of spot is 3mm. The simulated temperature field molten pool images are compared with the corresponding actual process experiments in the previous section to verify the accuracy of the simulation. As shown in Figure 7, the dotted line in this figure represents the melting point line of steel 45 on the substrate. When the temperature is higher than 1350˚C, it is considered that the substrate melts to form a melting pool. The molten pool obtained by the experiment has a width of 3.41mm and a depth of 1.01mm. The simulated molten pool width is 3.1mm, the depth is 0.93mm, and the errors are 9% and 8%, respectively, within the acceptable range of engineering error (see Table 2 for details).

![Figure 6. Geometric model](image)
3.2. Finite element analysis

3.2.1. Temperature field distribution characteristics. The simulation parameters are laser power 1800–2000W, printing speed 3–9mm/s, powder feeding rate 11g/min, ambient temperature 20°C. Under these process parameters, the printing time of each layer is 24s, so the time of 10 layers is 240s, and a cooling step of 100s is used at the last. Hence, the total time is 340s.

In Figure 8, the temperature distribution contours at 84s, 156s and 191s are (a), (b) and (c), respectively, with process parameters of power 2000W and printing speed 5mm/s. In the temperature field contours, the red zone has the highest temperature, which is the location of the molten pool, and the location away from the molten pool is the blue zone. From Figure (a) to Figure (c), it can be seen that the temperature field is a dynamic change with the increase of deposited layer during the LMD process, and the peak temperature of molten pool corresponding to single direction printing mode is 1789°C, 2185°C and 2420°C, respectively, which is due to the heat accumulation effect. The closer to the heat source, the temperature isotherm is denser. Away from the location of the heat source, the isotherm becomes sparse, forming a significant tailing phenomenon.
3.2.2. Effect of process parameters on temperature field. Figure 9 shows the thermal cycle curves of Node1 at different powers, where Figure 9(b) is its partially enlarged view of Figure 9(a). Figure 9(a) shows that when the power increases from 1800W to 2400W, the peak temperature of Node1 increases from 1490°C to 1852°C with an increase of 24%. That is to say, the peak temperature of Node1 node increases with the increase of laser power. This is because when the laser power increases, the heat input of the unit per unit time is increased, and the heat accumulation between the deposited layers is caused. The secondary peaks appearing after Node1 have the same rule, which shows that the node temperature fluctuates periodically under each power, reflecting a dynamic change process of temperature field.
Figure 9. Thermal cycle curve of Node1 under different powers (a) overall (b) enlarger.

Figure 10 shows the thermal cycle curve of Node2 under different printing speeds. As can be seen, when the speed increases from 3 mm/s to 9 mm/s, the peak temperature of Node2 decreases from 2398°C to 1530°C with a decrease of 36%. That is, the peak temperature of Node2 decreases with the increase of the printing speed. This is because that with the increase of the printing speed, the time of laser irradiation to the surface of each element becomes shorter, the energy of input molten pool decreases, and then the temperature decreases. Other nodes also have the similar changing rules.

Figure 10. Thermal cycle curves of Node2 under different printing speeds.

4. Conclusion
(1) The single-layer and single-track process experiments under different process parameters (laser power and printing speed) are carried out. The single-layer and single-track deposition specimens under different process parameters are obtained. The optimum process parameters are determined, that is laser power 1800 W or 2000 W, printing speed 5 mm/s and powder feeding rate 11 g/min.
(2) The microstructure of single-layer and single-track specimens under different process parameters is observed by optical microscope. It is found that the width of heat affected zone increases with the increase of laser power and decreases with the increase of printing speed. The top of the deposited layer is mainly composed of equiaxed dendrites. The middle and bottom are mainly columnar crystals, and the columnar crystals exhibit epitaxial grows perpendicular to the upper boundary line of the HAZ. By observing the morphology of the molten pool, and compared with the finite element results, the depth and width of the molten pool are basically the same, which verifies the accuracy of the finite element model proposed in the paper.
(3) During the process of laser melting deposition, the peak temperature of molten pool gradually increases with the increase of layers. The laser melting deposition process is a dynamic process with the characteristics of rapid heat and rapid cooling.

(4) When the printing speed is constant, as the laser power increases, the node temperature increases. When the laser power is constant, the node temperature decreases as the printing speed increases.

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