Numerical simulation of convex shape beam spot on stress field of plasma-sprayed MCrAlY coating during laser cladding process

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Abstract
To reduce the thermal stress at the clad layer and further reduce the crack generation in the laser cladding process, a method of controlling the cracks at the clad layer by changing the laser energy density is proposed. Comparative thermal–mechanical coupling finite element analysis was performed on the uniform rectangular and convex shape beam spot cladding processes on plasma-sprayed MCrAlY coating through the numerical simulation method based on the ANSYS software. Results show that rapid heating and cooling characteristics, which are typical in laser processing, are manifested in the cladding process using a uniform rectangular spot, whereas a convex shape spot can exert preheating and slow cooling effects to a certain extent, thereby reducing the temperature gradient of the cladding and non-cladding zones. In addition, on the precondition of equivalent cladding effect, the thermal stress at the clad layer is also low, enabling the effective mitigation of the cracking tendency of the clad layer. Relative to the laser beam-shaped diffractive optical element special for design and manufacturing, superposing two uniform rectangular spots with different sizes and energy densities is a simpler and more effective method of obtaining a convex shape spot.

Keywords Laser cladding · Numerical simulation · Thermal stress · Convex shape beam spot · Uniform rectangular beam spot

1 Introduction
Laser cladding is radiating high-energy-density laser beams and forming a layer of materials with special physical, chemical, or mechanical properties on the surface of a base material through rapid melting, expansion, and solidification. Compared with other surface machining technologies, laser cladding technology integrates the merits of a broad scope of applications, strong practicability, and flexible application, thereby attracting extensive attention and receiving great importance [1–8]. Currently, the major problems in laser cladding are high coating brittleness and great cracking tendency [9–16], which considerably restrict its scope of application in key components. Thus, cracking inhibition in laser cladding is of great realistic significance to the application of laser cladding technology in production. The main methods of inhibiting cracks on the clad layer include adjusting the stress state and reducing the tensile stress as much as possible [17–19], optimizing the process method and parameters [20–29], reasonably designing the clad layer [29–34], and changing the laser action mode [35, 36]. In terms of cladding material, laser cladding nano coating can effectively address the easy cracking problem of the clad layer.
through the strong toughening effect of the nanomaterial [29]. The commonly used measure for adjusting the stress state of the specimen at the clad layer is preheating and/or cold treatment. For instance, the influence of substrate preheating on laser cladding was investigated in literature [17]; laser cladding tests were conducted at different preheating temperatures, and the results show that laser cladding under the substrate preheating condition could significantly improve the specimen mass, effectively reduce the thermal stress in the cladding process, and reduce the crack generation at the clad layer. In addition, Wang [18] et al. studied the effects of the addition of a plastic phase—an austenitic stainless steel net on the cracks at the clad layer during laser cladding. Literature [19] discussed the influences of post-heat treatment on microstructure and properties of composite coatings prepared by laser cladding. Composite laser cladding technology is also an effective method of controlling cracks at the clad layer. In [20–28], induction heater [20–24], ultrasonic vibration [25], electromagnetic field [26], alternating current electric field [27], and pulsed current [28] were separately combined with laser cladding, thus controlling the crack formation at the clad layer very well. Zhai et al. [27] studied the effect of alternating current electric field on laser cladding NiCrBSi coating and the addition of alternating current electric field transformed dendritic crystals at the bottom of cladding layer into isometric crystals. Meanwhile, the cracks at the cladding layer were reduced, and microhardness and corrosion resistance of the coating were enhanced. Literature [28] conducted a comparative experimental study of conventional laser cladding and pulse current-assisted laser cladding for FGH95 Ni-based superalloy powders. The results showed that the degree of supercooling and nucleation rate was elevated, the grain size was reduced, and the compactness was improved due to the introduction of pulse current.

The essence of preheating and/or slow cooling treatment lies in reducing the temperature gradient in the laser cladding process. In fact, the solidification of the clad layer is an extremely fast process after laser cladding, and the process from stress generation to stress concentration until crack formation is also very fast. Therefore, the preheating and/or slow cooling treatment should run through the entire laser cladding process to maximize the effects of preheating and slow cooling treatment on improving the quality of the clad layer or eliminating crack generation. This problem can be effectively solved using the incubator dedicated for laser cladding. However, on the one hand, the incubator should synchronously operate with laser cladding. On the other hand, different incubators should be designed for different specimens, resulting in a certain difficulty in the laser processing operation and the incubator design, especially to the overall heating and the heat insulation of large specimens. In [24], the induction heating method was used to realize the local preheating of specimens, achieving a favorable effect. This method could not only greatly improve the cladding efficiency but also obtain a crack-free clad layer; however, the complexity of the entire system is increased by the added heat source. Shang et al. [36] pointed out that the laser cladding NiCrBSi structure could be effectively controlled by changing the energy density of a circular laser beam.

On the basis of the preheating and slow cooling treatment methods and changing the energy density of the laser beam, if the laser is properly transformed, the energy density distribution of the uniform rectangular spot commonly used in laser cladding can be changed to obtain a convex shape spot with high-energy density distribution in the middle- and low-energy density distribution at the edges along the laser scanning direction. During the laser cladding process, the specimen can be preheated at the front end of the spot, and the cladding treatment is carried out in the central high-energy-density zone, while the cooling speed of the clad layer can be decelerated at the rear end of the spot. In this way, no additional device is needed, and a similar effect to preheating and slow cooling can be reached, reducing the temperature gradient of the laser and non-laser cladding zones and mitigating the cracking tendency at the clad layer. Thermal–mechanical coupling finite element numerical simulation was conducted for the laser cladding process on a plasma-sprayed MCrAlY coating, with the spot presenting a uniform rectangular energy density distribution and those presenting convex shape energy density distribution via the ANSYS software to investigate the influences of the convex shape spot on the specimen preheating and slow cooling effect of laser cladding and the stress and verify its effectiveness in controlling cracks at the clad layer. Then, the implementation method of the convex shape spot is discussed.

2 Thermal–mechanical coupling finite element modeling

2.1 Thermal–mechanical coupling finite element analysis of laser cladding

In theory, the temperature and stress fields in the laser cladding process are bidirectionally coupled. However, the stress field has a relatively small effect on the temperature field. To simplify the analysis process, we applied the indirect coupling of the thermal stress field, ignoring the influence of the stress field on the temperature field [37]. During the numerical simulation, we first analyzed the temperature field in the laser cladding process and then used the result of the temperature field as the load and applied it to the stress field analysis. Figure 1 shows the numerical simulation analysis plan.
2.2 Mathematical model and meshing of the temperature field

The substrate material was γ-TiAl-based alloy (TAC-2), which was smelted by the Institute of High-Temperature Materials, Central Iron, and Steel Research Institute. The MCrAlY coating was prepared through the plasma spraying process using the Y2O3-strengthened high-temperature alloy composite powder NiCoCrAl (KF-113A) produced by Institute of Metal Materials and Beijing General Research Institute of Mining and Metallurgy. The substrate dimensions of the specimen were 30 mm × 20 mm × 5 mm, the thickness of the coating was 0.15 mm, and one half of the specimen, which was symmetric with the center line of laser scanning as shown in Fig. 2.

Generally, the smaller the mesh is, the higher the number of units in the model and the calculation accuracy are. However, increasing the number of elements will decelerate the operation speed. Therefore, flexible processing methods are necessary in the actual modeling and meshing process. In order to accurately reflect the distribution law of the laser cladding temperature field, a small mesh size is required. This approach not only ensures sufficient calculation accuracy but also avoids excessive meshing and calculation time. When modeling, a fine grid must be used for the area near the laser scanning area, and a coarse grid must be used for the area far from the laser scanning area. In other words, the upper part of the substrate is a fine mapping grid, the lower part is a coarse mapping grid, the middle is a transition free grid, and mapping meshing on the coating. The constructed finite element model is shown in Fig. 3.

According to the cladding material supply method, the laser cladding process can be divided into preset and synchronous laser cladding. Usually, unit life and death technology is used to simulate the material addition in the thermal–mechanical coupling finite element analysis of powder-feeding laser cladding. In other words, the surface coating component dies before the laser cladding, but is activated when laser cladding is applied to the component. For the laser cladding of plasma-sprayed pre-coated coatings, elemental life and death technology need not be used because the coating is already present in the substrate before laser cladding [38].

2.3 Mathematical model of the stress field

To describe the unsteady and nonlinear heat transfer models in the laser cladding process as accurately as possible, we must consider the nonlinear changes of the material’s thermophysical parameters with temperature, the influence of the latent heat of the phase change on temperature, and the thermal convection and heat of the sample. Radiation, at the same time, to simplify the model, some simplified assumptions have been proposed for the calculation of the temperature field [38]: (1) The material is continuous and isotropic. (2) The laser absorption coefficient of the material surface is constant. (3) The flow in the molten pool is ignored. (4) The gasification of materials is ignored. (5) The influence of the solid-state phase change on the temperature field must also be ignored.

When establishing the non-steady state and the nonlinear stress change model in the laser cladding process, the nonlinear change of the mechanical properties of the material with temperature must also be considered for increased accuracy.

![Fig. 2 Schematic of laser cladding process](image)

![Fig. 3 Finite element model of temperature field for laser cladding MCrAlY coating](image)
Meanwhile, the stress field is simplified as follows [39]: (1) The material is continuous and isotropic. (2) The flow in the molten pool is ignored, and the fluid is assumed to be a solid with a very low flow stress. (3) The elastoplastic material model is applied to coatings and substrates. (4) The heating caused by the plastic deformation of the material is ignored. In other words, the weak coupling of thermal stress is applied. (5) The initial stress is ignored.

The finite element model and the meshing are the same for the stress and temperature field analyses. The load input of the stress field analysis model is the analysis result of the temperature field. The entire displacement constraint is shown in Fig. 2, where the arrow direction indicates the reverse constraint. With laser scanning the center plane of symmetry plane, the displacement direction of the normal is limited, with reference to Fig. 2 UY. Then, three corner points are selected on the lower bottom of the sample, whose stiffness displacement along the thickness direction is the limit, which is UZ in Fig. 2. Finally, a corner point is selected on the upper surface of the sample, and its displacement in the X direction is limited.

The laser cladding process is prone to thermal stress because the temperature distribution during the laser cladding process is very uneven and the temperature changes greatly. Thermal strain is caused by temperature changes and stress. According to Hooke’s law, the thermal strain formula is expressed as follows [40]:

\[
\begin{align*}
\varepsilon_{xx} &= \frac{\partial u_x}{\partial x} = \frac{1}{E} \left[ \sigma_{xx} - \nu ( \sigma_{yy} + \sigma_{zz} ) \right] + \alpha \tau = \frac{1}{2G} \left( \sigma_{xx} - \frac{v}{1 + \nu} \Theta_s \right) + \sigma_x, \\
\varepsilon_{yy} &= \frac{\partial u_y}{\partial x} = \frac{1}{E} \left[ \sigma_{yy} - \nu ( \sigma_{xx} + \sigma_{zz} ) \right] + \alpha \tau = \frac{1}{2G} \left( \sigma_{yy} - \frac{v}{1 + \nu} \Theta_s \right) + \sigma_y, \\
\varepsilon_{zz} &= \frac{\partial u_z}{\partial x} = \frac{1}{E} \left[ \sigma_{zz} - \nu ( \sigma_{xx} + \sigma_{yy} ) \right] + \alpha \tau = \frac{1}{2G} \left( \sigma_{zz} - \frac{v}{1 + \nu} \Theta_s \right) + \sigma_z,
\end{align*}
\]

where \( \Theta_s = \sigma_{xx} + \sigma_{yy} + \sigma_{zz} \).

In the form of stress components, Eq. 1 can be expressed as follows:

\[
\begin{align*}
\sigma_{xx} &= 2G \varepsilon_{xx} + \eta \theta - \frac{\alpha E \tau}{1 - 2\nu}, \quad \sigma_{xy} = 2G \varepsilon_{xy}, \\
\sigma_{yy} &= 2G \varepsilon_{yy} + \eta \theta - \frac{\alpha E \tau}{1 - 2\nu}, \quad \sigma_{yz} = 2G \varepsilon_{yz}, \\
\sigma_{zz} &= 2G \varepsilon_{zz} + \eta \theta - \frac{\alpha E \tau}{1 - 2\nu}, \quad \sigma_{zx} = 2G \varepsilon_{zx},
\end{align*}
\]

where \( \nu \) is the Poisson’s ratio, \( E \) is the elasticity modulus, \( \alpha \) is the coefficient of thermal expansion, \( \theta = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz} \) is the volume change, \( \tau = T - T_0 \) is the temperature variation, \( G = \frac{E}{2(1 + \nu)} \) is the shear modulus, and \( \eta = \frac{E}{(1 + \nu)(1 - 2\nu)} \) is the Lame constant.

### 2.4 Laser heat source treatment

The main models used to describe the laser heat source include the Rosenthal analytical, Gauss distribution heat source, uniform heat source, semispherical heat source, ellipsoidal, and double-ellipsoid heat source models [38, 41–53]. For laser cladding, a diffractive optical element is usually used to transform the Gaussian beam into a rectangular beam with a uniform energy density distribution [54]. Thus, the uniform heat source model is usually applied in numerical simulation.

Two laser heat source models are used in the numerical simulation: uniform rectangular spot, with the following concrete parameters: laser power of 950 W, spot size of 5 mm × 3 mm, laser scanning direction along the 3-mm side of the spot, and a scanning speed of 600 mm·min⁻¹; convex shape spot (superposed by two uniform rectangular spots with the same center but different sizes), namely one uniform small rectangular spot with a laser power of 675 W and size of 5 mm × 3 mm, and one uniform large rectangular spot with a laser power of 675 W and a size of 5 mm × 15 mm, the scanning direction is along the 3/15-mm side of the spot, and the scanning speed is 600 mm·min⁻¹. The energy density distributions of the two spots are shown in Fig. 4.

Given that the laser source changes over time, the position of the boundary heat flow is constantly changing. If the position of the laser spot is expressed as a function of coordinates and time, then the equation will be difficult to solve. On the basis of the discrete characteristics of the finite element, a small-step distance jumping heat source is used to simulate the continuous scanning process of the laser beam. Each time, the laser beam moves by one unit.

To realize the moving load, the position and size of the load at each moment must be determined in the solution process. When the load moves to the next step, the load of the previous step is eliminated. To simulate the laser cladding process in which the heat source moves continuously, APDL (ANSYS Parametric Design Language) programming is used to apply the heat load. The definition of table in ANSYS is introduced.
in. In other words, the heat source table is defined by planes X and Y and function TIME. The movement of the entire heat source is realized by moving the center position of the heat source.

2.5 Thermophysical parameters of materials

The thermophysical parameters of the material play a very important role in the calculation of the temperature and stress fields whose values have a direct relationship with the shape and size of the laser cladding temperature and stress fields. The ANSYS program table shows the parameters at different typical temperatures. The parameter value at an unknown temperature can be determined by interpolation and extrapolation. The thermophysical parameters of MCrAlY and TiAl alloys are described in references [55, 56] (Tables 1 and 2).

In the stress field analysis, the main mechanical properties include elasticity modulus $E$ (Pa), yield strength $\sigma_s$ (Pa), shear modulus $G$ (Pa), coefficient of thermal expansion $\alpha$ (K$^{-1}$), and Poisson’s ratio $\nu$. The mechanical properties of high-temperature MCrAlY alloy [55] and TiAl alloy [56] are introduced in relevant references. The variation of the elastic modulus and yield strength of MCrAlY and TiAl alloys with temperature is shown in Fig. 5.

2.6 Treatment of boundary conditions

In the laser cladding process, 20 °C is the initial temperature of the entire sample, while the other side is under adiabatic conditions. The boundary condition of the upper surface of the sample is:

$$-\lambda \frac{\partial T}{\partial z} = Q(x,y,t) + h(T_w - T_e)$$

where $\lambda$ is the heat transfer coefficient, $Q$ is the surface heat flow function on the upper sample surface (laser heat source loads), $T_w$ denotes the surface temperature of the samples, $T_e$ is the ambient temperature, and $h$ is the total heat transfer coefficient. Laser loads were imposed by heat flux, and convection and radiation were imposed by the surface effect unit Surf152.

Considering the convection and radiation boundary conditions, the other surfaces are expressed as:

$$-\lambda \frac{\partial T}{\partial z} = h(T_w - T_e)$$

where $h = h_c + h_r$ is the total heat transfer coefficient, which covers the convective heat transfer coefficient ($h_c$), and the radiation heat transfer coefficient ($h_r$). $h_r$ can be expressed by the following formula:

$$h_r = \varepsilon\sigma(T_w^4 + T_e^4)(T_w + T_e)$$

where $\sigma$ is the Stefan–Boltzmann constant and approximately $5.67 \times 10^{-8}$ W·m$^{-2}$·K$^{-4}$. $\varepsilon$ denotes the radiation coefficient of the material surface. As shown in Table 3, the total heat transfer coefficients at different temperatures are calculated.

![Energy density distribution of laser beam spots: a uniform rectangular beam spot and b convex shape beam spot](image_url)

**Table 1** Thermal-physical properties of MCrAlY [55]

| Temperature/°C | Conductivity/(W·m$^{-1}$·K$^{-1}$) | Specific heat/(J·kg$^{-1}$·K$^{-1}$) |
|---------------|--------------------------------|----------------------------------|
| 20            | 4.3                            | 501                             |
| 400           | 6.4                            | 592                             |
| 800           | 10.2                           | 781                             |
| 1200          | 16.1                           | 764                             |
The latent heat of phase change can be considered by defining the enthalpy of the material that changes with temperature [57]:

\[ H = \int \rho C(T) dT, \]

where \( \rho \) is the latent heat of phase change. \( C \) and \( T \) denote density, the specific heat, and the absolute temperature, respectively.

The corresponding finite element numerical simulation model was established through the indirect thermal–mechanical coupling method via the ANSYS finite element software, and the concrete model construction is also discussed in detail in [58, 59].

### 3 Model calculation results and discussion

Figure 6 displays the temperature field nephogram at 1.5 s of laser scanning under two process parameters, where the zone with a temperature exceeding 1460 °C (melting point of TiAl alloy) in the Fig. 6 is a molten pool zone. Figure 6 indicates that the isothermal zone cladded using convex shape spot is larger than the uniform rectangular spot, i.e., the temperature gradient of the cladding and non-cladding zones is small.

The cross-sectional temperature field nephogram at the maximum temperature point at 1.5 s is shown in Fig. 7, and the isothermal line presents a crescent shape. The substrate melting depth and the interfacial metallurgical bonding breadth can be judged according to the 1460 °C isothermal line. When the uniform rectangular spot is used, the interfacial metallurgical bonding breadth and the substrate melting depth are 3.04 mm and 134 \( \mu \)m, respectively, and those when the convex shape spot is used are 3.03 mm and 145 \( \mu \)m, respectively, indicating that they achieve an equivalent overall cladding effect. The comparison of the two figures shows that the maximum temperatures achieved by using the uniform rectangular and convex shape spots are 1906 °C and 1820 °C, where the latter is slightly lower than the former. However, the laser irradiation time and the existence time of the molten pool are longer because the convex shape spot is relatively larger, and thus more heat quantity can be transferred toward the depth direction. Moreover, the temperature gradient is small in the depth direction, the practical cladding effects of the two process parameters are equivalent, and only that the ratio of the substrate melting depth to the interfacial metallurgical bonding breadth is relatively higher when the convex shape spot is used in the cladding process.

The temperature cyclic curve at the midpoint of the center line on the upper surface of the specimen is shown in Fig. 8. When the uniform rectangular spot is used for cladding, the temperature at the spot slowly rises before the laser beam scans to this spot; when the laser beam scans to this point, the temperature rapidly increases and then rapidly cools as the laser leaves, presenting rapid heating and cooling characteristics, which are typical in laser machining. During the cladding process using the convex shape spot, the temperature cyclic curve is similar to the laser spot shape, namely the convex shape, and at the front end is equal to local preheating of the specimen at 400 °C. However, influenced by the laser heat action, the temperature is relatively high in the cooling phase, presenting an incomplete symmetric distribution. In general, when the convex shape spot is used, the temperature gradient is small in both front and rear ends of the laser cladding, and
obvious preheating and slow cooling features are manifested, which can relieve the adverse effect of fast heating and cooling in laser cladding on the coating stress to some extent.

Early-stage research indicates that the tensile stress of the laser cladding specimen is the maximum along the laser scanning direction (transverse) [52], and high tensile stress is closely related to the crack formation at the clad layer. Therefore, only the influences of the two spots on transverse stress in the cladding process are discussed in this paper. Figure 9 shows the transverse stress cyclic curve at the mid-point of the laser scanning center line on the upper surface of the specimen. Before and after the molten pool is formed, the compressive stresses are equivalent under the two process conditions, but in terms of the role that tensile stress plays in the crack formation at the clad layer, the tensile stress formed by using the convex shape spot is obviously lower than that using the uniform rectangular spot in the subsequent cooling process. According to the calculation results, as cooling proceeds until 300 s, the tensile stress (may be considered as residual stress) of the uniform rectangular spot is 397.66 MPa, while that of the convex shape spot is 355.83 MPa, presenting a 10.5% decrease.

The transverse stress distribution on the laser scanning center line on the upper surface of the specimen at 300 s is presented in Fig. 10. The residual stress distributions under the two process conditions are similar. The transverse stress on the center line of the entire workpiece is tensile stress, the stress rapidly increases at the initial end of laser scanning, and this very high stress level is maintained in the central area until the end point of laser scanning. However, the residual stress of the convex shape spot is lower than that of the uniform rectangular spot, with an average of approximately 40 MPa in the central area. The previous numerical simulation proved that the convex shape spot is effective for controlling the crack generation in the laser cladding process.

### 4 Implementation method of convex shape beam spot

The convex shape laser spot can be implemented by two methods. (1) The diffractive optical element can transform the Gauss laser into a rectangular spot with uniform energy density or other laser beams presenting any power density distribution. Therefore, the special diffractive optical element producing a convex shape spot can be directly manufactured through the laser beam-shaped diffractive optical element design. However, on the one hand, the design and manufacturing

![Fig. 6 Temperature field nephogram at 1.5 s: a uniform rectangular beam spot and b convex shape beam spot](image)

| Table 3 Total coefficient of heat transfer at different temperatures |
|------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Temperature/°C   | 20      | 100     | 200     | 400     | 600     | 800     | 1000    | 1400    | 1600    |
| Total coefficient of heat transfer/(W·m⁻¹·K⁻¹) | 20      | 35      | 82.4    | 182     | 352     | 417     | 438     | 485     | 492     |
of special diffractive optical element producing a convex shape spot can be complicated; on the other hand, adjusting the convex shape spot output using the well-designed special diffractive optical element is inconvenient. (2) The universal diffractive optical element, which can transform a Gauss beam into a uniform rectangular beam, can be used to generate the convex shape spot by superposing two uniform rectangular spots with different sizes and energy densities. Figure 11 presents a schematic of convex shape beam spot generation through the double-beam superposition of uniform rectangular beam spot.

For the superposition of two uniform rectangular laser beams, the preheating and slow cooling effects of the convex shape spot can be conveniently adjusted by controlling the power of the two laser beams, the spot size, and the central position of the spot. For example, when the center of the rectangular spot with a large size and a low energy density along the scanning direction is located at the front end of the rectangular spot with a small size and a high energy density, the preheating time will be longer than the slow cooling time, and the preheating effect is superior to the slow cooling effect; on the contrary, if the center of the rectangular spot with a large size and a low energy density along the scanning direction is located at the rear end of the rectangular spot with a small size and a high energy density, the slow cooling time is longer than the preheating time, and the slow cooling effect is better than the preheating effect. If the laser scanning speed...
and power remain unchanged while the size of the large spot decreases, the energy density will increase, the preheating and slow cooling temperatures will rise, but the preheating and slow cooling time will decrease. Hence, an extremely small large spot will result in insufficient preheating and slow cooling time, with a limited effect on reducing the residual stress at the clad layer; when the large spot is increased, the preheating and slow cooling time can be lengthened, but the reduction of energy density will decrease the preheating and slow cooling temperatures. Given this, an extremely huge large spot will lead to insufficient preheating and slow cooling temperatures, which is not conducive for reducing the residual stress at the clad layer.

The previous analysis indicates that for the implementation of convex shape spot through double-beam superposition, the power of two uniform rectangular laser beams, the spot size, and the spot action center will exert great influences on the preheating and slow cooling of the clad layer, thus directly affecting the crack controlling effect, so the convex shape beam requires further optimization in follow-up research.

For the crack controlling method by changing the laser energy density distribution (convex shape spot is used), the crack control of the clad layer is synchronously implemented with laser cladding, which is advantageous. In addition, the local heating treatment consumes less energy. Furthermore, it can realize effects similar to preheating and slow cooling without needing any additional device. The implementation and control are quite simple and thus convenient and feasible as a crack control measure for the clad layer. Relative to the special diffractive optical element producing a convex shape beam, when double uniform rectangular beams are superposed, the preheating and slow cooling effects of the convex shape spot can be conveniently controlled by regulating the powers, spot sizes, and action centers of the two uniform rectangular spots in the convex shape spot. Thus, the method is simple and effective.

5 Conclusion

(1) The crack control method for the clad layer, which changes the laser energy density distribution, is proposed in this paper. The effectiveness of laser cladding on plasma-sprayed MCrAlY coating with the laser spot presenting a convex shape energy density distribution in reducing the thermal stress at the clad layer and relieving the crack generation was verified through the numerical simulation method based on the ANSYS finite element software.

(2) The numerical simulation results indicate that compared with the uniform rectangular laser spot, the laser cladding with a convex shape spot exerts preheating and slow cooling effects to some extent, thus reducing the temperature gradient of the laser cladding and non-cladding zones. Under the given parameters, the thermal stress can be reduced by over 10%.

(3) Relative to the laser beam-shaped diffractive optical element for design and manufacturing, the superposition of two uniform rectangular beam spots with different sizes and energy densities is a simple and effective method of acquiring the convex shape beam spot.

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Declarations

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