Single-channel multilayer forming mechanism of laser cladding Fe60 process under different laser heat source working mode

Chang Li (lichang2323-23@163.com)  
University of Science and Technology Liaoning  
https://orcid.org/0000-0002-8882-6055

Han Sun  
University of Science and Technology Liaoning

Junjia Zhao  
University of Science and Technology Liaoning

Xing Han  
University of Science and Technology Liaoning

Research Article

Keywords: Pulsed laser cladding, Light-powder interaction, Single-channel multi-layer cladding, Multi-physics field coupling

Posted Date: October 26th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3313615/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Single-channel multilayer forming mechanism of laser cladding Fe60 process under different laser heat source working mode

Chang Li*,1, Han Sun1, Junjia Zhao, Xing Han
(Chang Li*,1 and Han Sun1 are co-first authors)
(School of Mechanical Engineering and Automation, University of Science and Technology Liaoning, Anshan, Liaoning 114051, China)

*Corresponding author. E-mail address: lichang2323-23@163.com (Chang. Li)

ABSTRACT: Continuous wave (CW) and pulsed wave (PW) are the two principal modes of working to control the laser heat source. Different laser heat source working modes have an essential impact on the rapid cooling and heating temperature change rate during the cladding, which directly determines the cladding layer quality. The laser cladding process is meaningful to quantitatively reveal the mechanism of single-channel multilayer cladding and forming under different laser heat source working modes. In this paper, a multi-field coupled 3D numerical model of the single-channel multilayer cladding process under diverse laser working modes is proposed, and the thermal physical parameters of the cladding material are computed on the basis of CALPHAD method. The mechanism of the impact of distinct working modes on the multi-field coupled ephemeral evolution process of laser cladding is investigated by using the solid/liquid interface tracking technique, which comprehensively considers the light-powder interaction between the powder waist beam and the laser beam in diverse working modes. The temperature, flow and stress fields are computationally solved for a single-channel multilayer cladding process. On the foundation of this study, the mechanism of the impact of pulse duty cycle and pulse frequency on the cladding behavior of single-channel and multi-layers during pulsed laser cladding was dissected. The macroscopic morphology and microstructure of the cladding layer were observed by KEYENCE VH-Z100R ultra-deep field electron microscope, and the feasibility of the model was confirmed. This study provides an important theoretical rationale for enhancing the cladding quality under different laser working modes.

Keywords: Pulsed laser cladding; Light-powder interaction; Single-channel multi-layer cladding; Multi-physics field coupling

1 Preface

Laser cladding technology is an integral part of metal 3D printing, which is capable of repairing the surface dimensions of workpieces and extending their service life through the simultaneous action of laser irradiation on alloy powder and metal surfaces to form metallurgically bonded cladding layers [1]. At present, laser cladding is primarily utilized in industrial fields such as aerospace, defense and automotive ships [2]. The working modes of laser energy sources in laser cladding can be categorized into two types: continuous wave (CW) and pulsed wave (PW). The light source of CW working mode provide uninterrupted energy and continuous light output during working hours. PW working mode light source interval specific time excitation once, working time intermittent light [3]. Conventional laser cladding employs a continuous laser to reinforce the worksurface, and the cladding layer prepared in this manner produces a high number of cracks and porosity defects [4]. To resolve the above mentioned problems, pulsed laser cladding technology can be implemented, which can effectively improvement the cladding quality since the periodic heat input enables to produce less thermal stress and less small hole effect. This paper examines the multi-field interaction mechanism of single-channel multilayer laser cladding under various laser thermal source working modes. The conventional experimental method is characterized by
frequent trial and error, which can only implement single and lagging experimental material science characterization and cannot reveal the impact of various laser working modes on the instantaneous evolving multifield interaction in an effective way. Combining experimental analysis and numerical calculation can not only save a substantial amount of human and material resources, but also effectively reduce the probability of trial and error and shorten the product development cycle [5].

In recent years, numerous scholars at home and abroad have conducted a substantial amount of research on laser cladding. In 2017, Simeng Li et al. formulated as the 3D pulsed laser additive manufacturing model focusing on the action of pulsed waves onto the molten pool according to a level set method. The outcomes indicated that the pulsed wave impacted the molten pool with a more circular shape and a periodic heartbeat motion of the flow speed compared to the continuous wave [6]. In 2018, S Wei et al. coupled the level set and fluid volume to construct a numerical model for single-channel multilayer laser cladding and investigate the instantaneous variation law of continuous laser on the cladding temperature. The outcomes revealed that the temperature of multilayer cladding was higher than that of single-layer cladding at the same acquisition point [7]. 2019, H Liu et al. employed the impacts of preheating temperature and cladding speed on the temperature field of the continuous laser molten pool employing the birth-death unit technique. The proposed approach demonstrated that the temperature elevated with the preheating temperature and declined with the cladding speed. [8]. In 2020, Boxue Song et al. performed numerical simulations of the continuous laser molten pool evolution process at various powers. The analysis indicates that the molten pool size is actively associated to the laser power, and the convection velocity can be controlled by the laser power [9]. In 2021, Boxue Song et al. proposed a numerical modeling methodology to analyze the evolution mechanism by considering the coupling effect between the heat source and the molten pool surface. The outcomes revealed that the flow speed can attain the stationary level within a remarkably rapid period of time, and the molten pool shape is actively associated along to the laser heat source action time [10]. 2022, Wang C et al. computed temperature fields of low-power continuous laser cladding layers and analyzed the temperature distribution at different points. The analysis indicated that the upper the cladding temperature, the superior the quality of solidified cladding layer [11].

In summary, studies associated with laser cladding have primarily concentrated on the numerical calculation of single physical fields such as temperature and flow fields for continuous laser cladding of single-channel monolayers and single-channel multilayers, and flow fields for pulsed laser cladding of single-channel monolayers. The comparative analysis of the single-channel multilayer laser cladding forming mechanism and the multi-field coupling evolution process under various working modes has not been reported, and the temperature change impact of the material thermal property parameters is rarely considered in the modeling calculations. The laser cladding process in different laser working modes is a dynamic physical metallurgical process, which contains complex heat and mass transfer changes [12-14]. The material
physical attributes vary considerably with temperature, and the fields are mutually restrained and associated with each other, so only a single field can not effectively unveil the overall process of cladding. This paper constructs a multi-field coupling numerical model for laser cladding process according with various laser working modes, computes the material thermal physical characteristics on the basis of CALPHAD method, compares and analyzes the transient patterns of temperature, flow and stress fields of single-channel multilayer cladding process under different working modes, and supplies the theoretical foundation for optimizing the cladding process. Different laser working modes impact the multi-field coupling interaction law of laser cladding process as shown in Fig. 1.

![Fig.1 Laser cladding multi-field coupling interaction law](image)

2 Experimental equipment and materials

ASTM 1045 element species are tabulated in Table 1. Fe60 element species are tabulated in Table 2. The laser cladding device in PW working mode is shown in Fig. 2. Using the controlling system, mechanical arm and with the laser system to manipulate the German TongFast disc laser for laser cladding experiments in PW working mode, adopting argon gas as protective gas and powder carrier gas, equipped with water cooling device to cool down the cladding head for protection [15]. The principle of PW working mode laser cladding is shown in Fig. 3. The square wave functions are leveraged to control the laser heat source on and off, enabling it to implement different working modes of cladding, from left to right for first layer cladding and from right to left for second layer cladding. Using polishing machine and aqua regia to polish and etch the profile of the cladding layer, dry and set aside.

<table>
<thead>
<tr>
<th>Table 1 ASTM 1045 elemental composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
</tr>
<tr>
<td>Mass fraction</td>
</tr>
</tbody>
</table>
### Table 2 Fe60 elemental composition

<table>
<thead>
<tr>
<th>Category</th>
<th>Fe</th>
<th>Ni</th>
<th>W</th>
<th>B</th>
<th>Si</th>
<th>Cr</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass fraction</td>
<td>60.2</td>
<td>6</td>
<td>2.2</td>
<td>3.5</td>
<td>2.5</td>
<td>21</td>
<td>4.6</td>
</tr>
</tbody>
</table>

**Fig.2** Laser cladding equipment in PW working mode

**Fig.3** Schematic representation of laser cladding process in PW working mode

### 3 Theoretical model of laser cladding process

The model is founded under the hypothesis that:

1. Laser beam energy density obeys Gaussian distribution;
2. The liquid metal flow is laminar and incompressible Newtonian fluid;
3. The viscous paste region is a porous media region with isotropic properties;
4. Ignore the evaporation effectiveness of the powder and disregard the recoil pressure;
5. The material follows flow and reinforcement guidelines in the plastic zone.

#### 3.1 Temperature field control equation

Energy conservation control equation [16]

\[
\rho W_p u \cdot \nabla T + \rho W_p \frac{\partial T}{\partial t} = -\rho u \cdot \nabla E - \frac{\partial E}{\partial t} + \nabla \cdot (n \nabla T)
\]  

where \( W_p \) is the specific heat, \( n \) is the heat transfer coefficient, and \( \Delta E \) is the latent heat of melting, whose value is

\[
\Delta E = J_y
\]
where \( J_l \) is the liquid phase mass fraction and \( Y \) is the latent heat of phase change [17], expressed as

\[
J_l = \begin{cases} 
1, T > T_{\text{liquid}} \\
\frac{T - T_{\text{solid}}}{T_{\text{liquid}} - T_{\text{solid}}}, T_{\text{solid}} \leq T \leq T_{\text{liquid}} \\
0, T < T_{\text{solid}} 
\end{cases}
\]

(3)

where \( T_{\text{solid}} \) and \( T_{\text{liquid}} \) denote the solid and liquid phase line temperatures, respectively.

To simulate the laser cladding process in various working modes, a modified Gaussian heat source [18] is brought in to account for the masking role on the laser beam by the powder flow to express the heat flux

\[
Q = \psi(t) \frac{2\zeta(1-A)U}{\pi R^2} \exp \left( -\frac{2 \left( \left(x-V_g t\right)^2 + y^2 \right)}{R^2} \right) - \mathcal{Q} (z) 
\]

(4)

\[
\mathcal{Q} = h_c (T - T_{\text{amb}}) + \sigma_b c (T^4 - T_{\text{amb}}^4)
\]

(5)

\[
\psi(t) = \begin{cases} 
1, 0 \leq t \leq I_p \\
0, I_p < t \leq I_c \\
\psi(t + I_c) = \psi(t)
\end{cases}
\]

(6)

\[
I_c = \frac{1}{\omega}
\]

(7)

\[
I_p = I_d I_c
\]

(8)

\[
\Upsilon(z) = \begin{cases} 
0, z \neq 0 \\
1, z = 0
\end{cases}
\]

(9)

where \( \zeta \) is the laser heat flow density absorption rate, \( P \) is the power, \( R \) is the spot radius, \( V_g \) is the cladding speed, and \( T_{\text{amb}} \) is the initial temperature. \( A \) is the laser attenuation rate [19]. \( \psi(t) \) is the pulse signal control function. \( I_p \) pulse duration and \( I_c \) pulse period can be computed from the pulse frequency \( \omega \) and the pulse duty cycle \( I_d \) [20]. The \( \Upsilon(z) \) Dirac function controls the deposition of laser energy on the material surface.

The original temperature of the cladding layer is the indoor temperature

\[
T(x, y, z, t_0) = T_{\text{amb}}
\]

(10)

### 3.2 Flow field control equation

Control equation for mass conservation [21]

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0
\]

(11)

Where \( t \) is time, \( u=(u,v,w) \) is the metal flow speed.

Equation for conservation of momentum [22]
\[ \rho \frac{\partial u}{\partial t} + (u \cdot \nabla)u = -\nabla p + \nabla \cdot (\mu (\nabla u + (\nabla u)^T)) - \frac{2\mu}{3}(\nabla \cdot u)I + N_f \]  

\[ N_f = \rho g \beta (T - T_{s,l}) - S_0 \left( \frac{1 - J_f}{J_f^3} \right)^2 u \]  

\[ T_{s,l} = \frac{T_{\text{solid}} + T_{\text{liquid}}}{2} \]

where \( \mu \) is the hydrodynamic viscosity, \( p \) is the pressure, \( T_{s,l} \) is the melting point temperature, and \( N_f \) denotes the source term [23]. \( S_0 \) characterizes the porous medium morphological constant and \( X \) is a fractional number [24].

Liquid-gas momentum equation boundary conditions [25]

\[ F_{L/G} = \delta n^* \kappa - \nabla T \frac{d\sigma}{dT} \]

where \( \kappa \) is the capillary force and the difference between the thermal capillary force.

Liquid flow speed control by dynamic grid method using solid/liquid interface tracking technology [26]

\[ V_{L/G} = u \cdot n^* + V_z \cdot n^* \]

where \( V_z \) indicates the solid/liquid interface movement speed.

\[ V_z = \frac{2m_\zeta_m}{\rho_m \pi R_p^2} \exp \left( \frac{-2 \left( \left( x - V'_t \right)^2 + y^2 \right)}{R_p^2} \right) \zeta \]

The initial flow speed is 0m/s, i.e.

\[ u(x, y, z, t_0) = 0 \]

### 3.3 Stress field control equation

Plastic strain control equation [27]

\[ \varepsilon'_w = \frac{3(\sigma' - Y')}{2(G(\sigma - Y))} p^+ \]

\[ w^+ = \left( \frac{G(\sigma - Y - U - e)}{E} \right)^n \]

\[ G(\sigma - Y^+) = \frac{3}{2} (\sigma' - Y') : (\sigma' - Y') \]

\[ Y^+ = \frac{2}{3} C\varepsilon'_w - \mu Y' \]

where \( \sigma' - Y' / G(\sigma - Y) \) is the viscoplastic flow direction, \( \sigma' \) and \( Y' \) are the biases of the tensor \( \sigma \) and \( Y \), \( p^+ \) is the strain rate, \( Y \) is the isotropic hardening variable, \( U \) and \( e \) are the kinematic hardening variables, \( E \) is the tensile stress, and \( G \) is defined as the second invariant of \( \sigma \).
Plastic stress control equation [28]

\[
\sigma_v = Z \left( w^+ \right)^{\frac{1}{n}}
\]

\[
\begin{align*}
\varepsilon(x, y, z) &= 0 \\
\sigma(x, y, z) &= 0
\end{align*}
\]  

(23)  

(24)

Where \( Z \) and \( n \) are creep constants, \( \varepsilon \) and \( \sigma \) are strain and stress, respectively, and the initial stress and strain are 0.

4 Construction and resolution of finite element models

4.1 Mesh delineation and parameter choice

The substrate is an iron-based alloy ASTM 1045 and the powder is a carbon structural steel Fe60. Building a 3D laser cladding process thermal-elastic-plastic-fluid multi-field coupled finite element model under various working modes basing on the finite element platform. The free tetrahedral partitioning mesh is applied, containing 190384 domain cells, 24658 boundary cells and 736 edge cells, and the model mesh is partitioned as shown in Fig. 4. Fluid heat transfer, solid mechanics and differential algebraic equation modules are employed to determine the instantaneous temperature, flow and stress fields in various working modes of laser cladding. The model cladding parameters are summarized in Table 3.

Different laser modes of working in laser cladding have a straightforward bearing on the cladding temperature distribution, which affects the macroscopic morphology and mechanical properties of the cladding layer [29]. The instantaneous evolution of the multiphysics field of the laser cladding process was computed for various working modes from 0ms to 3700ms. The data acquisition method is shown in Fig. 4, and five points of acquisition line 1, acquisition line 2, A(4,1.5,0), B(2,0,0), C(4,0,0), D(6,0,0), and E(4,0,-0.5) are selected for data acquisition.

![Fig.4 Data acquisition method](image)

### Table 3 Cladding parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Numerical values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsed laser power U/(W)</td>
<td>1600</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>Scanning speed $V_s$ (mm/s)</td>
<td>3.0</td>
</tr>
<tr>
<td>Powder flow radius $R_p$ (mm)</td>
<td>2.6</td>
</tr>
<tr>
<td>Laser conversion efficiency $\zeta$</td>
<td>0.75</td>
</tr>
<tr>
<td>Pulse frequency $f_p$ (Hz)</td>
<td>16.7, 18.2, 20.0</td>
</tr>
<tr>
<td>Pulse duty cycle $I_d$</td>
<td>2:1, 3:1, 4:1</td>
</tr>
</tbody>
</table>

Molten pool thermal physical parameters and the melted substrate, powder materials has a straightforward association [30]

$$D_b = \Omega_{Fe} D_m + (1 - \Omega_{Fe}) D_p$$  \hspace{1cm} (25)

where the substrate thermal property parameter $D_m$, powder thermal property parameter $D_p$ and mixing fraction $\Omega_{Fe}$ jointly affect the molten pool thermal property parameter $D_b$.

Practice has proved that the change of temperature has a straightforward bearing on the material thermal property parameters, and disregarding the impact of temperature change, the numerical computation outcome will have a significant discrepancy with the actual cladding result. The CALPHAD approach is a computation of the thermodynamic properties of high-component regimes that is grounded in the thermodynamic and kinetic data of low-component material regimes. The calculation flow of CALPHAD method is shown in Fig. 5. By gathering the experimental phase diagram data and crystal structure data, constructing the Gibbs free energy model and optimizing the parameters, the phase diagram and thermodynamic properties of the material are derived. C Li et al. integrated the numerical model to the CALPHAD approach to quantify the impact exerted by the cladding parameters on the multiphysics field of the pulsed laser cladding process, indicating the accuracy and validity by the CALPHAD method computation [31]. Hence, a CALPHAD approach is employed to compute the thermal physical parameters of the material under various working modes of laser cladding. The curves of the thermal physical parameters of the material are shown in Fig. 6.
Fig. 5 Schematic diagram of CALPHAD method

(a) Density  (b) Thermal expansion coefficient

(c) Poisson's ratio  (d) Young's modulus

(e) Thermal conductivity  (f) Specific heat

Fig. 6 Thermal property parameter change curve

4.2 Model computational solving and result analysis

The DELL T5600 tower workstation is employed to computationally resolve the multi-physical field coupling model of laser cladding process under various working modes and obtain the instantaneous evolution of the multi-field coupling of laser
cladding process under various working modes. The function that controls the laser light source is shown in Fig. 7. In CW working mode, the waveform is straight, the light source is constantly on and the laser power remains stable at 1600W. In PW working mode, the waveform is rectangular, the pulse frequency is 20Hz, the pulse width is 40ms. 800ms when the laser thermal source is activated, the wave peak period lasts for 40ms, during which is always in the heating state. At 840ms, the laser heat source is switched off and there is no heat input in the molten pool. After the trough period lasts for 10ms, the laser thermal source is activated again and the above working condition is repeated until the end of cladding.

4.2.1 Computed results of the cladding temperature field for different laser working modes

The pulse duty cycle of 4:1, pulse frequency of 20Hz and laser power of 1600W are optional. The cladding temperature is extracted from 0ms–3700ms molten pool by combining this group of process parameters to compute the cladding temperature in various working modes. The analysis demonstrates a consistent temperature distribution in different working modes. The temperature field of the molten pool is approximately "teardrop-like" in distribution. The temperatures at the same instant of time for the first layer cladding with various laser modes are compared and showed in Fig. 8(a) and Fig. 8(c). Calculations reveal that the maximum temperature in CW working mode is 2818.6K, and the maximum temperature in PW working mode is 2642.6K, which is attributed to the existence of a trough period in PW working mode during the unit time, when there is no heat input and the temperature drops, and the continuous heating by the light source in CW working mode, and the temperature progressively enlarges. In the PW working mode, the pulsed laser cladding wave peak and wave trough cladding temperatures are contrasted as shown in Fig. 8(c) and Fig. 8(d). Calculations indicate that the cladding temperature decreases promptly as the pulsed laser progresses from the wave peak to the wave trough. When in the wave peak period, the highest temperature is 2642.6 K and the minimum temperature is 470.84 K. When in the wave trough, the
maximum temperature is 2132K and the minimum temperature is 473.46K. This is attributed to the continuous energy input from the laser light source to the inside during the wave peak period, which intensifies the thermal motion and increases the temperature.

According to the previous analysis, the impact of various working modes on the cladding temperature is basically the consistency, and the difference is primarily in the high and low temperature. Consequently, this subsection provides a comparative analysis of the temperature distribution of the first and second layer cladding in PW working mode, as exemplified by the wave crest period, as shown in Fig. 8(c) and Fig. 8(g). The computation reveals that owing to the thermal accumulation effect of temperature, the highest temperature of the second layer of cladding is 3047.8 K and the greatest temperature of the first layer of cladding is 2642.6 K. The temperature and heat affected zone of the second layer of cladding are larger than the first layer of cladding.
In purpose to uncover the mechanism of multi-physics field coupling transient evolution of laser cladding in various working modes, a group of data was extracted at 600ms intervals to evaluate the transient evolution of temperature under various acquisition trajectories. Fig. 9 indicates the comparison curve of temperature variation along the acquisition trajectory 1. Fig. 9(a) represents the temperature instantaneous change curves of the first layer cladding in various working modes. The calculations indicate that the trend of cladding temperature changes in various working modes is generally consistent, and the temperature exhibits an apparent single-peak distribution, with the highest cladding temperature progressively increasing as the cladding proceeds, and the closer the spot temperature is, the higher it is. At the same moment, the cladding temperature in CW working mode is higher than that in PW working mode. This is attributed to the continuous heating by the heat source in CW mode of work and the periodic variation of the heat source in PW mode of work, where there is a cooling period during the heating. A small decrease in the maximum temperature of the blue dashed line (trough period) compared to the highest temperature of the blue solid line (wave peak period) is evident in the magnified region, which is a consequence of the periodic thermal import from the laser heat source. The maximum temperature of the orange dashed line is instead slightly higher than the maximum temperature of the solid line, which is the result of the continuous thermal import from the laser heat source. Fig. 9(b) demonstrates the transient change profile of the second layer cladding temperature for various working modes. Calculations reveal that the temperature trend of the second layer of cladding is approximately the same as that of the first layer of cladding, so we will not elaborate too much here. Since the first layer of cladding has a preheating role on the second layer of cladding. As a result, the overall temperature of the second layer of cladding is greater. In the enlarged area, it can be noticed that in PW working mode, the cooling effectiveness produced by the trough period is weakened, when the cladding temperature remains stable, but the overall cladding temperature is still lower than that in CW working mode.
Fig. 10 illustrates the comparison curve of temperature change of acquisition trajectory 2. Fig. 10(a) and Fig. 10(b) indicate the temperature instantaneous variation curves of the first layer cladding and the second layer cladding for various working modes, respectively. Calculations reveal a centrosymmetric distribution of the cladding temperature, owing to the forming that the second layer of cladding is formed upon the first layer of cladding. Thus, the heat accumulation impact from the first layer of cladding will directly affect the second layer of cladding temperature. The whole temperature of the first layer is lower and the overall temperature of the second layer is higher.

Fig. 11 indicates the comparison curves of temperature variation at different acquisition points. The calculation demonstrates that the cladding temperature in PW mode fluctuates with equal amplitude, and the cladding temperature in CW mode is smoother, and the overall trend of the cladding temperature is basically the same for both at the same acquisition point. The difference is that the cladding temperature is higher in CW working mode. Hence, the PW working mode is chosen for analysis in this subsection. As revealed by the diagram, the cladding temperatures at point B, point
C and point D exhibit an obvious single-peak distribution and periodically move forward as the cladding proceeds, with the highest cladding temperature at point A being lower than that at point C. Before 2000ms, the temperature at the four points fluctuated with equal amplitude, and after 2000ms, the temperature fluctuated less. This is attributed to the absence of preheating of the substrate before the cladding. When the high-energy laser beam irradiates the molten pool, a greater temperature gradient is generated inside the substrate, which leads to a drastic temperature change, and in the late stage of the cladding, the thermal accumulation effect generated by the first layer of cladding produces a certain preheating role for the second layer of cladding, which results in a flat temperature change. The temperature change of cladding at point E is small.

![Fig. 11](image-url)

**Fig.11** Comparison curve of temperature change at various acquisition points

Since the wave peak and wave trough periods only impact the magnitude by which the cladding temperature and do not alter the trend of the cladding temperature, this subsection takes the temperature of the second layer of the cladding during the wave peak period for analysis. Fig. 12 represents the temperature field instantaneous variation curves along the 3690ms moment of acquisition trajectory 1 in various working modes. The calculation demonstrates that the cladding temperature in CW working mode is higher than that in PW working mode. This is explained by the fact that in CW mode, the laser thermal source continues to heating the molten pool which gradually elevates the cladding temperature, and in PW mode there is a wave trough period when the laser thermal source is shut off and the molten pool is in a state of naturally cooling and the cladding temperature declines. Fig. 12(a) indicates the variation curve of cladding temperature with various pulse duty cycle. The calculation reveals that the cladding temperature exhibits an explicit single-peak profile, and the cladding temperature decreases with the diminishing duty cycle of the pulse. This is because of the decrease in heating time in the same cycle owing to the decline in pulse duty cycle, resulting in a decrease in the cladding temperature. Fig. 12(b) illustrates the variation curve of the cladding temperature for various pulse frequencies. Computations demonstrate that the cladding temperature is associated with the pulse frequency, which is attributed to the fact that an increase in pulse frequency per unit time leads to an enlargement of the
number of times the laser heats, which increases the cladding temperature.

![Graph](image)

(a) Pulse duty cycle  
(b) Pulse frequency

**Fig. 12** Acquisition trajectory 1 temperature change comparison curve

Fig. 13(a) and Fig. 13(b) demonstrate the instantaneous change curves of temperature field along the 3690ms moment of acquisition trajectory 2 for various pulse duty cycles and pulse frequencies, respectively. Calculations indicated that the cladding temperature declined remarkably as the pulse duty cycle reduced, and the decline in cladding temperature was more moderate as the pulse frequency decreased. When the pulse duty cycle is 2:1, the maximum cladding temperature is about 1520K, and when the pulse frequency is 16.7Hz, the maximum cladding temperature is about 1580K. It is judge that the change of pulse duty cycle has more impact on the cladding temperature, and the alteration of pulse frequency has fewer impact on the cladding temperature.

![Graph](image)

(a) Pulse duty cycle  
(b) Pulse frequency

**Fig. 13** Acquisition trajectory 2 temperature change comparison curve

Fig. 14 depicts a comparative graph for instantaneous temperature variation at acquisition point A with the impact of various working modes and different process parameters. The computations reveal an overall "hump" distribution of the cladding temperature for the different working modes as the cladding proceeds. In CW working mode, the cladding temperature changes more smoothly, while in PW working mode,
the temperature is more obviously affected as a result of pulse changes, which exhibits periodic amplitude fluctuations. The first layer temperature amplitude fluctuates greatly, the second layer cladding temperature amplitude fluctuates less, and the highest temperature for the second layer of cladding is larger than the first layer of cladding. The reason for this is that the energy produced by the first layer is not completely diffused in time, and as the resource from the previous laser still is residual from the material when the new laser arrives, the energy is accumulated and the cladding temperature progressively elevates.

![Graphs showing temperature changes with pulse duty cycle and frequency](image)

Fig. 14 Comparison curve of temperature change at acquisition point A

4.2.2 Computed results of the flow field in different working modes

The moment the laser irradiates the powder, the powder and the substrate absorb a substantial portion of the heat and form a molten pool. Nevertheless, the molten pool is not in a stationary condition. The flow of the molten pool is mainly controlled by the Marangoni flow, the gravitational force inside and the solidification phase change, among which the gravitational force and the solidification phase change are inherent properties of the material [32]. The Marangoni flow is controlled by the temperature gradient, and the alloying elements as well as the fluid in the molten pool are actually in a real-time flow state. Practice has proven that various working modes of the heat source have a straightforward affect on the interior of the molten pool, thus changing the degree of refinement of the internal tissue grains and the mechanical properties of the cladding layer. It is essential to disclose the impact on the molten pool under the impact of various working modes. The formation principle of the molten pool is shown in Fig. 15. Control whether thermal transfer is heat conduction or heat convection can be evaluated by Peclet number [33]. Peclet computation formula

\[ P_{ec} = Re \times Pr \]  \hspace{1cm} (26)

where \( Re \) is the Reynolds number and \( Pr \) is the Prandtl number.
Choose a pulse duty cycle of 4:1, pulse frequency of 20Hz, and laser power of 1600W. The computational solution for the molten pool flow velocity in various working modes is carried out with the combination of this set of process parameters to extract the molten pool flow velocity outcomes from 0ms to 3700ms. The flow velocities at the same moment of cladding the first layer for different laser modes are compared and shown in Fig. 16(a) and Fig. 16(c). Calculations demonstrate that two white elliptical arcs represent the solid phase line and the liquid phase line from the outside to the inside, respectively. Due to the circulating Marangoni effect, the fluid flows from the center to the periphery of the molten pool. This is because of the drastic temperature change and significant decrease in temperature at the edge of the molten pool, and the fluid on both sides and the solid substrate squeeze and collide with each other, forming a region of higher flow speed. The flow speed is symmetrically distributed in an "ellipsoidal" shape with respect to the laser cladding path. The maximum flow speed in CW working mode is 0.33m/s, and the molten pool size is about 6.5×5.5×1mm. The highest flow velocity in PW working mode is 0.31m/s, and the molten pool size is about 5×5×0.7mm. This is attributable to the continuous heating in CW mode of operation per unit time, and the existence of a wave trough period in PW mode of operation, when the laser thermal source is off and no external factors interfere, the temperature drops, the flow speed decreases, and the molten pool size diminishes.

The PW working mode is applied as an example for molten pool flow field analysis. Fig. 16(c) and Fig. 16(d) indicate the flow field clouds during the peak and trough periods, respectively. Calculations demonstrate that the flow speed during the wave peak period is higher than the flow speed during the wave trough period. As there is no externally acting laser, the central part of the molten pool shifts back during the wave trough period, and the central region with a flow speed of 0 m/s enlarges and the flow speed stabilizes at 0.2 m/s, indicating that a portion of the flow speed remains in the molten pool after the heat source is turned off during the wave trough period. This is attributed to the residual of the flow speed in the preceding wave peak period still in the wave trough period. This fluctuation of the periodic variation of the flow speed has a
better ability to regulate the internal flow. Fig. 16(c) and Fig. 16(g) illustrate the flow field clouds for the first and second layer of the fusion cladding, respectively. Calculations reveal that the maximum flow speed of the first fusion cladding layer is 0.31 m/s, and the molten pool size is about 5×5×0.7 mm. The maximum flow rate of the second fusion cladding layer is 0.36 m/s, and the molten pool size is about 5.5×5.3×0.9 mm. This is owing to the cumulative impact of the heat generated by the first layer of cladding which affects the second layer of cladding, the second layer of cladding increases in temperature, the flow speed enlarges and the molten pool size grows. During the same period of time, the molten pool flow speed and size are larger in CW working model than in PW working model, which will not be described too much here.

![Flow velocity distribution clouds in various working modes](image-url)

Fig.16 Flow velocity distribution clouds in various working modes
Fig. 17 indicates the comparison of the instantaneous flow speed variation at the collection point A of the first layer of cladding under the impact of various working modes and different process parameters. Fig. 17(a) and Fig. 17(b) indicate the molten pool flow speed profiles under the impact of different pulse duty cycles and various pulse frequencies for the first layer of cladding, respectively. The calculations reveal that the flow field exhibits a decline for different working modes. The molten pool flow velocity in CW working mode is faster than PW working mode due to the existence of an air-cooling period in PW working mode, where the temperature decreases and the flow velocity diminishes. The flow speed at the acquisition point A progressively reduces as the cladding proceeds. In the PW working mode, the flow speed exhibits obvious periodic changes, and the flow speed is positive associated with the pulse duty cycle and pulse frequency, which is attributed to the enlarge of heat source excitation duration and pulse excitation number per unit time, and the elevated temperature leads to higher buoyancy and increased flow speed.

Fig. 18 illustrates the comparison of the instantaneous flow speed variation at the acquisition point A of the second layer fusion under the impact of different working modes and various process parameters. Fig. 18(a) and Fig. 18(b) indicate the molten pool flow speed profiles under the impact of different pulse duty cycles and various pulse frequencies for the second layer of cladding, respectively. The calculations demonstrate that the flow speed tends to increase in CW working mode. In PW working mode, compared with the "trapezoidal" distribution of the flow velocity in the first layer, the "conical" distribution of the flow velocity in the second layer is complicated by the variation of the flow velocity. The flow speed magnitude diminishes with enhancing pulse duty cycle and pulse frequency. In the second layer of cladding, the characteristics of the wave peak period have disappeared from the curve, and only the magnitude of the flow velocity can reflect the characteristics of the action of the wave peak period. This is attributable to the fact that the first layer of cladding has a preheating impact on the second layer of cladding, which makes the action effectiveness of the wave period weaker.
4.2.3 Computed results of stress field in different working modes

Due to the various working modes of the laser light source, the heat input per unit time will change greatly, making different temperature gradients inside the specimen. Inconsistent cooling rate of substrate and powder, resulting in thermoplastic deformation and formation of residual stresses [34]. Different process parameters and various working modes result in distinct cladding temperatures, which leads to more complex thermal stress variations and has a straightforward impact on thermal stress formation. This paper computes the evolution of thermal stresses in laser cladding under various process parameters and different working modes to supply a theoretical rationale for enhancing the quality of the cladding layer.

Choose a pulse duty cycle of 4:1, pulse frequency of 20Hz, and laser power of 1600W. The thermal stresses in various working modes were computationally resolved with this group of process parameters, and the stress fields from 0ms to 3700ms in the specimen were extracted, as shown in Fig. 19. The computations demonstrate that the stress distribution is approximately the consistency for different working modes. The cladding stresses at the same moment of cladding the first layer for dissimilar laser modes are compared and shown in Fig. 19(a) and Fig. 19(c), respectively. The maximum stress in CW working mode is 353 MPa and the highest stress in PW working mode is 348 MPa, which is due to the existence of cooling period in PW working mode and continuous heating of the molten pool in CW working mode with higher cladding temperature and greater stress value per unit time. In PW working mode, as shown in Fig. 19(c) and Fig. 19(d). When in the wave peak period, the largest stress in the front end of the molten pool is about 330MPa, when in the wave trough period, the maximum stress is about 205MPa, which is attributed to the laser light source is no longer heating the molten pool in the wave trough period, the stress is lowered.

The accumulated heat from the first layer of cladding has a direct affect on the second layer of cladding. According to the previous analysis, the effect on the cladding stress is fundamentally the same for different working modes, and the difference is mainly in the magnitude of the stress value. Consequently, this subsection analyzes the
stress distribution of the first layer fusion and the second layer fusion as an example of the wave trough period in PW working mode, as shown in Fig. 19(d) and Fig. 19(h). The first fusion cladding layer spot behind the stress is contraction-like distribution, the spot in front of the dispersion distribution, the second layer of fusion cladding spot behind the stress contraction is not obvious, the stress distribution is more uniform. The greatest stress of the first layer of cladding is 348 MPa, and the greatest stress of the second layer of cladding is 360 MPa. This is owing to the accumulated thermal effect produced by the first layer of cladding acting on the second layer of cladding, where the temperature of the second layer of cladding is raised and the stress distribution area and stress values become larger.
Fig. 19 Stress distribution clouds in different working modes

Fig. 20 depicts the instantaneous variation curves of the cladding stresses extracted along the acquisition trajectory 1 for different cladding layers. Fig. 20(a) indicates the stress instantaneous change curves of the first layer fusion cladding in various working modes. The calculations reveal that the cladding stresses in various working modes are significantly bimodal and periodically shifted forward, the stress in the center is 0 MPa, the size of the region with 0 MPa progressively becomes larger as the cladding proceeds. At the moment of 1190ms, the stress-free area is 1.2mm in CW working mode and 1mm in PW working mode, which is due to the periodic heat input in PW working mode leading to a lower temperature at the same moment and the formation of a smaller molten pool with a smaller stress-free area. Fig. 20(b) demonstrates the stress instantaneous variation curves of the second layer fusion cladding in different working modes. The calculation reveals that the trend of the second layer cladding stress is roughly the same as that of the first layer cladding stress, which is not repeated here. Nevertheless, the second layer is computed on the basis of the first layer. The first layer has a certain preheating role on the second layer, and the cladding temperature is accumulated and remains stable in the later stages of cladding. As a consequence, the area where the second layer is clad with a stress of 0 MPa is also larger and the area size remains constant, with a stress-free area of 1.5 mm in CW working mode and 1.3 mm in PW working mode.

Fig. 21 demonstrates the instantaneous variation curves of the cladding stresses extracted along the acquisition trajectory 2 for different cladding layers. Fig. 21(a) and Fig. 21(b) indicate the stress instantaneous variation curves for the first layer fusion cladding and the second layer fusion cladding under various working modes, respectively. The calculation reveals that the stress value changes are more complicated, and at 4 mm, the stress shows a trend of enlarging first, then diminishing and finally expanding. At the same moment, the stress affects a wider range in CW working mode and a narrower range in PW working mode. In the same position, the first layer is less affected by the cladding stress and the second layer is more affected by the cladding.
Fig. 21 Acquisition trajectory 2 stress change comparison curve

Fig. 22 depicts the comparative graph of the instantaneous stress variation at acquisition point A under the impact of various working modes and different process parameters. Calculations demonstrate that as the cladding proceeds, the cladding stress in the PW working mode fluctuates with equal amplitude, with a large change in the cladding stress in the first layer and a small change in the cladding stress in the second layer. The cladding stresses in the CW mode of work are smoother, and the overall trend of the cladding stresses is virtually the same for both. Before 0ms~2300ms, the cladding stress progressively enlarges, at 2300ms~3300ms, the cladding stress appears a "V" change, and at 3300ms~3700ms, the cladding stress diminishes slightly. The maximum stress value in CW working mode is greater than that in PW working mode. This is attributed to the increase in stress due to the continuous heating by the laser source in CW working mode and the elevated cladding temperature. The laser light source in PW working mode is cyclically heating the molten pool. During the wave trough period, the laser light source is turned off and the molten pool is in a natural cooling state, the temperature drops and the stress is diminished. Fig. 22(a) plotted the stress variation curve for various pulse duty cycles. The cladding stress grows with the increase of pulse duty cycle. This is attributed to the enlarged time of laser heating the molten pool caused by the enhanced pulse duty cycle, enlarged cladding temperature and increased cladding stress. Fig. 22(b) plotted the stress variation curve at different pulse frequencies. The cladding stress is positive related to the pulse frequency, which is explained by the fact that the lower the pulse frequency, the fewer times the laser source heats the molten pool per unit time, the lower the cladding temperature and the decrease of the cladding stress. The greatest cladding stress of the second layer is larger than the maximum cladding stress of the first layer owing to the preheating role of the first layer cladding on the second layer.
5 Laser cladding experiments in different working modes

The experimental test block is shown in Fig. 23. The "water ripple"-like cladding layer is uniformly distributed on the surface of the substrate, and the macroscopic morphology of the cladding layer is excellent. The macroscopic contour morphology of the laser cladding layer in PW working mode was characterized by using KEYENCE VH-Z100R ultra-deep field electron microscope, and the experimental apparatus is shown in Fig. 24. The CW macroscopic surface profile of the cladding layer is shown in Fig. 25. The outcome reveals that the surface defects in the macroscopic profile of the cladding layer are relatively large and the surface roughness is relatively large. The PW macroscopic surface profile of the cladding layer is shown in Fig. 26. The outcome reveals that the macroscopic profile of the cladding layer has an apparent "water ripple" distribution, with uniform and continuous ripples, no significant pores, cracks and other surface defects.
The periodic variation of the pulsed laser light source has a remarkable impact on the behavior of the solidification phase change of the cladding layer [35]. Fig. 27 depicts the impact of morphological parameters and cooling rate on the microstructure [36]. The lower the morphological parameter, the blockier the cooling rate and the denser the solidification organization. The temperature gradient $D$ and the migration rate $M$ are the two primary factors affecting the structure of the solidified tissue [37-38]

\[
\begin{align*}
D &= \frac{\Delta T_x}{\Delta x} \\
M &= V \cos \alpha
\end{align*}
\]  

(27)

where $\Delta T_x$ is the temperature change and $\Delta x$ is the distance.

The proximity to the top of the molten pool diminishes the alpha angle and enlarges the $M$ value. Accordingly, the molten pool solidification growth rate degrades from the surface to the bottom [39]. From the bottom to the top, the angles of $M$ and $V$ are taken to be 75°, 45° and 15° respectively for computation. The temperature gradient $D$ is determined by model computation, as shown in Fig. 28, with points A, B and C simulating the values of $D$ at the top, middle and bottom of the cladding layer, respectively. $M$ can be obtained from the cooling rate $D \times M$ and the shape control factor $D/M$. The predicted parameters of the molten pool microstructure at various positions are summarized in Table 4.
Table 4 Prediction parameters

<table>
<thead>
<tr>
<th>Position</th>
<th>$D\times M$(K/s)</th>
<th>$D/M$(Ks/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dot A</td>
<td>4926.6</td>
<td>586.6</td>
</tr>
<tr>
<td>Dot B</td>
<td>2757.7</td>
<td>612.8</td>
</tr>
<tr>
<td>Dot C</td>
<td>854.0</td>
<td>1416.8</td>
</tr>
</tbody>
</table>

Fig. 28 D-value computational cloud chart

Fig. 29 Microstructure

The microstructure of the cladding layer is shown in Fig. 29. Comparing the theoretical results with the experimental results, point A is located at the top, where the coexistence of fine and equiaxed dendrites with lower $D/M$ and higher $D\times M$ can be observed. Point B is located in the dendrite region, where cellular dendrites can be visualized. point C is located at the bottom, where planar crystals can be visualized, with higher $D/M$ and lower $D\times M$. The experimental outcomes are consistent with the theoretical results of the field, fully verifying the validity and accuracy of the model.

In purpose of detecting the mechanical properties cladding layer in PW working mode, the HV-1000 micro hardness tester was utilized to examine the hardness of the specimen at various locations, as shown in Fig. 30(a). The Vickers hardness inspection outcome is shown in Fig. 30(b), and the outcomes indicate that the highest hardness of the cladding layer is 712.9 HV and the lowest hardness is 663.3 HV. The maximum hardness of the substrate is 630.1 HV and the minimum hardness is 570.7 HV. The hardness of the cladding layer is higher than that of the substrate.
To better compare the differences in hardness of specimens under CW working mode and PW working mode, the composition diagram is shown in Fig. 31. The results show that the hardness of CW laser cladding is significantly different from that of PW laser cladding. The average hardness of PW laser cladding is higher than that of CW laser cladding, which are 593.4 HV and 580.2 HV, respectively. This shows that PW laser cladding technology has a better effect on improving the hardness of materials.

Uneven surface of the cladding layer can be caused by plastic deformation and high frequency vibration of the workpiece during laser processing. The surface roughness of the cladding layer was inspected using the JB-8C measuring instrument, as shown in Fig. 32. In the experimental results, the roughness comparison between CW laser cladding and PW laser cladding is shown in Fig. 33. The results show that the arithmetic mean deviation of CW contour is larger than that of PW contour, which are
Ra=2.128μm and Ra=1.602μm, respectively. In contrast, under the same process conditions, the quality of the surface cladding layer under PW working mode is better.

Fig.32 Roughness measuring instrument

Fig.33 Roughness test outcome in different working modes

6 Conclusions

(1) A multi-field coupled numerical model for single-channel multilayer laser cladding in various laser working modes has been formulated, and the temperature, flow and stress fields of the cladding process have been computed and analyzed for comparison. Calculations reveal that the temperature, flow rate and stress are greater in the CW mode of working than in the PW mode of working at the same moment. The cladding multiphysics field changes smoothly in CW mode of working, and the multiphysics field fluctuates periodically in amplitude in PW mode of working.

(2) The first layer of cladding provides a definite preheating function on the second layer of cladding. The temperature, flow speed and stress are greater during the wave peak than during the wave trough in the PW working mode. The fluctuation of temperature, flow speed and stress amplitude of the first layer is enlarger than that of the second layer.

(3) The PW macroscopic contour of the cladding layer is apparently "water ripple" distribution, no significant surface defects. At the same time, the macroscopic contour, experimental hardness and roughness under CW and PW working mode are compared. The results show that PW laser cladding has a better effect on improving the hardness of
the material under the same process conditions, and the quality of the surface cladding layer under PW working mode is relatively significant. This research offers an essential theoretical foundation for optimizing the cladding quality under the different laser working modes.

**Declarations**

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Author contributions**

Chang Li acquired the grant and revised the paper; Han Sun performed modeling and wrote the paper; Junjia Zhao extracted and analyzed the data; Xing Han checked the grammar.

**Data availability**

The data that supports the findings of this study are available within the article.

**Funding**

This work was supported by Applied Basic Research Program of Liaoning Province (2023JH2/101300226).

**References**


https://doi.org/10.1016/j.matdes.2017.01.065

https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.164

https://doi.org/10.1007/s00170-018-2740-0

https://doi.org/10.1080/10407782.2020.1777795

https://doi.org/10.1016/j.ijthermalsci.2020.106579

https://doi.org/10.1016/j.optlastec.2021.107843

https://doi.org/10.1016/j.addma.2022.102708

https://doi.org/10.1016/j.optlastec.2020.106287

https://doi.org/10.1007/s001700070039

https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.031

https://doi.org/10.1016/j.pmatsci.2017.10.001

https://doi.org/10.1016/j.addma.2020.101175


https://doi.org/10.1007/s00339-022-06362-7

https://doi.org/10.3390/mi14020493

https://doi.org/10.1007/s00170-023-11155-0

https://doi.org/10.1007/s00170-022-10518-3

https://doi.org/10.1007/s10762-021-03043-x

https://doi.org/10.1016/j.ijhydene.2021.11.221

https://doi.org/10.1016/j.ijhydene.2014.01.041

https://doi.org/10.1016/j.ijhydene.2015.12.044

https://doi.org/10.2351/1.4983235