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Effect of Scanning Strategy on Microstructure Evolution and Stress Control in Laser Cladding Repair of Ti6Al4V Alloy

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Abstract: Laser cladding provides a cost-effective and high-quality solution for repairing aircraft engines. A finite element model was developed in this study to simulate and analyze the stress distribution during the cladding of a complex curved groove structure made of Ti6Al4V. The mechanism underlying the microstructure at the interface was revealed. The stress concentration locations in the curved groove structure are located at the intersection of the cladding layer and sidewall, as well as at both ends of the cladding layer and the groove bottom. By applying reverse swing scanning, a more consistent distribution of stress fields can be obtained. Optimizing the scanning strategy reduced the maximum stress in the repair layer from 717 MPa to 711 MPa. The experimental stress distribution data are in good agreement with the computational results. The cladding layer undergoes changes in heat cycling and nucleation conditions, leading to the formation of alternating columnar and equiaxed grain morphologies.

Keywords: laser cladding repair; curved groove structure; numerical simulation; stress distribution; titanium alloy



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1. Introduction

Titanium alloy has the advantages of low specific gravity, high specific strength, high specific stiffness, good corrosion resistance and excellent high-temperature mechanical properties [1,2], and is widely used in aerospace, chemical, metallurgy, energy, medical and health fields [3–5]. In the aerospace field, the application of titanium alloy mainly includes aircraft structural parts such as fuselage and landing gear, as well as compressor discs, drums, compressor blades, etc. [6–8]. In recent years, the proportion of titanium alloys used in military and civil aircraft has been increasing. In high thrust weight ratio aero-engines, the proportion of titanium alloys used has reached 25% to 40%. The quality of the blades as the core components of the engine directly affects the performance of the entire engine [9,10]. Currently, engine rotor blades are mainly manufactured using the method of integral blade discs. This method can effectively reduce the weight of the rotor and improve the service life and operating efficiency of the rotor. However, when partial damage occurs to the blade disk, due to its integrity, the entire rotor will be scrapped, resulting in a large amount of material waste. Currently, the replacement cost is approximately five times that of the maintenance. Stress concentration is an important factor leading to the generation of fatigue cracks and reduction in fatigue life [11,12]. Therefore, studying the stress distribution of titanium alloy engine blades during maintenance is of great significance for regulating stress and improving blade life. Laser cladding technology has the advantages of a high degree of process automation, low thermal stress and high material utilization [13–16]. It is a reasonable way to repair the surface of metal components such as titanium alloys [17].

Titanium alloy blades are subject to multiple external forces and fields such as high temperature, thermal alternating, vibration and alternating loads in complex working

environments, and are prone to multiple damages such as wear, corrosion and creep [18]. Liu Jiakun [19] conducted a diffusion welding repair study on DD3 nickel-based superalloy single crystal blades and GH4169 forged disk. The DD3 blade was combined with the GH4169 wheel disc × heat in a vacuum of 10^{-3} Pa to 1150 °C for 1 h, applying a bonding pressure of about 30 MPa, and then cooling it in a vacuum chamber to finally achieve a solid phase connection between the blade and the disk. The results showed that during the repair process, the size of the entire diffusion region was 35 μm. From DD3 nickel-based superalloy single crystal blades to the interface, the γ' phase gradually changes from a cubic shape to a smaller cylindrical shape, and its size also decreases, mainly due to the influence of concentration gradient changes. In addition, in the diffusion zone, due to the strengthening effect of fine crystal precipitation, its hardness reaches 6.4 GPa, but its strength decreases compared to the base metal, which was 433 MPa. In the same year, Galilea [20] adopted SLM (selective laser melting) to optimize post-processing for the microstructure and defects in the repair process of nickel-based alloy blades and proposed an economical repair method. It was found that after overall HIP heat treatment and subsequent aging treatment, SLM samples produced two types of TCP precipitates, the first being a μ or Laves phase, and the second being Ta/Ti carbide. In addition, short aging heat treatment can obtain a refined γ/γ' phase.

The multiple melting and solidification of the cladding layer and its surrounding areas, as well as the expansion, contraction and mutual restraint of materials, have led to the generation of and change in stress [21–25]. Currently, the stress issue has become one of the main issues restricting laser cladding repair and its large-scale use [26]. In 2017, Mohammad K. Alam [27] conducted a study on the stress distribution during laser cladding of AISI420 martensitic stainless steel. It was found that the hardness and stress of the sample increased with the increase in laser power and scanning speed. In addition, the cooling rate during laser cladding can lead to eutectic δ and the formation of phases such as ferrite, martensite, austenite and metal carbides. In 2014, Parisa Farahmand [28] used a combination of experimental and simulation methods to study the distribution of temperature and stress fields in high-power direct diode lasers (HPDDL) during the cladding process of single and multi-layer multi-channel samples. It was found that the temperature gradient and cooling rate in this method are very smooth, which can better control the stress level of the cladding layer. In multi-layer and multi-pass specimens, the stress distribution is concentrated in the overlapping area of adjacent cladding layers and the connection with the base metal. At the same time, due to multiple cycles, greater stress concentration occurs in the subsequent cladding layer. In 2019, Sun [29] established a three-dimensional finite element model of temperature and stress fields during laser cladding. The results show that high temperatures and large thermal gradients can occur near the heat source, which is prone to stress generation. Due to the large plastic tensile deformation of materials, the longitudinal stress during laser cladding is very sensitive to crack propagation. The coating is prone to cracking along the vertical scanning direction.

The repair process involves complex thermal cycles. High heat input usually leads to deformation, impacting the quality of the repaired area. However, the research on the stress field of laser cladding repair mainly focuses on flat plates and simple components and mostly focuses on the stress field after the completion of cladding. Few studies address stress variations in complex components and cladding procedures. Thus, this study explores how the scanning strategy influences stress distribution through heat input control. It utilizes finite element simulations and experiments to analyze stress distribution and microstructural changes during the repair process.

2. Experiment

2.1. Materials and Equipment

In this experiment, Ti6Al4V with a size of 60 mm × 30 mm × 10 mm was selected as the substrate material, and its microstructure and morphology are shown in Figure 1. Ti6Al4V in this study undergoes annealing at 750 °C for 2 h. At room temperature, Ti6Al4V is $\alpha + \beta$ Biphasic structure. The chemical composition of the Ti6Al4V powder substrate is shown in Table 1. Ti6Al4V powder is prepared by vacuum atomization with a particle size of 75–130 μm . The powder morphology and specific element distribution are shown in Figure 2. The main components of Ti6Al4V are Ti, Al and V. Before conducting laser cladding repair experiments, Ti6Al4V powder needs to be placed in a vacuum drying box for drying and dehumidification to prevent moisture content in the powder from affecting the experimental process.

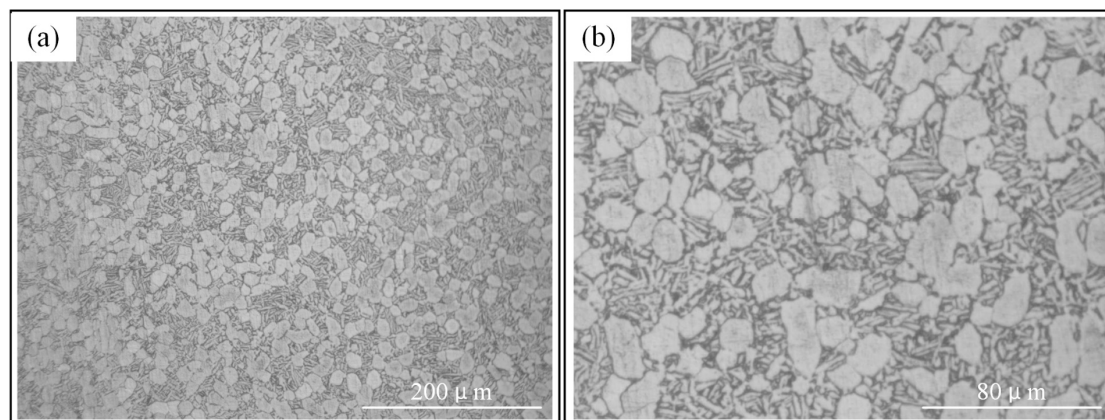


Figure 1. Microstructure of Ti6Al4V substrate: (a) 200 $\times$; (b) 500 $\times$.

Table 1. Chemical composition of Ti6Al4V powder (wt%).

Composition	Al	V	Fe	C	N	H	O	Ti
wt%	5.5–6.8	3.5–4.5	0.30	≤0.10	≤0.05	≤0.20	0.015	Bal.

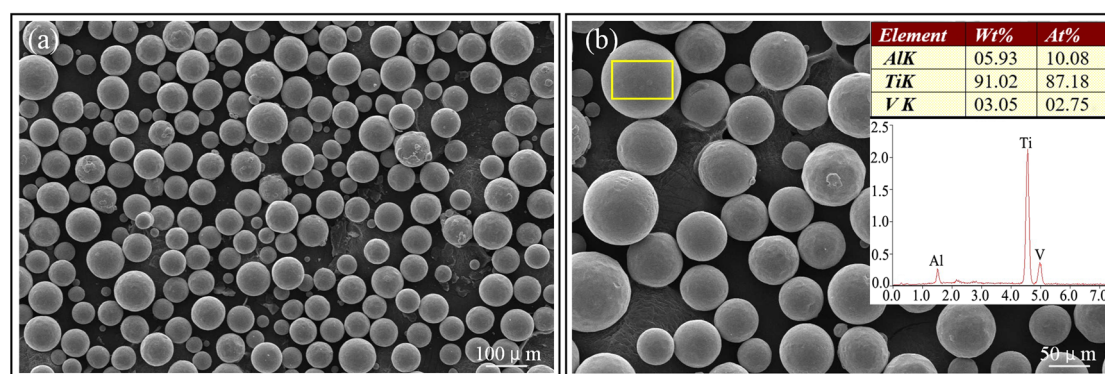


Figure 2. SEM images of Ti6Al4V powder: (a) powder morphology; (b) distribution of different components in Ti6Al4V powder.

The laser cladding experimental equipment specifically includes an RFL-C6000 fiber laser with a maximum output power of 6000 W from Wuxi Rayke fiber Laser Technology Co., Ltd. in Wuxi, China and a KUKA robot model KR60 produced by Kuka Robot (Shanghai) Co., Ltd. in Shanghai, China. The front end of the robot is equipped with a laser powder coaxial cladding head, which can achieve laser cladding experiments under coaxial powder feeding. The powder feeding equipment is an intelligent airborne dual

cylinder powder feeder, which can effectively achieve stable mixing and conveying of different powders, with a maximum powder feeding capacity of 60 g/min. During the experiment, the circulating water cooling system is always turned on to ensure the cooling effect of the laser. To prevent oxidation of Ti6Al4V during laser cladding and repair due to the influence of air, 99.99% purity argon is used to control the atmosphere during the entire manufacturing process. In the direction of laser powder coaxial conveying, a protective gas conveying system is added. At the same time, a special sealing chamber with a size of 600 mm × 300 mm × 350 mm was designed according to the size of the prepared component.

2.2. Manufacturing Process

In this experiment, laser cladding technology was used to repair damaged Ti6Al4V. The specific repair process is divided into two steps, namely, the surface processing of the Ti6Al4V plate and the laser cladding and filling process of the groove. First, the upper surface of the Ti6Al4V substrate is processed into a curved surface by a milling machine, and then a groove is cut at 30° on the curved surface. The component to be repaired is shown in Figure 3. After that, the established groove model is imported into the layered slicing software. After setting relevant parameters, the scanning path is automatically generated, and the code is exported to the KUKA robot teaching device to obtain the robot's motion path. Finally, applying laser cladding technology and a high-energy density laser as the sole heat source, the metal powder is coaxially coupled to the laser output and the substrate is melted into a liquid molten pool, cooled and solidified to form a deposition layer, which is deposited layer by layer until the entire groove is filled, thereby completing the repair process. The experimental principle of the laser cladding repair process for Ti6Al4V is shown in Figure 4. Process parameters are shown in Table 2. According to the previous studies [2,30], this process is chosen to repair TC4.

Before conducting laser cladding repair experiments, the Ti6Al4V substrate is pre-treated to remove impurities such as oxide films, debris particles and oil stains remaining on its surface. Firstly, a milling machine is used to process the curved surface and groove of the Ti6Al4V plate to ensure the accuracy of the groove and groove. After that, the surface of the plate is wiped to remove residual debris, and then the entire upper surface and the interior of the groove are cleaned with anhydrous ethanol to remove residual alcohol. Finally, the Ti6Al4V substrate is placed in a vacuum drying box for constant temperature drying.

Three different scanning strategies were used to study the impact of stress distribution. The three scanning strategies are shown in Figure 5.

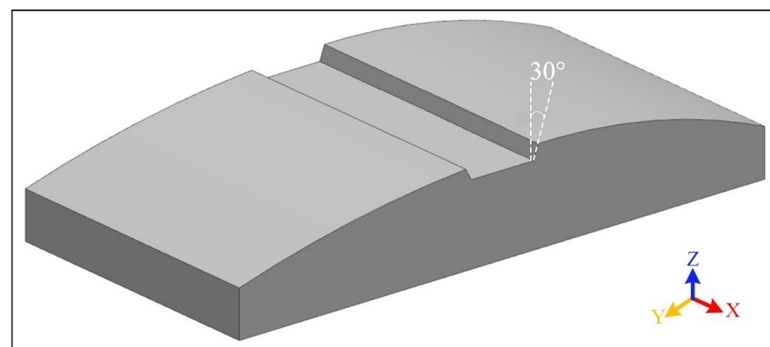


Figure 3. Schematic diagram of the component to be repaired.

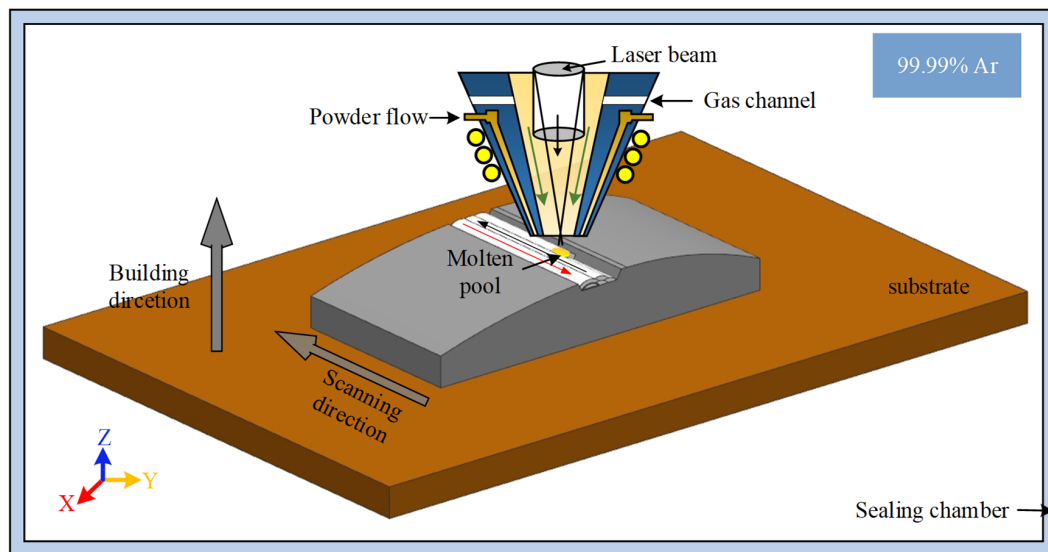


Figure 4. Schematic diagram of Ti6Al4V laser cladding repair.

Table 2. Process parameters.

Laser Power W	Scanning Speed $\text{mm} \cdot \text{s}^{-1}$	Powder Feeding Rate $\text{g} \cdot \text{min}^{-1}$	Overlap Ratio %
1200	10	8	50

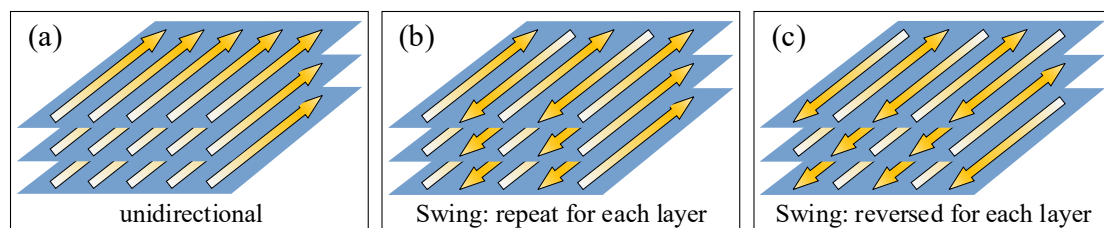


Figure 5. Schematic diagrams of laser cladding scanning modes: (a) unidirectional way (b) swinging motion repeated for each layer (c) swinging motion reversed for each layer.

2.3. Microstructure Characterization

Due to the obvious traces and oxide film on the surface of the metallographic specimen caused by wire cutting, it is necessary to first use anhydrous ethanol to clean the oil stains and particles generated on the surface of the specimen during wire cutting. Then, water abrasive papers of 160 #, 400 #, 800 #, 1500 # and 2000 # are used to grind the sample until its surface shows no obvious scratches under a light. Secondly, a diamond grinding paste with a surface particle size of 1 μm is used for polishing, and the entire polishing process is conducted on an MPD-2W polishing machine. After the specular effect is achieved on the surface of the sample, the polishing process ends. To observe the clear microstructure on the surface of the metallographic specimen, Kroll reagent ($\text{HF}:\text{HNO}_3:\text{HBO}_3 = 5:12:1$) was selected to corrode the Ti6Al4V laser cladding repair metallographic specimen for 20–30 s. Before corrosion, it is necessary to use anhydrous ethanol to clean the remaining abrasive paste particles off of its surface. The corroded anhydrous ethanol is used to clean the remaining corrosion liquid on its surface. After drying the metallographic sample with a blower, the sample's microstructure is observed using a metallographic microscope. The size of the metallographic specimen is 10 mm $\times$ 5 mm $\times$ 4 mm; the sampling location and dimensions are shown in Figure 6. Yellow dotted frame in Figure 6a is the section to be observed. The yellow, light blue, and blue areas in Figure 6b represent the heat affected zone, the remelting zone, and the sediment layer, respectively.

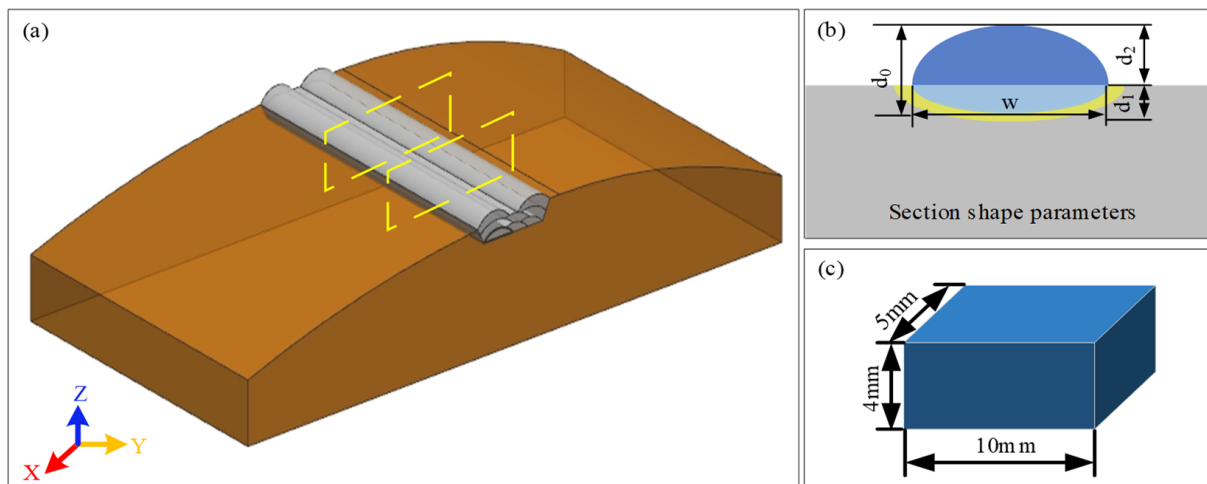


Figure 6. Schematic diagram of metallographic sample: (a) sampling location; (b) sectional shape of the cladding layer; (c) metallographic specimen size.

2.4. Stress Test

Once the Ti6Al4V laser cladding repair component has fully cooled, X-ray diffraction is used to test the residual stress. The stress detection equipment uses a Proto-LXRD type X-ray stress analyzer with 512 channel position-sensitive detectors, which produced by Guangzhou Beituo Science and Technology Co., Ltd. in Guangzhou, China. In the experiment, the diffraction crystal plane is set to (213) crystal plane, corresponding to a 2θ angle range of 20° . The ψ angle is optimized to set 17 stations within $\pm 45^\circ$. Before formal stress measurement, propanol is used to remove oil stains from the surface of the titanium alloy, and then it is placed in a drying oven for drying.

3. Numerical Modeling

3.1. Geometric and Mesh Models

MSC.MARC was used to carry out the simulation in this study. The hexahedral element was chosen for mesh generation. The number of elements is 16,864. The smallest size in the molten region is 0.2 mm. The upper surface of the geometric model of a curved groove structure was established as a hyperbolic tangent connection, with two curved surfaces having radii of 125 mm and 65 mm. After machining, the minimum height on both sides of the curved surface is 5 mm. At the same time, a groove area model was established, with the distance from the bottom of the groove to the lowest surface being 8.5 mm and the groove angle on both sides of the groove being 30° . Due to the influence of surface tension and gravity on the deposition layer under natural conditions, the final deposition layer assumed an arc shape. Therefore, in the process of establishing geometric models, the cladding layer adopted an arc shape. Generally, the mesh size has a negative correlation with computational accuracy and a positive correlation with computational efficiency. To ensure both computational accuracy and efficiency, this model uses a combination of dense and sparse grids for grid division. From the deposition area to the boundary of the substrate, a 3:1 and 2:1 transition grid was used for division. The geometric and mesh model is shown in Figure 7a.

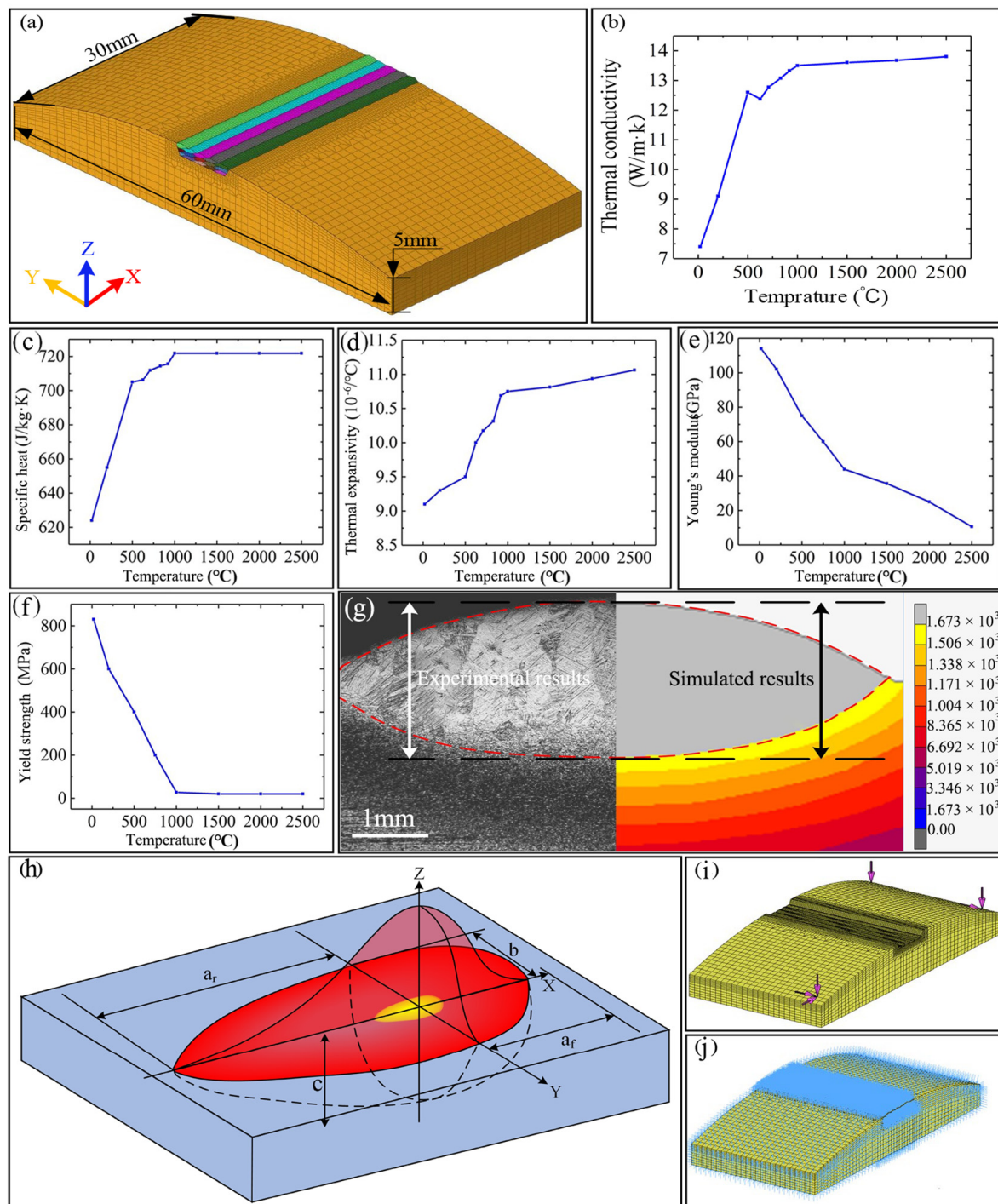


Figure 7. Modeling process: (a) geometric and mesh models; (b–f) thermophysical parameters; (g) comparison of experimental and numerical results; (h) heat source model; (i,j) constraint condition.

3.2. Ti6Al4V Thermophysical Parameters

The calculation of the stress field in the laser cladding process mainly involves the following physical performance parameters of materials, namely, thermal conductivity, thermal expansion coefficient, Young's modulus, specific heat capacity, yield strength, etc. In the process of simulating the laser cladding process of titanium alloy, selecting correct and reasonable material performance parameters is a necessary condition to ensure the normal convergence of the calculation results. The substrate and cladding material used in this study are both Ti6Al4V, and its thermal conductivity is shown in Figure 7b.

3.3. Heat Source Model

The double ellipsoidal heat source model can accurately describe the shape difference between the front and rear of the molten pool during movement, and make the simulation results more accurate. For the actual laser cladding process used in this paper, the shape of the molten pool is irregularly distributed before and after, and the rear is longer than the front. To accurately describe this phenomenon and ensure the accuracy of the calculation results, a double ellipsoidal heat source model was selected to characterize the morphology of the molten pool, as shown in Figure 7c.

The most significant feature of the double ellipsoidal heat source model is its asymmetric shape. Different heat flux distribution expressions are used for the front and rear parts [31,32]. The heat flux function in the front and rear parts is as follows:

$$q_f(x, y, z) = \frac{6\sqrt{3}f_f Q \eta}{a_f b c \pi \sqrt{\pi}} \times e\left(\frac{-3x^2}{a_f^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c^2}\right) \quad (1)$$

The heat flux density function for the second half is the following:

$$q_r(x, y, z) = \frac{6\sqrt{3}f_r Q \eta}{a_r b c \pi \sqrt{\pi}} \times e\left(\frac{-3x^2}{a_r^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c^2}\right) \quad (2)$$

where f_f and f_r are the energy coefficients of the front and rear ellipses of the heat source model, respectively, $f_f + f_r = 2$. Q is the heat input rate. H is the thermal efficiency. A_f and a_r are the long axis length of the front and rear ellipses, respectively. b is the short axis length. c is the depth of the heat source.

3.4. Boundary and Constraint Conditions

In the process of titanium alloy laser cladding repair, the interaction between laser, powder and substrate is very complex. Therefore, in the actual calculation process, the finite element model was appropriately simplified. The specific settings are as follows:

- (1) The ambient temperature of the space is consistent with the normal room temperature, which is 20 °C;
- (2) The density and Poisson's ratio of Ti6Al4V during laser cladding repair are set such that they do not change with temperature, and the properties of the base material and the powder material are consistent;
- (3) The interaction between the gas generated in the laser cladding process and the powder, weld pool, etc., is not considered;
- (4) The interaction between Ti6Al4V and the heat source during the laser cladding repair process is consistent with the classical theory of heat transfer.

Before starting the laser cladding repair process, the temperature of the substrate and titanium alloy powder is set to be consistent with the ambient temperature of 20 °C. The initial condition is as follows:

$$T(x, y, z, 0) = T_a \quad (3)$$

where T is the substrate and powder temperature, and T_a is the ambient temperature.

In addition, the model is loaded with boundary conditions, mainly including displacement constraints, element surface heat flow and volume heat flow. The displacement constraint is set to add three points of constraint at the three vertex positions of the Ti6Al4V substrate, that is, the Z constraints, X and Z constraints and the X, Y and Z constraints are set at the three vertices. At the same time, all external surfaces of the model are set as heat exchange surfaces. The volumetric heat flow is the area where the laser heat source acts during the connection process, and it needs to be loaded into each deposition layer and its vicinity. The initial and boundary conditions are set as shown in Figure 7i,j, respectively.

4. Results and Discussion

4.1. Effect of Scanning Strategy on Stress

The stress field distributions after deposition and cooling under different scanning methods were extracted and compared, as shown in Figure 8. During the entire cooling process, the stress distribution increased by about 220 MPa. The order of stress from large to small is reverse swing scanning for each layer > repeated swing scanning for each layer > and unidirectional scanning. However, the difference is that the stress distribution under two swing scan paths is closer after deposition, while after complete cooling, the stress distribution under one-way scan and repeat swing scans per layer is closer. This indicates that the stress distribution during laser cladding deposition is more affected by the scanning direction within the single layer, while the stress distribution during cooling is more affected by different scanning directions between layers.

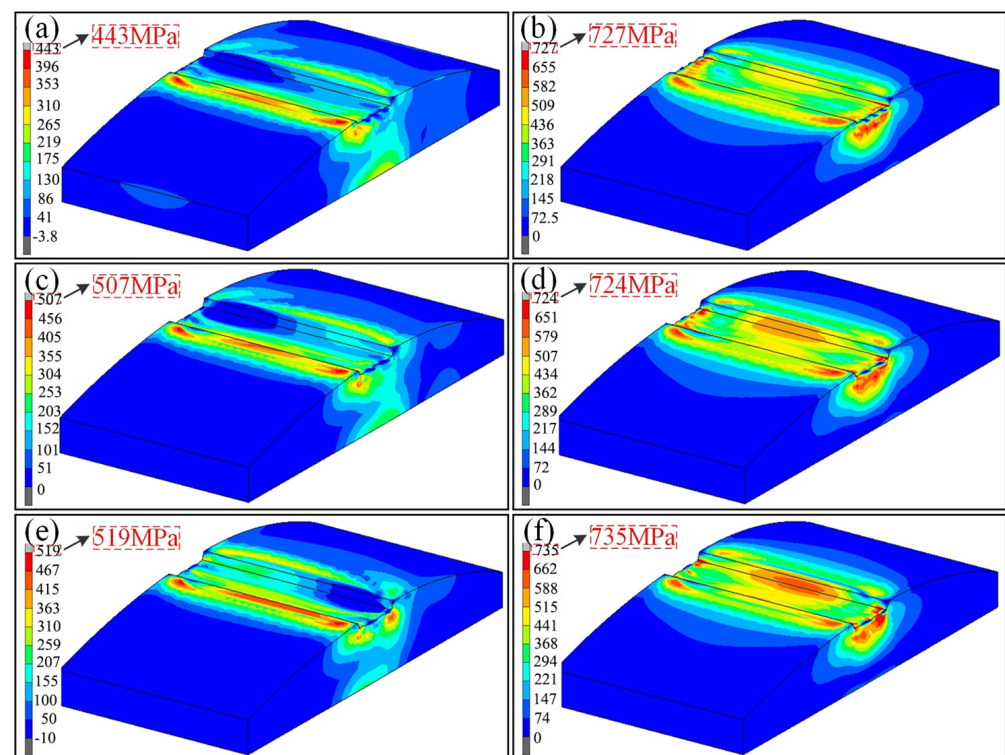


Figure 8. Stress field distributions under different scanning modes: (a,b) unidirectional scanning; (c,d) repeated swing scans for each layer; (e,f) reverse swing scan per layer.

After observing the distributions of stress concentration areas after deposition, it was found that the distributions of stress concentration under the three scanning modes were consistent at the junction of the first cladding layer, the sidewall and the bottom of the groove. The main reason lies in the geometric discontinuity at the junction of the sidewall and the groove. At the same time, the temperature field at the junction is relatively low through the printing process of the last four layers of cladding, and the cooling shrinkage phenomenon is more obvious here. After complete cooling, the overall stress distribution is asymmetric from left to right, and the stress in the first layer of cladding is even higher.

To further analyze the stress distribution under different scanning methods, the stress results on the upper surface and the left and right sides of the sample under three conditions were taken, as shown in Figure 9. Comparing Figures 9d and 9g, it can be found that the printing process of the third layer of the deposited layer under two swing scanning modes is completely consistent, so the stress distribution on its upper surface is the same. The stress on both sides of the groove is concentrated around the starting point of each pass, and the stress distribution is relatively uniform at the four corners of the groove. Due to the

deposition sequence, more stress concentrations are generated in the middle of the sidewall and the upper edge of the substrate where the first layer is deposited. In the interior of the cladding layer, the region adjacent to the last deposition layer has a higher temperature gradient and faster cooling rate during the cooling process, resulting in higher stress distribution in some regions. In Figure 9a, due to its unidirectional scanning direction, the stress is concentrated at the beginning of the left side, resulting in significant asymmetry.

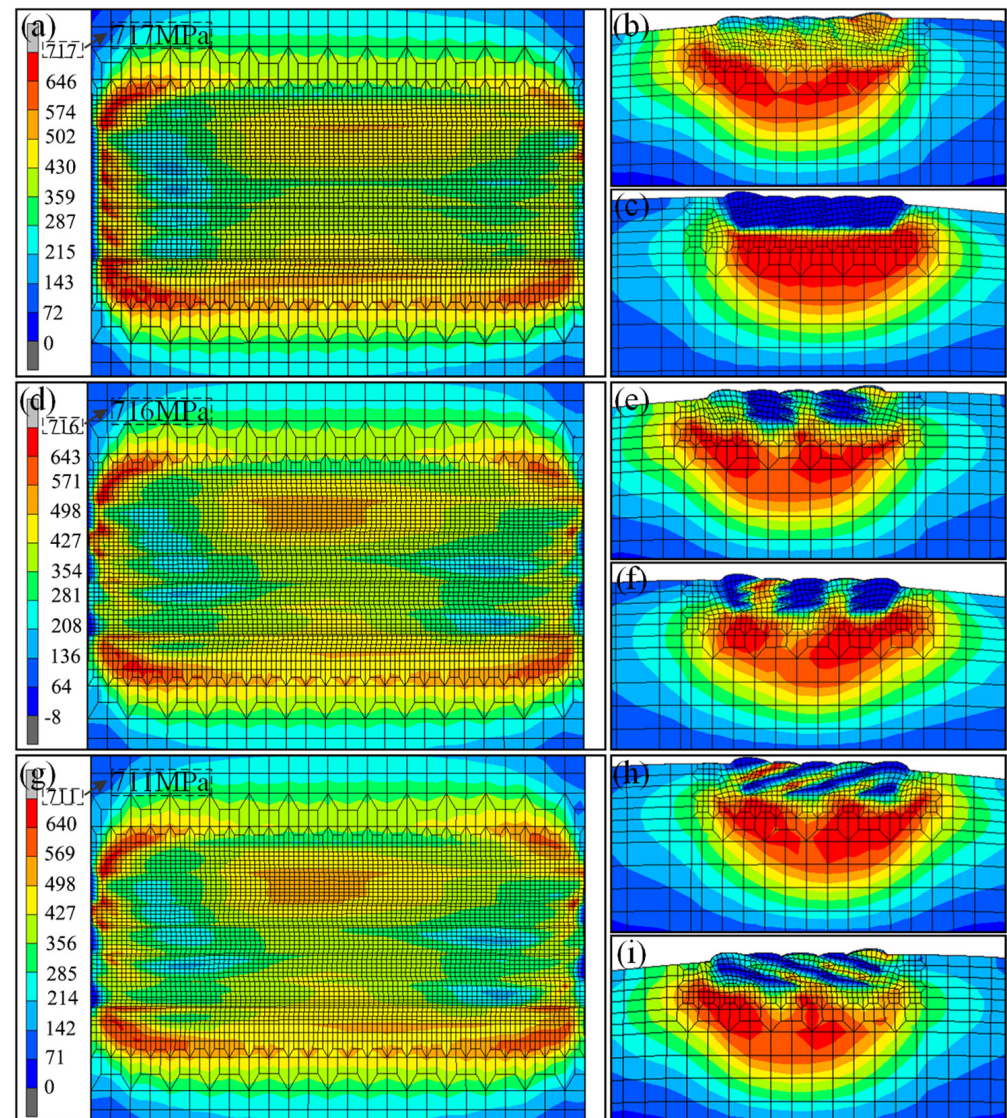


Figure 9. Cross-sectional stress field distributions: (a–c) unidirectional scanning; (d–f) repeated swing scans for each layer; (g–i) reverse swing scan per layer.

Comparing the stress distributions on the sides of the three scanning methods, it was found that the maximum stress occurred at the transition from the bottom of the cladding layer to the substrate, and the overall stress distribution range of the cladding layer remained consistent. In the unidirectional scanning cladding layer, the stress is mainly concentrated on the left side, and there is a small area of stress concentration at the interlayer; on the right side, there is only a relatively low-stress distribution at the contact with the substrate, and the overall stress distribution is asymmetric. However, in the case of using two swing scanning modes, there is an alternating distribution of stress on the side, with high-stress regions and low-stress regions alternately connected. Due to its most complex scanning method, reverse swing scanning per layer has a more complex

distribution of stress on the side. It indicates that the stress concentration areas under the three scanning methods are more distributed near the starting point of laser cladding.

To further study the distribution of stress fields in different regions under different scanning paths, three points at the edge of the groove bottom surface, the middle of the groove bottom surface and the edge of the groove sidewall are set as points A, B and C, which are signed by red five-pointed stars. The distribution of their positions is shown in Figure 10.

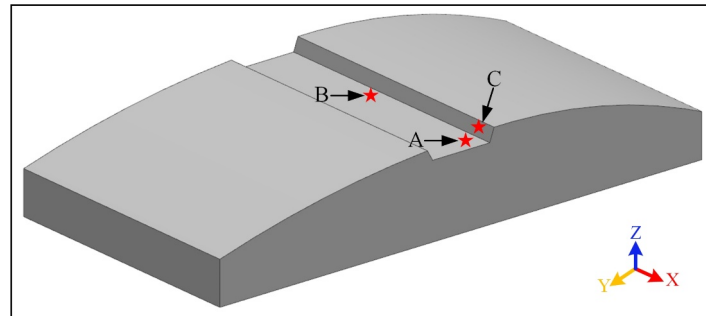


Figure 10. Curve extraction position.

Stress history curves of different regions under different scanning methods are shown in Figure 11. The first four stress distribution curves of the first layer at points A, B and C were extracted to study the stress distribution state during single-layer deposition, as shown in Figure 11a–c. As can be seen from these figures that for point A, during the unidirectional scanning process, a total of three peaks appeared, consistent with the thermal cycle curve. The overall rule is that temperature increases and stress decreases. During multiple cycles, the maximum stress reached during the cooling process remains unchanged at around 200 MPa. However, from the beginning of the third deposition process, the minimum stress value that can be achieved begins to rise one by one, indicating that the heating process at point A is no longer complete. For the swing scanning process, there are two stress wave peaks at the tail ends of the second and fourth cladding layers. During the first deposition, the stress distribution of the specimen under the swing scanning mode completely coincides with that of the unidirectional scanning mode. However, during the second scanning pass, the stress of the sample appears to shake up, resulting in a phenomenon where the stress first increases, then remains unchanged, and then increases during the first and second passes of cladding.

The first increase is mainly due to the gradual movement of the laser heat source and the decrease in temperature at point A, leading to the generation of tensile stress. When the first deposition ends and the second deposition begins, the temperature at point A decreases to room temperature, and its stress does not change substantially. At the rear end of the second pass of the cladding layer, as the laser heat source gradually approaches, the thermal expansion of the high-temperature region leads to a secondary increase in the stress at point A. Then, with a further increase in temperature, the stress at point A decreases and gradually rises in the form of a parabola during the next cooling process. Compared to unidirectional scanning, the stress peak value of swing scanning is higher, mainly due to the more concentrated heating and cooling processes and the impact of secondary stress rise. At point B, because it is located at the center of the substrate, the stress change process of different scanning strategies is consistent. The stress variation trend at point C at the edge of the sidewall is consistent with that at point A. However, due to the distance from the heat source center, the overall thermal impact on the sidewall is relatively small, and its stress peak value is greater. Here, the stress peaks of unidirectional scanning and swing scanning are the same.

Figure 11d shows the effect of the second layer cladding process on the stress change at point A. From this figure, it can be seen that the stress changes under swing scan 1 and unidirectional scan mode are consistent with Figure 11a. Due to the change in scanning

direction, swing mode 2 is affected by thermal expansion at the front end as the laser heat source approaches, resulting in the highest stress peak.

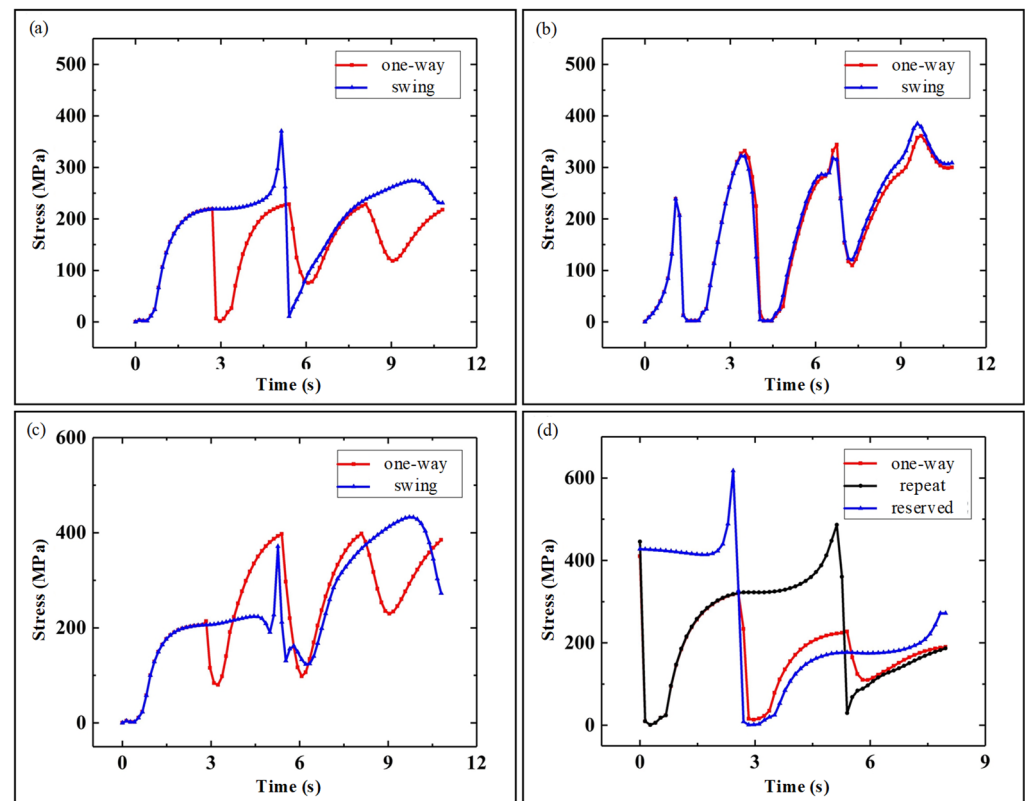


Figure 11. Stress history curve: (a) point A of the first layer; (b) point B of the first layer; (c) point C of the first layer; (d) point A of the second layer.

4.2. Microstructure Evolution in the Process Layer

To explain the distribution and formation mechanism of the microstructure inside the titanium alloy laser cladding repair specimen, the cross-sectional microstructure of the cladding layer at the groove of the specimen was analyzed. Ti6Al4V is $\alpha + \beta$ biphasic in structure. At room temperature, the microstructure of Ti6Al4V mainly presents as follows: α phase. During the cladding process, under laser irradiation, the base material and powder material rapidly rise in temperature, reaching the β transition temperature T_β (994 °C) [33] or above and the α phase transforms into the β phase. As the laser beam continues to move forward, the β phase rapidly cools, reconverts to the α phase. However, due to the small range of laser heat sources, heat concentration and excessively fast cooling rate, the process of transforming the β phase into the α phase is incomplete. To precipitate the α supersaturated solid solution of phase α' martensite forms a needle-shaped α/α' phase.

The left edge area, right edge area and bottom edge area of the sample were chosen for microstructure analysis. It can be seen that the sample combines well at the edges and bottom. There are no obvious defects such as lack of fusion and cracks. Only a small pore was found on the top of the cladding layer near the left edge zone. The heat-affected zone of the sample extends downward from the highest point on both sides of the groove, and its width tends to gradually increase. This is mainly because the overall sample adopts a groove structure, and the higher the position, the shorter the time to receive the overall laser irradiation. In addition, under the inclined plane, the overall laser irradiation area increases, the concentration of the light spot becomes weaker, and the heat is more dispersed. Extending from the top of the edge zone downward, the width of the heat-affected zone ranges from 250 μm and gradually expands to 500 μm . At the same time, the

substrate at the groove and the bottom corner is melted, resulting in a nearly arc-shaped cladding zone and heat-affected zone.

In addition, it can be seen from Figure 12 that a small number of equiaxed crystals are generated near the fusion line at the bottom of the sample. This is mainly because the heat during processing is mainly dissipated through heat transfer to the substrate at room temperature during the underlying printing process. At this time, the overall cooling rate is faster, promoting the emergence of equiaxed crystals, and the remelted substrate provides a large number of nucleation particles. With the accumulation of heat, due to the low thermal conductivity of the titanium alloy itself, the temperature gradient and solidification rate of the sample continue to decrease, and above the equiaxed crystals, β columnar crystals begin to form. In the bottom regions of both sides and the center of the sample, columnar crystals tend to grow perpendicular to the fusion line. This is mainly because, driven by the maximum temperature gradient, grains tend to grow in the direction of maximum heat dissipation.

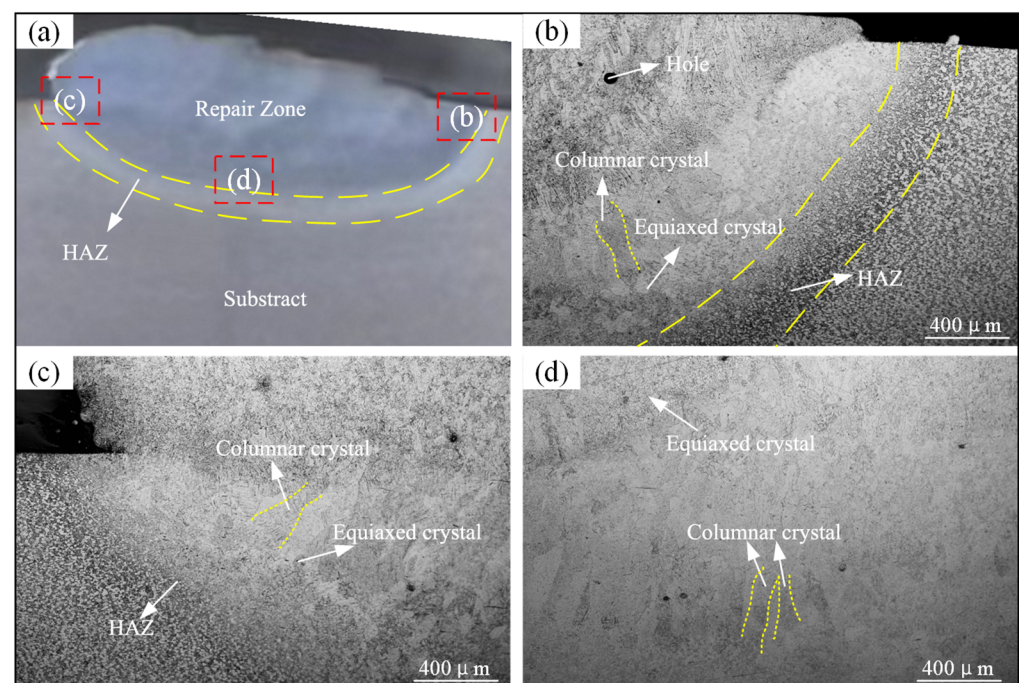


Figure 12. Microstructure of the bottom of the sample repaired by laser cladding on the curved surface structure of titanium alloy. (a) overall morphology (b) right edge area (c) left edge area, (d) bottom edge area.

Figure 13 displays the microstructure at the top of the laser cladding repair specimen with the curved surface structure. It can be seen from the figure that the microstructure caused by the small thermal gradient and cooling rate is mainly fine columnar crystals near the top of the sample under the effect of heat storage. Due to the influence of heat dissipation direction and maximum temperature gradient, the growth direction of these columnar crystals gradually develops to be perpendicular to the upper surface. The size of columnar crystals gradually decreases and eventually develops into equiaxed crystals with the increase in height. The upper surface has been in contact with cold air for a long time, not subject to remelting heating again during the printing process of the last layer. The surface cooling gradient is large, forming more nucleation particles and promoting the formation of equiaxed crystals.

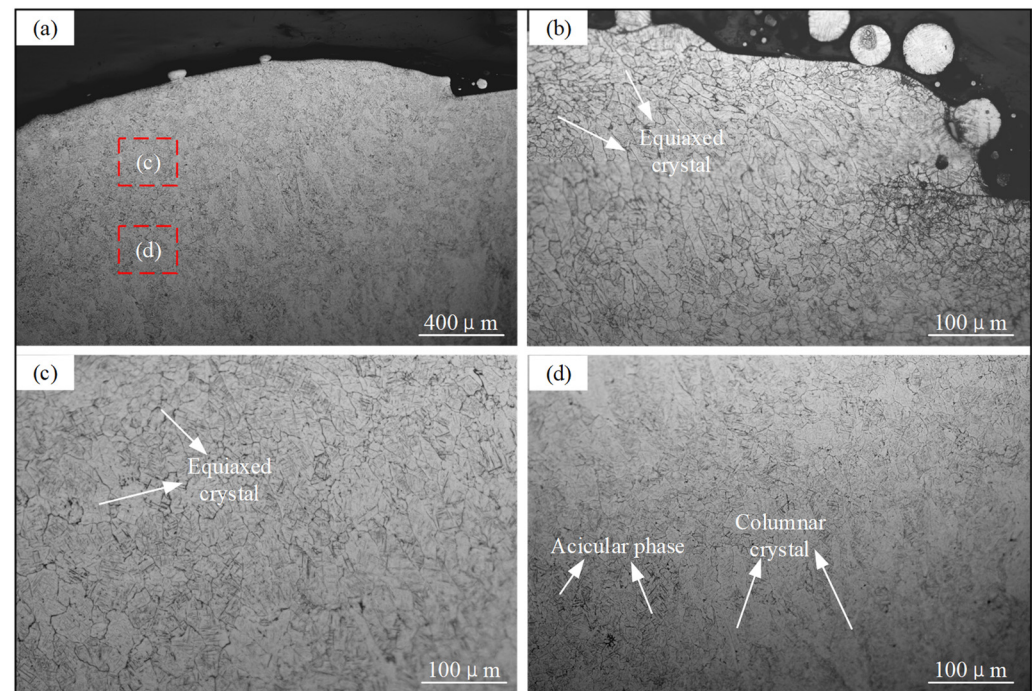


Figure 13. Microstructure of the top of the sample repaired by laser cladding on the curved surface structure of titanium alloy: (a) overall morphology (b) surface area (c) equiaxed crystal area, (d) columnar crystal area.

The microstructure in the middle of the titanium alloy curved surface structure laser cladding repair sample is shown in Figure 14. From Figure 14, it can be seen that the internal structure of the sample cladding layer is mainly β columnar crystal, but between different layers in the repair area there is an equiaxed crystal zone, resulting in an alternating distribution of “columnar crystal, equiaxed crystal, columnar crystal” structure. In the process of laser cladding repair, the heterogeneous nucleation of equiaxed grains on partially melted powder and the epitaxial growth of columnar grains on the bottom of the pool are two main solidification mechanisms. The competition between the above two solidification mechanisms in the molten pool dominates the grain morphology selection process and determines the deposited grain structure of the layer-by-layer deposition component. In this experiment, after each layer is completed, an interlayer cooling time of 60 s was set to allow sufficient time for the cooling process after each layer of the cladding layer was printed. Therefore, when printing the second layer of the cladding layer, a larger temperature gradient brings about a higher cooling rate, and the effect of heat transfer is enhanced, resulting in the formation of a large number of nucleation particles between layers. This inhibits uneven nucleation on the surface and promotes the formation of equiaxed crystals. Secondly, due to the existence of grooves in the titanium alloy groove sample, some of the molten pool solidified on the side wall, and the overall cladding layer elongated, resulting in a larger heat dissipation area and higher cooling speed, which is also conducive to the formation of equiaxed crystals. At the same time, due to the growth of columnar crystals along the vertical direction of the fusion line, as the columnar crystals continue to grow, competition occurs between the grains, thereby inhibiting their respective growth. Then, with the development towards the interior of the single pass cladding layer due to the reduction in cooling speed and heat storage, the size of the equiaxed grains continues to increase and equiaxed grains with short columnar or olive-shaped morphology appear, gradually developing into fine columnar crystals.

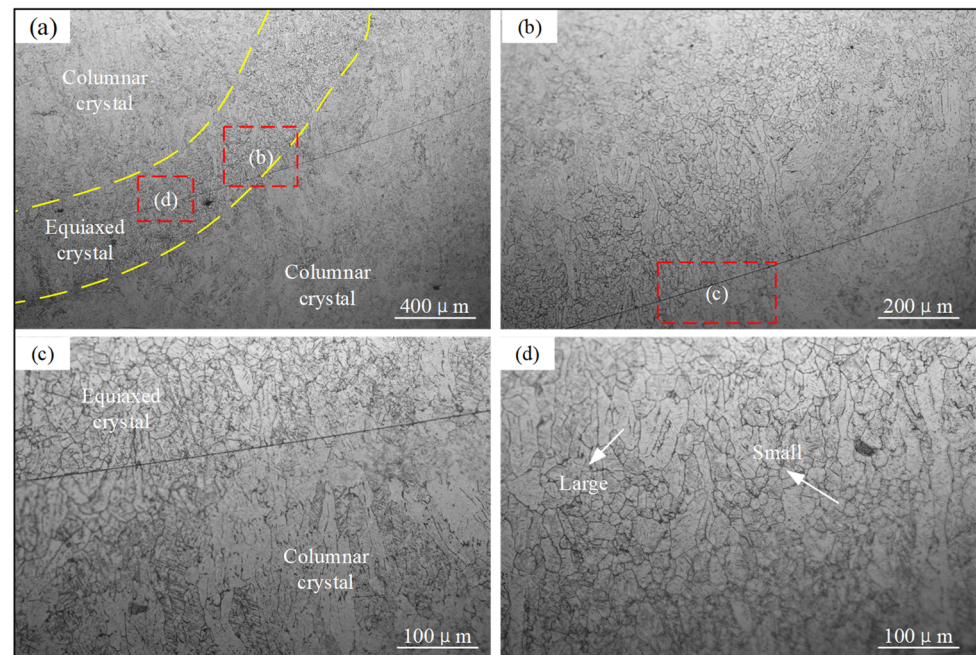


Figure 14. Microstructure of the middle of the sample repaired by laser cladding on the curved surface structure of titanium alloy: (a) overall morphology (b) equiaxed crystal area (c) interface of equiaxed and columnar crystal, (d) large and small equiaxed crystal.

The solidification grain size and morphology of the layered structure of titanium alloy are determined by nucleation and growth conditions [34], which greatly depend on the thermodynamic and metallurgical state of the local molten pool during the rapid solidification laser cladding repair process. During the laser cladding process, a portion of the absorbed laser energy is used to melt the captured metal powder and the surface layer of the substrate, forming a molten pool on the underlying deposition layer. The remaining absorbed laser energy is consumed by rapid thermal conduction into the substrate. In summary, the printing of the repair area containing three cladding layers was completed in this experiment. At the bottom of the entire repair area near the substrate, the crystal morphology is equiaxed and gradually develops into coarse columnar crystals that grow perpendicular to the fusion line as the height increases. In the interlayer bonding zone, fine equiaxed crystals are formed and gradually develop into short columnar and olive-shaped larger particle equiaxed crystals as the height increases, then gradually transform into fine columnar crystals facing the upper surface, and finally, equiaxed crystals are formed again at the top of the sample. The overall distribution order is “large size equiaxed crystal–coarse columnar crystal–fine equiaxed crystal–short columnar equiaxed crystal–fine columnar crystal–fine equiaxed crystal”.

4.3. Stress Verification

In this research, because the microstructure material used for laser cladding repair of titanium alloy curved surface structures is a polycrystalline material at the bottom of the sample, the strain corresponding to the macro stress of the polycrystalline material is considered to be a statistical result of its internal lattice strain. Therefore, the X-ray diffraction method [35] can be used to determine the internal stress distribution by measuring lattice distortion.

Figure 15 shows the stress detection location of the laser cladding repair sample for the curved surface structure of titanium alloy. There are a total of seven points on the upper surface, represented by P-1 to P-7. There are three side surface points, represented by S-1, S-2 and S-3. The stress results measured by experiments at different points are shown in Table 3.

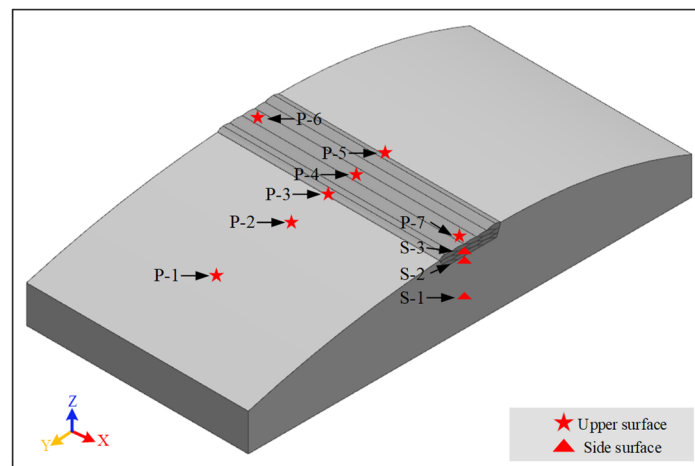


Figure 15. Sampling locations for stress detection.

Table 3. The stress results measured from experiments.

Locations	Stress Results (MPa)		Average (MPa)
P-1	−284	−278	−281
P-2	−32	−40	−36
P-3	+123	+135	+129
P-4	+350	+361	+355.5
P-5	+128	+146	+137
P-6	+320	+315	+317.5
P-7	+386	+345	+365.5
S-1	−190	−176	−183
S-2	−31	−28	−29.5
S-3	+93	+101	+97

Comparing the stress values at multiple locations of titanium alloy curved structures in the X, Y and Z directions, it can be seen that the stress values measured at different points fluctuate around the simulation results, with a certain proportion of deviation at some points; however, the overall change trend is consistent with the simulation results, as shown in Figure 16.

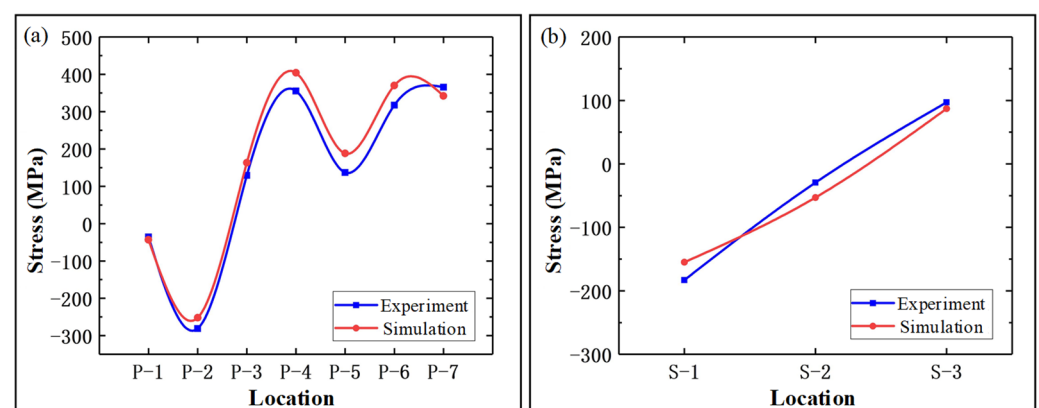


Figure 16. Comparison of simulation and experimental results of (a) upper surface, (b) side surface.

5. Conclusions

We analyzed the distribution of stress fields in the Ti6Al4V curved groove structure under various scanning modes. The simulation findings were confirmed to ensure their accuracy. Additionally, an analysis was conducted on the distribution and alterations in microstructure at various locations. The subsequent inferences can be derived:

- (1) The swing scanning mode results in elevated peak temperatures and strains during numerous thermal cycles. Following the process of complete cooling, stress concentration commonly arises near the initial point of cladding. The reverse swing scanning approach for each layer demonstrates the lowest stress peak and produces a more homogeneous stress distribution. Optimizing the scanning strategy reduced the maximum stress in the repair layer from 717 MPa to 711 MPa.
- (2) The solidified grain size and shape in the cladding zone show non-uniformity because of variations in nucleation and growth circumstances. The grain shape in the cladding layer varies between columnar and equiaxed crystals as one moves from the bottom to the top.
- (3) The stress distributions acquired using X-ray non-destructive testing on the cladding layer, top surface of the substrate and side surface of the sample align with the stress values obtained throughout the simulation procedure. The error between simulation and measurement is not more than 50 MPa, thereby validating the simulation's feasibility.

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