

# Research on Model Slice and Forming Method of Thin-walled Parts

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**Abstract.** According to the structural characteristics of thin-walled parts, a model slicing method is proposed, and its mathematical process is established. The three-dimensional transient temperature field in the process of synchronous powder feeding laser cladding is studied and verified by numerical simulation method, and the thin-walled parts formed by later experimental processing are processed by the results of numerical simulation. Using the simulation results of temperature field as the basis for optimizing the processing parameters, the forming path of thin-walled parts is programmed and optimized, and the experimental verification shows the reliability of this method.

## 1 Introduction

Additive technology is more and more used in aerospace field, because the structure of parts in these fields is often complex and tends to be more and more complex, and it is increasingly difficult to be competent for the manufacturing task of these parts only by traditional manufacturing technology [1-3]. Additive manufacturing technology can give full play to its advantages for small batch of complex structural parts in aerospace field. For example, EOS Company of Germany formed turbine blades of aircraft engines by laser selective melting technology, and GE Company of America manufactured fuel nozzles of aircraft engines by laser selective sintering technology [2-5].

Thin-walled parts are a kind of common structure, which exists in many fields. Because of its inner contour, this structure is difficult to manufacture by traditional manufacturing methods. For this structure, SLM technology is usually used for manufacturing, but it may not be feasible in some cases, so it is necessary to turn to LSF technology [6]. If only three-degree-of-freedom LSF technology is used to add materials to form the whole model in a single direction, the problem lies in that for large overhanging structures, in order to ensure that the materials of overhanging parts are supported, the supporting structures should be manufactured at the same time. After the manufacturing is completed, these supporting structures need to be removed, resulting in material waste, affecting the forming efficiency and complicated post-processing.

The mixed forming technology based on LSF has more freedom, which is expected to solve the above problems. Many scholars try to reduce the supporting structure by optimizing the forming direction [7-9], but the effect that can be achieved is still limited. Because the supporting structure is inevitable in the

manufacturing process, and the problems brought by the supporting structure still exist.

In order to realize unsupported additive forming of thin-walled parts, many scholars at home and abroad have carried out related research, among which there are many ideas. One of them is to split firstly and then splice. That is to split the model into several sub-parts by some method, which can be manufactured in one direction on three-axis additive equipment, and then splice these parts to form a complete model.

Singh and Dutta put forward a concept of 'building map' modeled by Gaussian mapping. The so-called building map is the intersection of buildable directions of all points on the surface of the model. Firstly, the model is divided into buildable parts and non-buildable parts according to the initial building direction, and the building map is calculated for the non-buildable directions. Then the appropriate building direction is selected according to the two evaluation criteria of surface quality and collision-free, and then the model is divided continuously until all parts of the model can be built along a specific direction. Among them, building drawings involves a large number of complex intersection calculations, and it may take a lot of time to encounter complex models [7]. In 2008, they put forward another migration slicing method [8], aiming at the non-planar feature profiles formed by the intersection of some curved surfaces. A series of non-planar slicing layers were obtained, so as to solve the unsupported forming problem of specific overhanging structures.

Sundaram and Choi put forward an unsupported forming method for five-axis laser-assisted Direct Metal Deposition (DMD) [9]. Firstly, they find out all surface points in the model whose inclination angle is greater than the allowable value, and then they find out the point with the smallest coordinate value in Z direction. Passing through the point, the intersecting contour is obtained by

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intersecting the model with the horizontal plane, which is swept along the construction direction to obtain a solid called tool body. The overhanging feature is obtained by subtracting the tool body from the original model, and the overhanging feature is carried out along the specified direction. This method is suitable for dealing with some simple geometry, especially the model of rotary combination.

In the paper, Zhang and Liou mentioned two methods for unsupported manufacturing [10], one is called ‘transition wall’. When the contour of the upper layer exceeds the contour of the lower layer, the overlapping part of the upper layer and the lower layer is built firstly, and then the platform is turned over 90°, and the overhanging area of the upper layer relative to the lower layer continues to be built. When the above-mentioned methods interfere, another method is proposed in this paper. Firstly, the traveling direction at each point of the slice contour is defined as the cross product of the surface normal of the point and the tangent of the slice contour of the point. Then the optimal building direction of each point on the previous slice contour is mapped to the unit sphere by Gauss, and the optimal direction of the next slice is determined by the minimum enclosing spherical crown surface method. It is difficult to control this kind of unequal thickness slice accurately in the actual manufacturing process.

In view of the lack of unsupported forming methods for thin-walled parts at present, this paper studies the existing manufacturing methods of thin-walled parts, and puts forward a forming method of thin-walled parts based on temperature field simulation. Starting from relatively simple thin-walled parts, it theoretically discusses the possibility of forming thin-walled parts and the specific implementation steps.

## 2 Slicing method

Additive forming forms parts by layering parts and then accumulating materials layer by layer. Theoretically, no matter what the shape of a part is, as long as the part can be processed in layers, the layered information can be obtained and then formed layer by layer, the solid part can be manufactured. However, in fact, due to gravity and material tension, the forming process may encounter trouble when there is a part of the upper contour that is not in the lower contour. If the material can keep falling under the action of gravity and tension at this time, the forming process can continue. However, if the material can't keep falling before solidification under the action of gravity and tension, the forming of this part will fail, and the forming of the subsequent part can't be carried out.

In this case, a simple method is to add a support structure at the place where the suspension is too large to provide support for this part of the material and prevent the material from falling off. This method is simple to implement, but wastes materials. At the same time, the subsequent removal of supporting materials is a troublesome step. On the one hand, it may hurt the surface of parts [11]. On the other hand, the process is

time-consuming, and it is even impossible to remove the support of some complex structures.

Manufacturing support structure is the main solution to solve the problem of forming large overhanging structure with unidirectional additive, but if multi-directional additive forming can be realized, the forming of large overhanging structure can be realized without manufacturing support structure, thus avoiding the problems caused by manufacturing support structure. One of the keys to realize multi-directional additive forming is the processing of parts, which can be divided into several parts by a certain method, and each part can be formed along a single direction. On the whole, all parts of parts are formed along different directions, and finally a complete part is formed.

Traditional additive equipment usually has only three degrees of freedom, namely three coordinate axes, and can only carry out additive in one direction. One-way additive forming has a forming inclination limit. When the included angle between the normal direction of the object surface and the forming direction is greater than a certain value, the material can't keep still under the action of gravity and its own tension, and the phenomenon of flowing and falling occurs, resulting in the failure of forming, as shown in Figure 1.

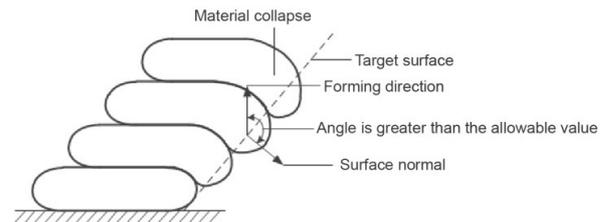


Fig. 1. Failure of the support-free forming along single direction.

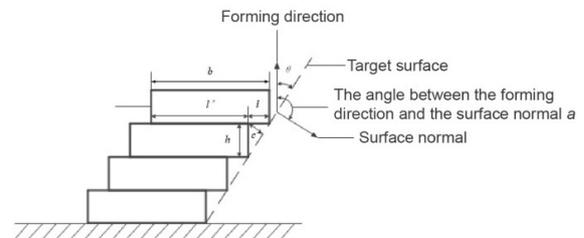


Fig. 2. Model of the support-free forming along single direction.

For convenience, the additive forming layer is simplified into a rectangle for analysis. When forming inclined surfaces by unidirectional additive, the overlapping parts of two adjacent layers must be large enough to ensure that the upper layer material will not collapse during forming, as shown in Figure 2. Now, a concept of interlayer overlap ratio [12] is introduced to measure the connection degree between adjacent printing layers, as shown in formulas (1)-(8).

$$\eta = \frac{l'}{b} = \frac{b-1}{b} \quad (1)$$

$$\eta \geq \eta_{\min} \quad (2)$$

$$l = b(1-\eta) \quad (3)$$

$$\tan \theta = \frac{1}{h} = \frac{b(1-\eta)}{h} \quad (4)$$

$$\sin \theta = \frac{c}{h} \quad (5)$$

$$\alpha = \theta + \frac{\pi}{2} \quad (6)$$

$$1 \leq b(1 - \eta_{\min}) = l_{\max} \quad (7)$$

$$\tan \theta_{\max} = \frac{l_{\max}}{h} = \frac{b(1 - \eta_{\min})}{h} \quad (8)$$

Among them,  $\eta$  indicates the overlap rate between layers;  $l$  represents the overhang length between adjacent printing layers;  $l'$  indicates the overlap length between adjacent printing layers;  $b$  represents the width of a single printing path;  $\alpha$  indicates the angle between the surface normal of a certain point and the forming direction;  $\theta$  indicates the included angle between the tangent plane of a certain point and the forming direction;  $h$  represents the printing layer height;  $c$  represents the tip height.

It can be seen that the forming limit inclination angle in one direction is related to the width  $b$  of single printing path, the height  $h$  of printing layer and the overlap ratio between layers, that is to say, it depends on the parameters of additive equipment itself, and different limit inclination angles  $\theta_{\max}$  can be obtained by setting different parameters. However, no matter how to adjust the parameters, in order to make the forming process and ensure the quality, the value of  $\theta_{\max}$  should not be too large. At the same time, this value can be used to adjust the tilt angle of the worktable, which can eliminate the use of supports.

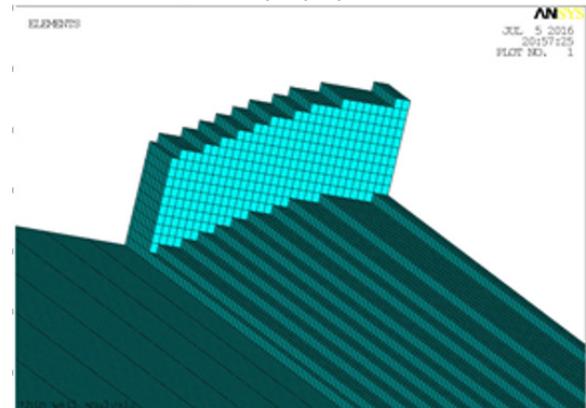
### 3 Geometric model and mesh generation

The laser cladding forming process is a typical nonlinear problem. Under the irradiation of high energy density laser beam, the temperature in the laser beam irradiation area rises rapidly, and the metal material melts to form a molten pool. After a series of complex physical and chemical reactions, the matrix material and the powder alloy material form a metallurgical bond, thus obtaining the cladding layer. This process is generally a process of rapid cooling and heating, which is a typical transient analysis. If the analysis method of thermal-mechanical coupling is carried out according to the actual situation, the calculation of the model will be quite complicated, so it is necessary to simplify various factors in the laser cladding process.

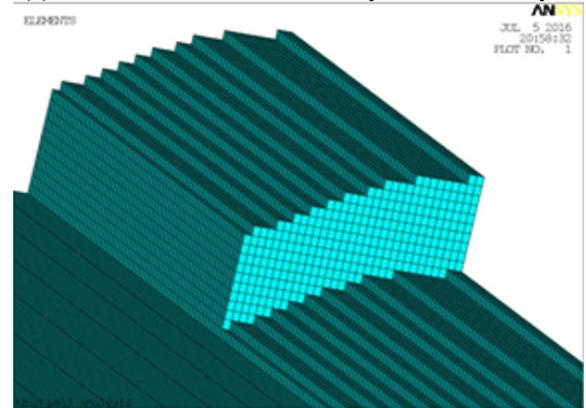
The following simplified assumptions are made in the finite element analysis of laser cladding forming process:

- (1) Assume that the whole cladding surface is plane;
- (2) Applying the classical heat transfer theory to the interaction between materials and laser;
- (3) The material is isotropic;
- (4) Ignore the influence of various substances in the air on the input laser;
- (5) The influence of the flow of liquid metal in the molten pool on the temperature field is not considered;
- (6) Ignore the influence of plastic deformation of materials.

The shape of the substrate is cuboid, on which thin-walled parts are formed by powder feeding laser cladding, and the geometric shape is symmetrical, and the load on the thin-walled parts in the forming process is also symmetrical. Therefore, we can consider only half of the model for simulation calculation, so that the number of grids obtained after the model division can be reduced by half without changing the calculation accuracy, which greatly improves the calculation speed. The length  $\times$  width  $\times$  height of the thin-walled parts formed by melt coating is  $L_c \times W_c \times H_c = 20\text{mm} \times 0.6\text{mm} \times 12\text{mm}$ , with 24 layers, each layer is 0.5mm high, and the length  $\times$  width  $\times$  height of the base part is  $L_j \times W_j \times H_j = 20\text{mm} \times 8\text{mm} \times 5\text{mm}$ .



(a) The unit activated in the first step of the second layer.



(b) The unit activated in the tenth step of the second layer.

**Fig. 3.** The unit state when the dead unit be activated.

In the process of powder feeding laser cladding forming, with the continuous deposition of metal powder materials, the substrate is gradually clad, so the cladding layer unit does not exist before cladding, but gradually forms with the continuous progress of laser cladding forming process. To simulate this process, the 'life and death unit' technology in ANSYS can be used to simulate the dynamic growth process of cladding layer in space and time. The life and death of a unit means that if the selected unit is activated or killed, the corresponding unit in the model will be 'born' or 'died'. The option of life and death unit is used to control whether the selected unit is killed or reactivated. In specific problems, the life and death state of the element can be determined according to the calculation results of ANSYS, such as strain, stress, temperature [12-15], as shown in Figure 3.

### 4 Temperature field simulation

The finite element numerical simulation of temperature field in the process of laser cladding forming thin-walled parts was carried out. By using APDL programming language and life-and-death cell technology in finite element analysis software ANSYS, the transient temperature field of single-pass and single-pass multi-layer laser cladding on the surface of 45# steel substrate with Ni60 alloy powder is simulated, which provides a basis for laser cladding of three-dimensional solid parts in the next step.

When the selected characteristic parameters of heat source radius are  $a_1 = 0.4$  mm,  $a_2 = 0.6$  mm,  $b = 0.3$  mm, and  $c = 0.35$  mm, Figure 4 is the temperature field isosurface diagram formed after the last substep of the fourth step is completed. In order to further determine the depth of the molten pool formed on the substrate during laser cladding, the temperature field isosurface diagram on the substrate is extracted again. As shown in Figure 5, it is the last step of the fourth step. The boundary temperature of the red area in the figure is  $1572\text{ }^\circ\text{C}$ , while the melting point temperature of the matrix material is  $1390\text{ }^\circ\text{C}$ , which reaches the melting point temperature of the matrix material. Therefore, it can be considered that the brown area represents the molten pool formed on the matrix at that time. It can be seen from the figure that the melting depth of the molten pool formed on the substrate is shallow, which is in line with the low dilution rate characteristic when laser cladding processing is actually carried out.

The characteristics and changes of temperature field of thin-walled parts formed by laser cladding are studied by selecting different points on cladding layer and substrate. The scanning mode in the process of laser cladding forming thin-walled parts is shown in Figure 6.

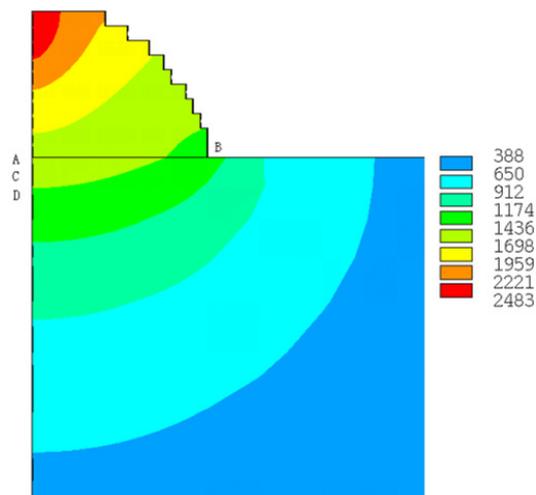


Fig. 4. The temperature distribution of cross section.

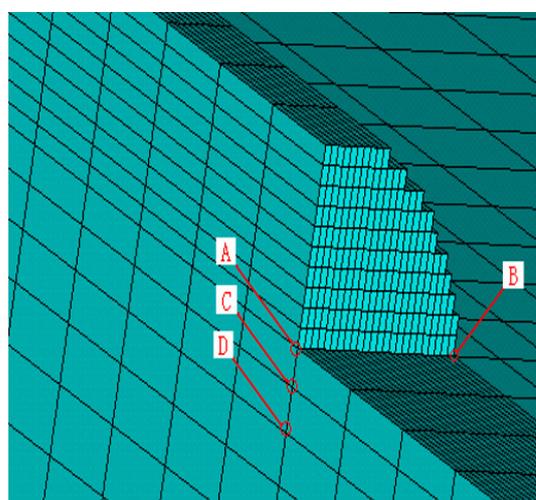


Fig. 5. The location of the four points.

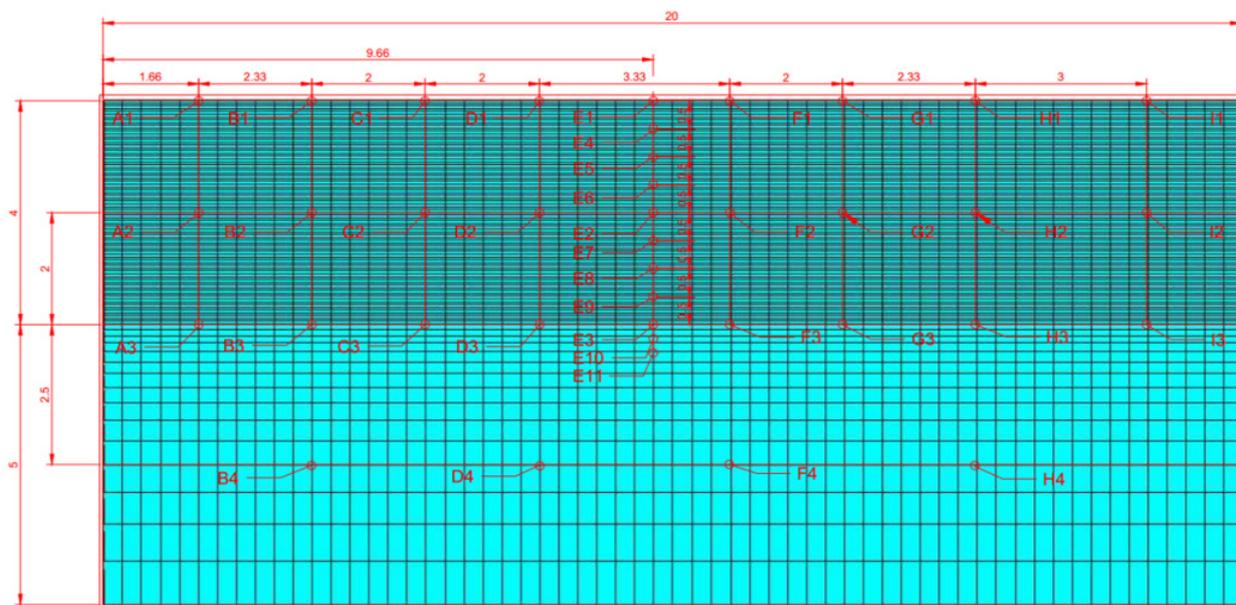
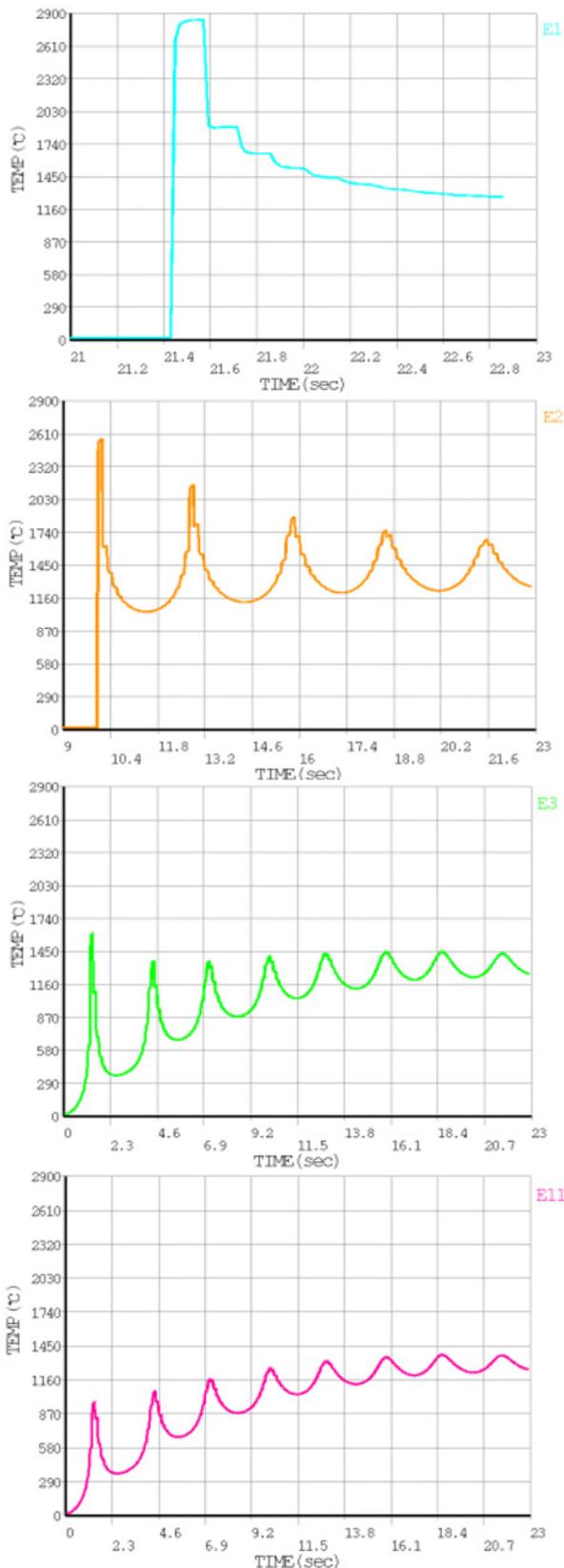


Fig. 6. The selection points diagram of laser fuse forming thin wall.



**Fig. 7.** The same cross section temperature variation curves for different heights.

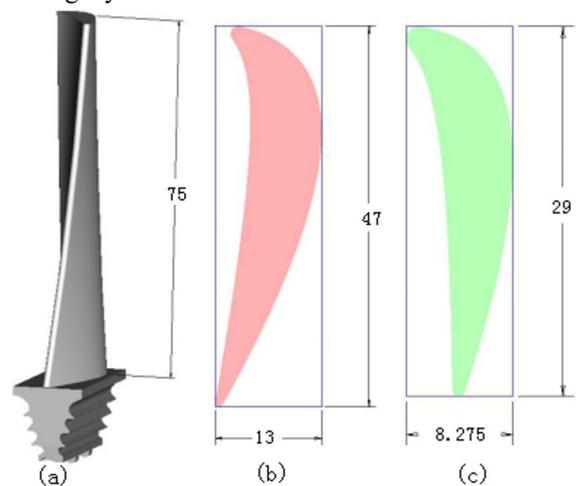
Figure 7 is the graph of temperature changing with time at different positions E1, E2, E3 and E11 on the

substrate and cladding layer under the conditions of laser power  $P=450W$  and scanning speed  $V_s=7mm/s$ . The basic morphological characteristics of temperature curves at the same cross-section but at different height positions on the cladding layer are consistent with each other, and the curves rise rapidly in a straight line in the heating stage, while the curves in the cooling stage decrease slightly more slowly than those in the heating stage. The curve of the whole temperature changes with time is zigzag, and the peak value of the temperature at the point on the surface of the cladding layer becomes larger and larger as the cladding layer accumulates higher and higher.

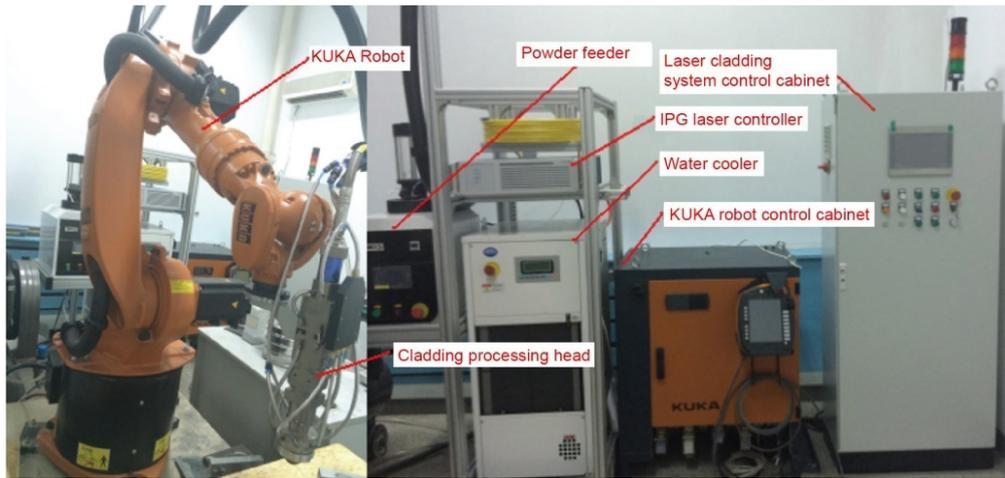
The temperature change process of the point on the cladding layer shows the characteristics of rapid heating and rapid cooling. When the laser beam starts to act on the point, its temperature value rises sharply. When the laser beam centre moves to this point, its temperature reaches its peak. When the laser beam leaves this point, its temperature drops sharply. Since the point on the substrate is not directly affected by the laser beam, and its heat is mainly conducted to the substrate through the cladding layer, the curve of its temperature change with time rises relatively gently, as shown in Figure 7.

### 5 Experimental verification

In the process of laser cladding forming parts, the dynamic distribution of temperature field on the formed parts has a very important influence on the final forming quality of the parts. The process of forming parts by laser cladding is essentially a process in which metal powder material melts under the irradiation of laser beam to form a molten pool, and when the laser beam scans, the molten pool is cooled and solidified to form a cladding layer.



**Fig. 8.** The 3d model of turbine blade and the main size information.



**Fig. 9.** The system of Laser cladding.

The blade height of three-dimensional model of turbine blade to be machined in experiment is 72mm, and the cross-sectional information of the bottom layer and the top layer is shown in Figure 8.

The laser cladding equipment used in this experiment is shown in Figure 9, and the parameters are shown in Table 1.

**Table 1.** Parameters of Experimental Equipment.

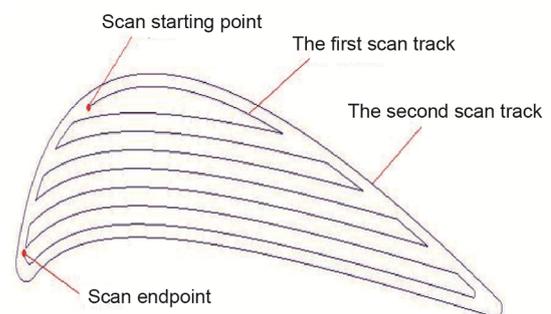
	Name	Parameter
Laser light source	IPG laser	500W
Feeding device	Robot	KUKA-KR 16-2
Powder feeder	RAYCHAM	Single tube
Powder	Ni60	

Z-scan mode is as shown in Figure 10. The programming workload can be greatly reduced by using z-scan mode, because only two tracks are generated in each layer. However, according to the actual processing effect, it is found that the thickness of the cladding layer varies greatly on each layer when processing in this way. Because the thickness of the cladding layer is very small in the initial stage of processing, with the continuous processing, the thickness of the cladding layer gradually increases, which eventually causes the unevenness of the cladding layer. Because of the cumulative effect of machining defects in the laser cladding forming process, it is easy to cause the failure of the cladding parts with the processing, so this scanning method is not suitable for blade cladding processing.

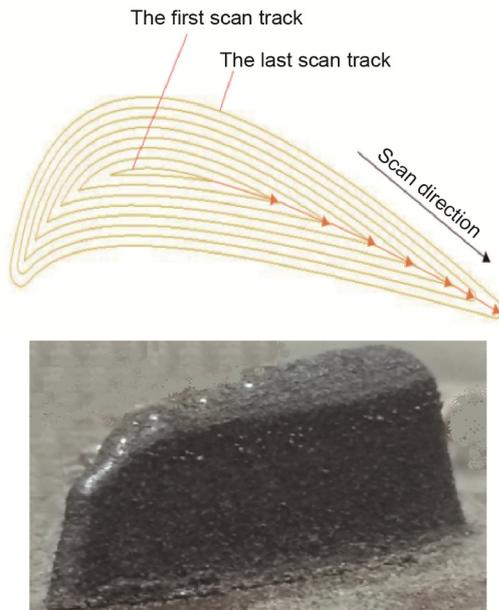
The scanning mode from inside to outside is as shown in Figure 11. According to the actual cladding forming effect, with the gradual increase of the cladding layer height, because the inner part of the blade is clad first, the metal powder is clad on the inclined surface when the outer ring is clad. However, because the metal powder sent by the powder feeder falls on the inclined

processing surface, the metal powder is easily lost and the cladding layer is not easy to form. With the accumulation of defects, the distortion effect of machined parts is gradually caused. Therefore, this scanning method is not suitable for machining parts with larger height direction.

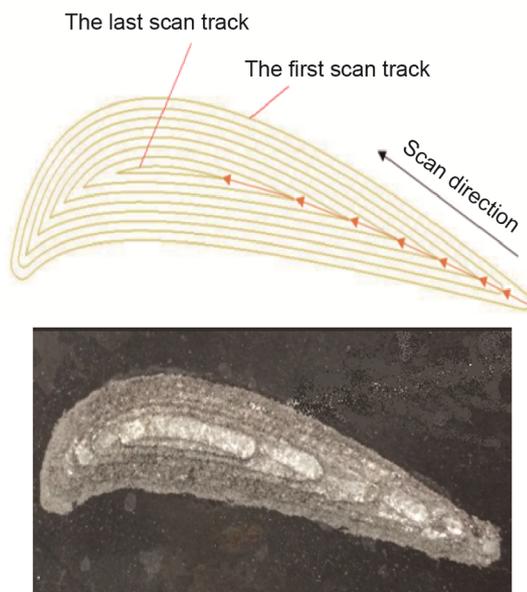
The scanning mode from outside to inside is as shown in Figure 12. From the actual processing effect, it can be seen that the method of scanning from outside to inside overcomes the deficiency of scanning from inside to outside, and obtains ideal results.



**Fig. 10.** Z-scanning path and its forming effect.



**Fig. 11.** Contour scanning path (from inside to outside) and its forming effect.



**Fig. 12.** Contour scanning path (from outside to inside) and its forming effect.

## 6 Conclusion

The method solves the forming problem of thin-walled parts. A simple partial model can be obtained by splitting a complex model firstly, and a segmentation plane perpendicular to the forming direction is generated along a large overhanging position from bottom to top, and then the model is segmented along the segmentation plane in reverse order. This paper solves the overhang problem and the interference problem in the previous bottom-up segmentation mode.

Cross-section shape curve of cladding layer is drawn in this paper, and the mathematical model is applied in simulation, which makes the simulation process more close to the actual machining process. According to the simulation process under the condition that the laser

power changes in real time by the logic judgment function of the program, in the process of laser cladding forming, the temperature of the molten pool is stabilized within an ideal range, thus ensuring the smooth progress of laser cladding forming.

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