Numerical Simulation of Temperature Field of Direct Laser Metal Deposition Shaping Process of Titanium Alloys

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Abstract: In order to control the thermal stress of forming process, based on “element birth and death” technology of finite element method, a numerical simulation of three-dimensional temperature field and stress field during multi-track & multi-layer laser metal deposition shaping (LMDS) process is developed with ANSYS parametric design language (APDL). The dynamic variances of temperature field and stress field of forming process are calculated with the energy compensation of interaction between molten pool-powder and laser-powder. The temperature field, temperature gradient, thermal stress field and distribution of residual stress are obtained. The results indicate that although the nodes on different layers are activated at different time, their temperature variations are similar. The temperature gradients of samples are larger near the molten pool area and mainly along z-direction. Finally, it’s verified that the analysis results are consistent with actual situation by the experiments with same process parameters.

Introduction

Laser metal deposition shaping (LMDS) technique has been widely used in many industrial applications such as aerospace, automobile, weapons and so on[1]. LMDS accumulates metal powder materials according to two-dimensional profile information one layer off another, and finally the three-dimensional solid parts are formed in substrate, with the laser cladding method. And it’s a fusion and solidification process essentially, which involves complicated interactions between the laser beam, metal powders, the base material (substrate), and processing gases. Typical physical phenomena in laser cladding include laser-powder interactions, heat transfer, fusion, and solidification. There are approximately [2-4] variables which strongly influence the characteristics of the clad part. These variables include actual laser power, spatial distribution (model) of the laser beam, powder delivery gas flow, powder feed rate, material parameters, powder parameters, powder carry method, height increment per layer, percentage overlap between tracks, and tool-path patterns. Some of these processing parameters are strongly coupled with each other. These processing parameters are necessary to obtain the desired dimensional accuracy and material integrity of laser clad parts. Process optimization requires both theoretical and experimental understanding of the associated physical phenomena.

In the past decades, many analytical and numerical LMDS models have been developed by researchers, revealing the temperature gradient ([1], [5]-[12], [17]-[20]), as human people difficult to measure many of the physical phenomena, directly ([13]-[16]). Recently, three-dimensional laser forming simulations have been conducted using commercial FEA software or manual programming.Long et al[20] developed a three-dimensional temperature field and stress field during
multi-track & multi-layer laser metal deposition shaping (LMDS) process with ANSYS parametric design language (APDL). In their work, a multi-track & multi-layer part was deposited on a substrate, and the temperatures of those nodes in molten pool were set as the melting point at each incremental step. IBARRA-MEDINA J et al. [17] verified experimentally that the spatial concentration profile of a converged coaxial powder flow can be approximated by a Gaussian distribution.

In this paper, according to the “element birth and death” [20] technique, a three—dimensional finite element model was developed with APDL. To minimize the deformation and craze in cladding by residual stress that result of temperature gradient, we calculated the energy compensation of interaction between molten pool-powder and laser-powder, in numerical simulation of heat transfer. By this way we can obtain more precise results of numerical simulation. It offers a cost-efficient way to better understand the related complex physics in a laser cladding process, which helps to reveal the effects and significance of each processing parameters on the desired characteristics of cladding parts.

Assumptions

To show the process of laser metal deposition shaping of Titanium alloy, we make the following assumptions:

a. Laser beam profile is assumed to be Gaussian and constant along the Z direction.

b. The solid and liquid phases are considered as a continuum medium.

c. The shape of the powder particle is spherical, and it gets melted in the region of the liquid surface immediately.

d. The X-directional, Y-directional and Z-directional displacement of the two Y-directional end faces of substrate are all restricted to zero.

e. The thermal thermo-physical parameters of deposited material and substrate are treated as a function of temperature. Both are isotropic materials.

f. In the process, gasification of surface is ignored.

Laser-powder interaction

When the laser beam pass through the concentric powder stream that jetted from a coaxial nozzle, the power of laser is attenuated by absorption, reflection, and scattering effects of powders. Meanwhile, the temperature of powders rises and even phases changes before reaching the substrate. It has been verified experimentally that the spatial concentration profile of a converged coaxial powder flow can be approximated described by a Gaussian distribution as defined in the following equation [17]:

\[ N(r, l) = N_{\text{max}}(l) \exp\left(-\frac{2r^2}{R_f^2}\right) \]  

Where \( N \) is the number of powder particles in a unit volume, and it is a function of radial distance \( r \) and axial distance \( l \) in an axial-symmetrical coordinate; \( N_{\text{max}}(l) \) is the peak concentration at the center of powder flow (where \( r = 0 \)), and \( R_f \) is the effective radius of the powder stream at axial distance \( l \). According to the Beer-Lambert law, the attenuation of laser beam intensity after passing through a distance \( l \) in the powder flow can be expressed as

\[ q_{\text{ext}} (r, l) = q(r) \exp(-\sigma_{\text{ext}} Nl) \]  


Where \( q_{il}(r,l) \) is new attenuated laser power density, \( q_{i}(r) \) is original power density, and \( \sigma_{ext} \) is the mean extinction area of powder particles. Laser power attenuation can be calculated step by step along the axial axis (from nozzle exit to the melt pool surface), where the attenuated laser power density of the upper layer is used as the incident power density of the adjacent lower layer. The powder particles get heated when absorbing the laser energy. The temperature rise of the powder particles can be calculated with the following heat balance equation:

\[
q_{il}(r,l) \cdot \alpha_{f} \cdot \pi r_{f}^{2} \cdot \Delta f = \frac{4}{3} \pi r_{f}^{3} \cdot \rho_{f} \cdot C_{p} \cdot \Delta T
\]

(3)

Where \( \alpha_{f} \) is the absorption coefficient of particles, \( r_{f} \) is the radius of the particle, \( v_{f} \) is the particle velocity, is the particle density, \( C_{p} \) is the specific heat of the particle, and \( \Delta T \) is the temperature rise of particles. The temperature rise of particles can also be calculated layer by layer along the axial axis using the attenuated laser power of each layer.

**Government equation**

\[
\frac{\partial (\rho h)}{\partial t} + \text{div}(\rho U h) = \text{div}(\Gamma_{h} \text{grad} h) + S_{h}
\]

(4)

Where \( h \) is enthalpy. The diffusion coefficients is \( \Gamma_{h} \), and source terms is \( S_{h} \), respectively. The first term of left equation is Non–Steady term, and the second term is convective transport term, the first term of right equation is diffusion term, and the second term is general Source term.

**Latent heat of fusion**

In the process of LMDS, the metal material will be phase change, and it will absorb or release some energy. So we must take into account the latent heat. The latent heat of fusion can be calculated with enthalpy

\[
H = \int_{T_{0}}^{T} \rho c(T) dT
\]

(5)

Where \( \rho \) is the powder density, \( c(T) \) is the TC4 powder specific heat.

**Boundary conditions**

\[
q = q_{i}(r)A_{b} + q_{f} - A_{b}(T - T_{0}) - \sigma \alpha(T^{4} - T_{0}^{4})
\]

(6)

Where \( A_{b} \) denotes the heat transfer coefficient of the forced convection, \( T_{0} \) is the ambient temperature, and \( \sigma \) and \( \varepsilon \) denote the Stefan-Boltzmann constant and the emissivity, respectively. \( q_{f} \) is the Gauss heat source, \( q_{i} = \frac{q_{i}(r)}{\pi r_{f}^{2}} \cdot \text{exp} \left[ -\frac{r^{2}}{R_{b}^{2}} \right] \), \( r = \sqrt{(x-v_{s} t)^{2} + y^{2}} \), \( R_{b} \) is effective radius of the laser beam. \( r \) is radius of Laser, \( v_{s} \) is scanning velocity of the laser beam. The actual laser power absorbed by the workpiece is a function of the material absorptivity \( \alpha \) and the laser beam incident angle \( \theta \). An absorption coefficient is defined in an empirical equation as \( A_{a} = \alpha \left[ \cos(\theta) \right]^{0.2} \) \( (\alpha = 0.1) \), \( L_{m} \) is the latent heat of fusion. \( T_{m} \) is the melting point. The powder addition speed \( F_{f} \) can be formulated according to:

\[
F_{f} = N_{f}(r)v_{f} \cdot \frac{4}{3} \pi r_{f}^{3} \cdot q_{f}
\]

\( q_{f} \) is the extra energy brought by the addition of the heated powder (assuming the powder has the same material properties as the substrate) can be expressed as

\[
q_{f} = F_{f} \cdot \rho \left[ C_{p}(T - T_{0}) - C_{p}(T_{m} - T) - L_{m} \right]
\]

(7)
Model of finite element method
As shown in Fig.1 based on “birth and dead element” technique, we built the model of finite element method of LMDS with APDL (ANSYS Parametric Design Language).

![Fig.1 The FEM model](image)

![Fig.2 Schematic diagram of short edge parallel reciprocating scanning method](image)

The overall computational domain size is 50mm*4mm*3 mm in X, Y and Z. The size of grid is 1mm*1mm*1mm, and the element is SOLID5. The metal material of both the clad and substrate are TC4 (Ti-6Al-4V). The chemical compositions are listed in Table 1, and its partial thermo-physical parameters are listed in Table 2. The scanning method is short edge parallel reciprocating scanning method (as shown in Fig. 2).

Table 1 Chemical compositions of TC4

| Chemical compositions | H  | O  | Al | N  | C  | V  | Si | Fe | Ti |
|----------------------|----|----|----|----|----|----|----|----|----|
| percent (W%)         | ≤  | ≤  | ≤  | ≤  | ≤  | ≤  | ≤ 0.039 | ≤  | bal |
|                      | 0.009 | 0.16 | 6.02 | 0.027 | 0.05 | 4.00 | 0.15 |

Table 2 Partial thermo-physical parameters of TC4

|                  | temperature (°C) | Heat transfer coefficient (W/°C *m) | Specific heat (J/kg*°C) | density (kg/m3) | Elastic modulus (Pa) | Linear expansion coefficient (1/°C) | poissonratio (PRXY) |
|------------------|-------------------|------------------------------------|--------------------------|------------------|----------------------|-----------------------------------|--------------------|
|                  | 20                | 17                                 | 500                      | 4420             | 1.2E11               | 0.9E-5                            | 0.3                |
|                  | 200               | 15                                 | 580                      | 4420             | 1.1E11               | 0.965E-5                          | 0.31               |
|                  | 400               | 15                                 | 595                      | 4420             | 0.88E11              | 1.107E-5                          | 0.325              |
|                  | 600               | 16                                 | 615                      | 4420             | 0.7E11               | 1.004E-5                          | 0.342              |
|                  | 1530              | 20                                 | 760                      | 4420             | 0.035E11             | 1.005E-5                          | 0.38               |
|                  | 1650              | 20.5                               | 840                      | 4420             | 0.03E11              | 1.006E-5                          | 0.384              |
|                  | 2000              | 21                                 | 730                      | 4420             | 0.001E11             | 1.008E-5                          | 0.39               |

Simulation results and analysis of the temperature field
We assumed the Laser beam power is 1500W, the effective radius of Laser beam is 1mm, scanning velocity of the Laser beam is 5 mm·s⁻¹, the powder addition speed is 3 g·min⁻¹, ambient temperature is 293 K, in the process. The whole process lasted for 120s.
As shown in Fig.3, the temperature field distribution at different time. So it need 40s for scanning single layer, as Fig3(a), (b) shown the temperature field distribution while Laser scanning the middle point and end point of first layer respectively. The same way, In Fig3(c), (d) shown the temperature field distribution while Laser scanning the middle point and end point of first layer respectively. Fig3 (e) (f) shown the temperature field distribution while Laser scanning the centre point and end point of first layer respectively. We discovered that the movement of the temperature field distribution was associated with the laser beam. And the heat-affected region was extending gradually, temperature of the substrate and cladding rising gradually. For associated with layers was adding, the clay region was heated continually in the process. The energy was accumulating to obvious slow the cooling rate of new cladding. Although for heat transfer the substrate only two ways by convection and radiation, the substrate temperature rised.

In Fig4 (a)(b)(c)(d)shown The temperature variations of points in different layers coordinate of the points are (0.03,0,0),(0.03,0,0.001),(0.03,0,0.002)(0.03,0,0.003), respectively.

a. Temperature variations at point(0.03,0,0)b. temperature variations at point(0.03,0,0.001)

a. Temperature variations at point(0.03,0,0.002)d. temperature variations at point(0.03,0,0.003)

Fig4. Temperature variations of points in different layers
Compared Fig 4 (a) with Fig 4 (b), we can discover the temperature of the substrate declined obviously, that is because of the effect that Powders shaded to the substrate of energy absorption. From the Fig 4(b) we can be see that the temperature variations of points in first layer changed periodically, but amplitude of the change was down gradually. And the system Temperature rised. It’s the joint result of thermal accumulation and the laser scanning periodically, when laser pass through the point, Temperature of the point rapidly went up and down. When the laser pass through the points of second layer and third layer at t=60s and t=100s respectively. For Powders shield and absorption, the amplitude of temperature variation of other points are less than the variation amplitude that laser direct scanning the point of first layer at t=20s. For thermal accumulation effect, the system temperature was raise. 

Temperature variation of the points in 2nd or 3rd layers was similar to the variation of first layer. Just delayed 40s, 80s respectively. (In Fig 4 (c), Fig 4 (d))Because of the points was not activated in those time.

The Fig 5 are temperature gradient of different times, the following can be concluded: (1) The temperature gradients of samples are larger near the molten pool area; (2) it was mainly along z-direction.

**Comparisons to experimental results**

For detected the temperature field of the forming process, to compare with the numerical results, we used the same processing parameters (the Laser beam power is 1500W, the effective radius of Laser beam is 1mm, scanning velocity of the Laser beam is $5 \text{mm} \cdot \text{s}^{-1}$, the powder addition speed is $3 \text{g} \cdot \text{min}^{-1}$, ambient temperature is $293 \text{K}$) in a cladding experiment, in which TC4(Ti-6Al-4V) powder was deposited on a same TC4 substrate. A schematic diagram of the experimental setup is demonstrated in Fig. 6 (a), the photograph of the real object in Fig. 6 (b) shown.

![Fig. 6 The laser direct metal forming system](image)

(a) Schematic diagram of titanium alloy LMDS; (b) The photo of Titanium alloy LMDS system
The pre-processing of experimental steps was as follows: first the TC4 substrate was abraded, to detach the oxide which in the surface and smoother. Then cleaned the surface by acetone, at last the substrate and powders was dried in vacuum at 120°C. We detected the temperature field with infrared temperature measurement instrumentation and thermocouple. We made fixed-point measuring with thermocouple and real-time measuring with infrared temperature measurement instrumentation. The range of the infrared temperature measurement instrumentation and the thermocouple is 400-2500°C and 0-1800°C, respectively. As measuring the substrate with thermocouple, and measuring the molten pool with infrared temperature measurement instrumentation, the range of both are enough, we range considered. The temperature measuring equipment was shown in Fig.7.

![Fig.7 Photo of Temperature measuring equipment](image)

(a) infrared temperature measurement instrumentation (b) thermocouple

We obtained the fixed-point measuring result of temperature variations at the point (0.03,0,0) as shown in Fig.8(a) shown. As the effect of shaded and energy absorption of powders, the temperature of points in the substrate are less then points in the cladding. The trend of the temperature variations in consonance with Fig.4(a) shown. And we compare the numerical results with experiment results, Finally, the inaccuracy is less than 10%. In Fig.8(b) show the real-time measuring temperature results of region that approach the molten pool. As the effect of shaded and energy absorption of the organic glass, the temperature of points that measured are somewhat less than reality, but the temperature field distribution of reality in consonance with results of numerical simulation(in Fig.3(b). And we compare the numerical results with experiment results, Finally, the inaccuracy is less than 16%.

![Fig.8 Measuring results](image)

(a) fixed-point measuring result of temperature variations at the point(0.03,0,0) ;(b) real-time measuring temperature results of region that approach the molten pool

**Conclusions**

1. A numerical simulation of three-dimensional temperature field and stress field during laser metal deposition shaping (LMDS) process is developed with ANSYS parametric design language (APDL). The dynamic variances of temperature field of forming process are calculated with the energy compensation of interaction between molten pool- powder and laser-powder.
2. Although the nodes on different layers are activated at different time, their temperature variations are similar.
3. The temperature gradients of samples are larger near the molten pool area and mainly along z-direction.
4. We verified that the analysis results are consistent with actual situation by the experiments with same process parameters.
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