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ARTICLE

3D Dynamic Simulation Analysis of Thermal-Mechanical Coupling during 7075 Aluminum Alloy Micro-droplet Deposition Manufacture

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Abstract: In aluminum alloy droplet deposition manufacture process, thermal warping, layering and hot cracking of formed 3D components are the most common defects, which have been found to be associated with the large temperature gradient and thermal stress concentration. To obtain insight into the common defects formation mechanism in metal micro-droplet deposition manufacture, a 3D transient finite element (FE) simulation model has been developed by the APDL(ANSYS) code and element birth-death technique. The distribution and variation of time-dependent temperature and thermal stress fields were predicted and the thermo-mechanical behaviors were analyzed in fabricating aluminum alloy 3D components. And then, a series of deposition experiments were conducted using 7075Al alloy droplets under the setting process parameters (same to the initial and boundary conditions). The results show that the experimental results basically agree with the simulation results of thermo-mechanical behaviors. The reliability and correctness of the simulation model were verified experimentally by the measured temperature field and the observation of thermal deformation and hot cracking of formed 3D component. The work provides a useful theoretical and experimental guide for optimizing metal droplets deposition manufacture.

Key words: droplet deposition; thermal-mechanical coupling; element birth-death technique; thermal stress

Metal micro-droplet deposition manufacture (MDDM) is an important method of metal parts additive manufacturing (AM) technology [1-3]. In the process of fabricating functional metal components, the metal droplets fusing together to form components is a complicated fluid and thermal behavior process, which includes impacting, remelting, cooling and solidifying of metal droplets [4-6]. Obtaining good metallurgical bonding of droplets, optimizing the microstructure and restraining the thermal deformation and hot cracking of forming component are regarded as three key control objects, which determine the forming qualities of components. For achieving a good metallurgical bonding between adjacent droplets by remelting their interfacial region, it is necessary to determine an appropriate remelting temperature condition. Liu analyzed and measured the thermal behaviors of a nickel droplet impacting on three different substrates [7]. The thermal behavior of multi-droplets during spray atomization and deposition process was studied by Xu[8]. Chao investigated the remelting and bonding of deposited aluminum alloy (7075Al) droplets at different droplet and substrate temperatures [9].

During metal micro-droplet deposition manufacture, the metal droplet materials are dynamically deposited and the heat source is instantly inputted with a certain track. The above process characteristic makes the internal different areas of formed component with larger temperature gradient in the whole fabricating stage [10]. The growth of internal grain formed parts presented an obvious direction selectivity; and the thermal stress concentration could be produced, further leading to thermal deformation and hot cracking of formed parts [11]. Therefore, it is very important

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to accurately ascertain the production mechanism and the dynamic distribution of temperature and thermal stress fields. On this basis, it is urgent to obtain the theoretical guide for optimizing the microstructure and restraining the thermal deformation and hot cracking of forming 3D component in MDDM.

The metal droplet deposition manufacture is a nonlinear, non-equilibrium and transient heat conduction process accompanied with liquid-solid phase transitions in the whole fabricating stage. So, it is difficult to research the distribution and variation of temperature and thermal stress fields of forming process by adopting a direct measurement method. At present, the numerical simulation method was mostly adopted to investigate the thermal stress and thermal deformation of formed components caused by moving heat source (laser and welding arc) in AM technology. Zhang[12] analyzed the distribution of thermal stress concentration and the tendency of stray grain formation during multi-bead pulsed laser powder deposition. Zhao[13] investigated the effects of depositing directions on the thermal process of weld-based rapid prototyping. In a word, during laser and weld-based rapid prototyping, the distribution and variation of forming temperature and thermal stress fields have been well predicted and analyzed by numerical simulation.

But, there is seldom investigation on the thermo-mechanical behaviors of MDDM in fabricating 3D aluminum alloy components. In the present paper, a 3D finite element numerical model was developed to simulate the thermal process of metal droplets deposition using element birth and death technique. A deposition experiment of aluminum alloy component was carried out to validate the simulation results. The work provides a meaningful guidance for optimizing MDDM process.

1 Process Principle and Experimental Setup

Fig.1 shows schematic diagram of process principle and experimental setup of metal micro-droplet deposition manufacture. The experimental setup was developed, which mainly included a drop-on-demand generator, a droplet deposition system, a temperature measurement and control system, a process monitor system, and an inert environment control system. The ejection of droplets and the motion of deposition substrate are controlled by the experimental system according to the AM procedure file, and the metal part is fabricated by sequentially depositing metal droplets layer by layer.

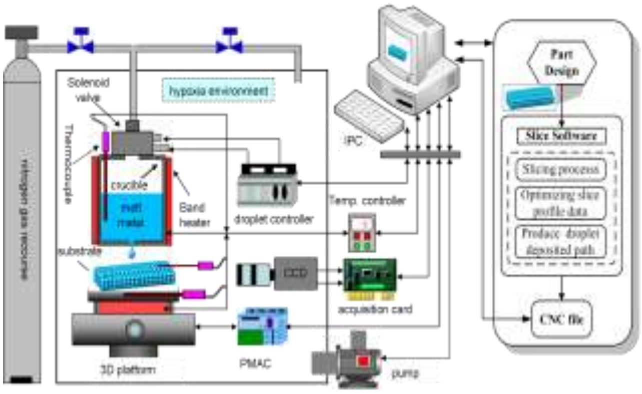

Fig.1 Schematic diagram of process principle and experimental setup

2 Establishing Theoretical Calculation Model

2.1 Heat input and output analysis

During the metal micro-droplet deposition manufacture process, the molten metal droplet (as a heat source) is dynamically deposited and inputted into the fabricated part with a certain track, and the heat accumulation of formed parts depends on the heat input and output, which can be described as the following equations:

$$\int_0^t H_{\rm cum}{\rm d}t = \int_0^t H_{\rm input}{\rm d}t - \int_0^t H_{\rm output}{\rm d}t \tag{1}$$

$$\int_0^t H_{\rm cum}{\rm d}t = \int_0^t H_{\rm drop}{\rm d}t - \int_0^t H_{\rm cond}{\rm d}t - \int_0^t H_{\rm conv}{\rm d}t - \int_0^t H_{\rm rad}{\rm d}t \tag{2}$$

where, $H_{\rm cum}$ is the heat accumulation in MDDM process, $H_{\rm drop}$ is the heat source of droplet, $H_{\rm input}$ is the heat input of heat source which is equal to $H_{\rm drop}$, and $H_{\rm output}$ is the heat loss in deposition process, including the heat conduction to the deposited part $H_{\rm cond}$, the heat convection to the ambient $H_{\rm conv}$ and the heat radiation to the ambient $H_{\rm rad}$.

2.2 Heat conduction equation

The temperature field analysis of MDDM is no internal heat source, non-axisymmetry and unsteady heat conduction problem. The third dimensional transient heat conduction equation in cartesian coordinate system can be given as:

$$\rho c\frac{\partial T}{\partial t} = Q + \frac{\partial}{\partial x}(K_x\frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(K_y\frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(K_z\frac{\partial T}{\partial z}) \tag{3}$$

where, ρ is material density, c is specific heat, T is temperature, t is time, K_x, K_y and K_z are heat conductivities of mini-element at x, y and z direction, respectively.

2.3 Thermal-structural coupled finite element matrix equation

In ANSYS thermomechanical analysis, the thermal-structural coupled finite element matrix equation derived from the stress equation of motion and the heat conservation equation coupled by the thermoelastic constitutive equations is as follows[12]:

$$\begin{Bmatrix}\{F\}\\ \{Q\}\end{Bmatrix} = \begin{bmatrix}[M] & [O]\\ [O] & [O]\end{bmatrix}\begin{Bmatrix}\{\ddot{u}\}\\ \{\ddot{T}\}\end{Bmatrix} + \begin{bmatrix}[C] & [O]\\ [C^{tu}] & [C^{t}]\end{bmatrix}\begin{Bmatrix}\{\dot{u}\}\\ \{\dot{T}\}\end{Bmatrix} + \begin{bmatrix}[K] & [K^{ut}]\\ [O] & [K^{t}]\end{bmatrix}\begin{Bmatrix}\{u\}\\ \{T\}\end{Bmatrix} \tag{4}$$

where, $\{F\}$ is the sum of the element nodal force, $\{Q\}$ is the sum of the element heat generation load and element convection surface heat flow vectors, [M] is the element mass matrix, [C] is the element structural damping matrix, [K] is the element stiffness matrix, {u} is the displacement vector, [C^t] is the element specific heat matrix, [K^t] is the element diffusion conductivity matrix, {T} is the temperature vector, [K^{ut}] is the element thermoelastic stiffness matrix, and [C^{tu}] is the element thermoelastic damping matrix.

2.4 Initial and boundary conditions

The initial and boundary conditions applied to the meshed finite elements can be represented mathematically as follows.

$$T_e = T_e(x, y, z, t) \quad (5)$$

$$q^* = h_f (T_s - T_B) \quad (6)$$

where, T_e is the distribution of temperature in boundary, q^* is the convective heat flux vector, h_f is the convective heat transfer coefficient, T_s is the surface temperature of part and T_B is the environmental temperature. In the deposition substrate temperature T_{sub} = 450 ℃, the initial droplets temperature T_{drop}=700 ℃, the gaseous environmental temperature T_B=35 ℃, and the natural-convection heat transfer h_f=40 W/(m^2·℃).

2.5 Finite element meshed model

According to the actual process feature, a 3D finite element meshed model of droplet deposition manufacture was developed, which includes a substrate (40 mm×16 mm×4 mm) and a fabricated component (30 mm×8 mm×5 mm) as shown in Fig.2. The thermal-structural coupled finite element solid5 (Hexahedral eight nodes) was used to mesh model and analyze the nonlinear transient heat transfer and thermal stress issue. The node positions of 1~10 were set and located in the 1~5 layers of 3D finite element meshed model. Fig.3 shows the droplets deposition direction and trajectory layer by layer. The APDL code and element birth-death technique was adopted to realize dynamical loading of the droplet material and heat source with the setting deposition direction and trajectory.

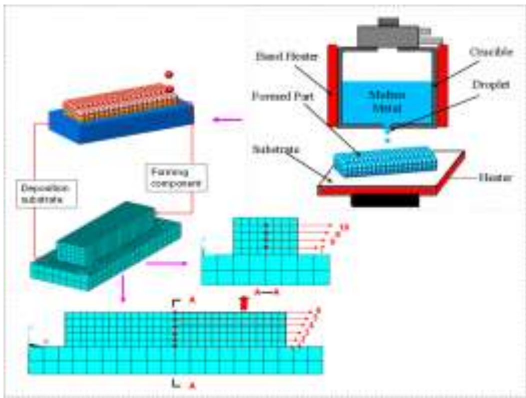

Fig.2 3D finite element model of droplet deposition manufacture

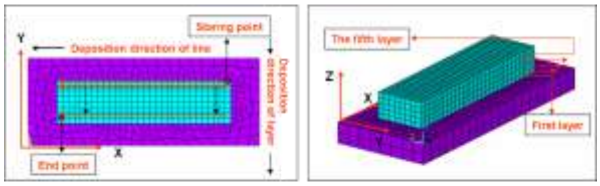

Fig.3 Droplets deposition direction and trajectory layer by layer

2.6 Material thermomechanical properties

Because the material thermomechanical properties have an impact on the accuracy of numerical simulation results, the thermal-structural finite element analysis requires accurate values of thermal conductivity, specific heat, material density, latent heat of fusion, linear expansion coefficient, elasticity modulus and shear modulus. The thermomechanical properties of material are dependent on temperature, as shown in Table 1.

3 Simulation Results and Analysis

3.1 3D distribution and evolution of temperature field

Fig.4 shows the simulation results of temperature field. It is observed that the high-temperature area (over 600 ℃)

Table 1 Thermomechanical properties of 7075Al alloy

Temperature/ ℃	Density/ kg·m^{-3}	Specific heat/ J·(kg·K)$^{-1}$	Thermal conductivity /W·(m·K)$^{-1}$	Enthalpy/ J·g^{-1}	Linear expansion coefficient/10^{-6}K^{-1}	Elasticity modulus/GPa	Shear modulus/GPa
25	2811.2	860.4	121.1	13.26	22.99	70.77	26.55
100	2796.5	900.7	129.4	52.85	24.55	67.85	25.40
200	2775.6	943.7	138.6	145.13	26.66	63.95	23.86
300	2753.4	983.6	146.6	241.51	28.82	60.06	22.31
400	2729.8	1024.2	154.1	341.51	31.01	56.16	20.77
500	2704.9	1136.6	160.5	452.16	33.25	51.22	18.81
600	2630.0	5697.9	131.6	669.83	39.46	50.42	3.58
700	2477.9	1123.4	83.86	1044.07	51.11	10.11	0.00

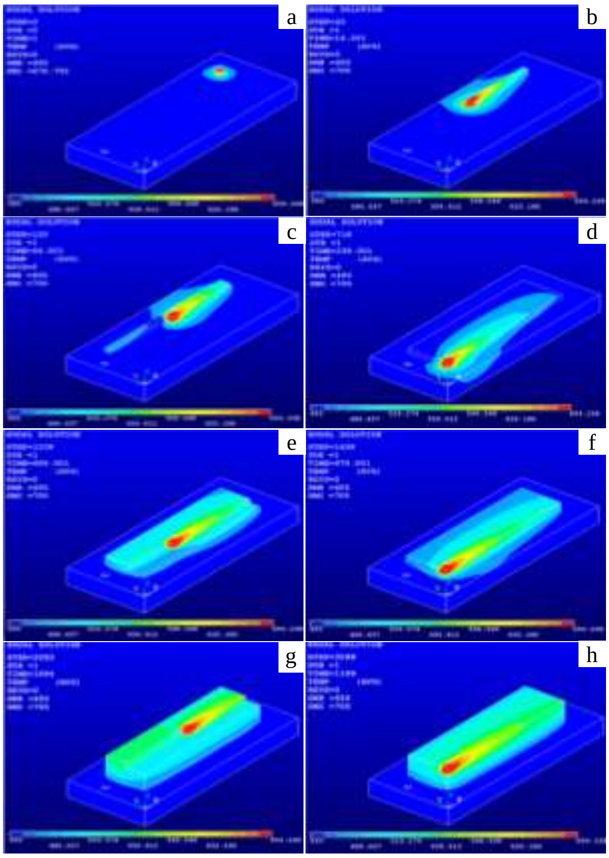

Fig.4 Temperature field evolution of micro-droplet deposited 3D component: (a~d) deposition of first layer, (e~f) deposition of second layer, and (g~h) deposition of fifth layer

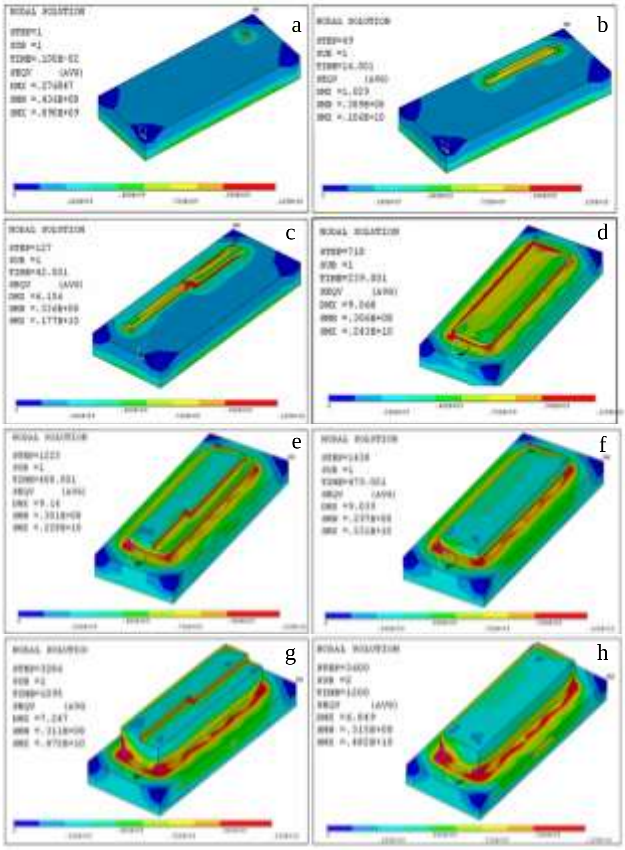

Fig.5 Evolution of Von Mises equivalent thermal stress in droplet deposited 3D component: (a~d) deposition of first layer, (e, f) deposition of second layer, (g, h) deposition of fifth layer

of previously formed part mainly focuses on the droplet deposited position and surrounding local, which also becomes larger gradually with the rising of deposition layer height. During deposition of first layer (4a~4d), the droplets directly contact with the deposition substrate, the temperature difference between them is larger, the cooling rate of deposited droplets is rapid, and the heat of droplets is instantly transferred to the substrate, leading to lower surface temperatures of previously deposition droplets.

3.2 3D distribution and evolution of thermal stress

During metal micro-droplet deposition manufacture, the driving force for thermal deformation and hot crack formation is the severe thermal stresses, which have been developed upon solidification of the deposited droplets. Corresponding to the 3D temperature gradient simulation results, distributions of thermal stress have been calculated. Fig.5 shows the evolution of Von Mises equivalent thermal stress in droplet deposited 3D component. It is observed that thermal stresses mainly concentrate on the interface between the deposition droplets and the substrate during deposition first layer (Fig.5a~5d). Along with the increasing of deposition layer height (Fig.5e~5h), the heat accumulation effect is enhanced, and the temperature gradients are decreased in different layers, which decreases the thermal stresses in deposition layers (2~5). Fig.5h shows the distribution of thermal stress field at the time of completing part. The thermal stress concentrates mainly on both ends of part and the bonding area between the deposition part and the substrate, caused by the temperature gradient and material thermo-mechanical properties.

For further analysis, the thermal stress cycle curves of position nodes 1~10 were acquired in *x*, *y* and *z* direction. As shown in Fig.6, the positive stress values express compressive stress and the negative stress values express tensile stress in ANSYS. In *x* and *z* direction, the thermal stresses of nodes 1~6 mainly display the tensile stress and the values are larger. However, in *y* direction, the thermal stresses of nodes 1~6 mainly display the compressive stress and the values are relatively small. For the nodes 7~10 in *x* and *y* direction, the thermal stresses initially display the compressive stress and subsequently display the tensile stress. In *z* direction, the thermal stresses of nodes 7~10 mainly display the compressive stress.

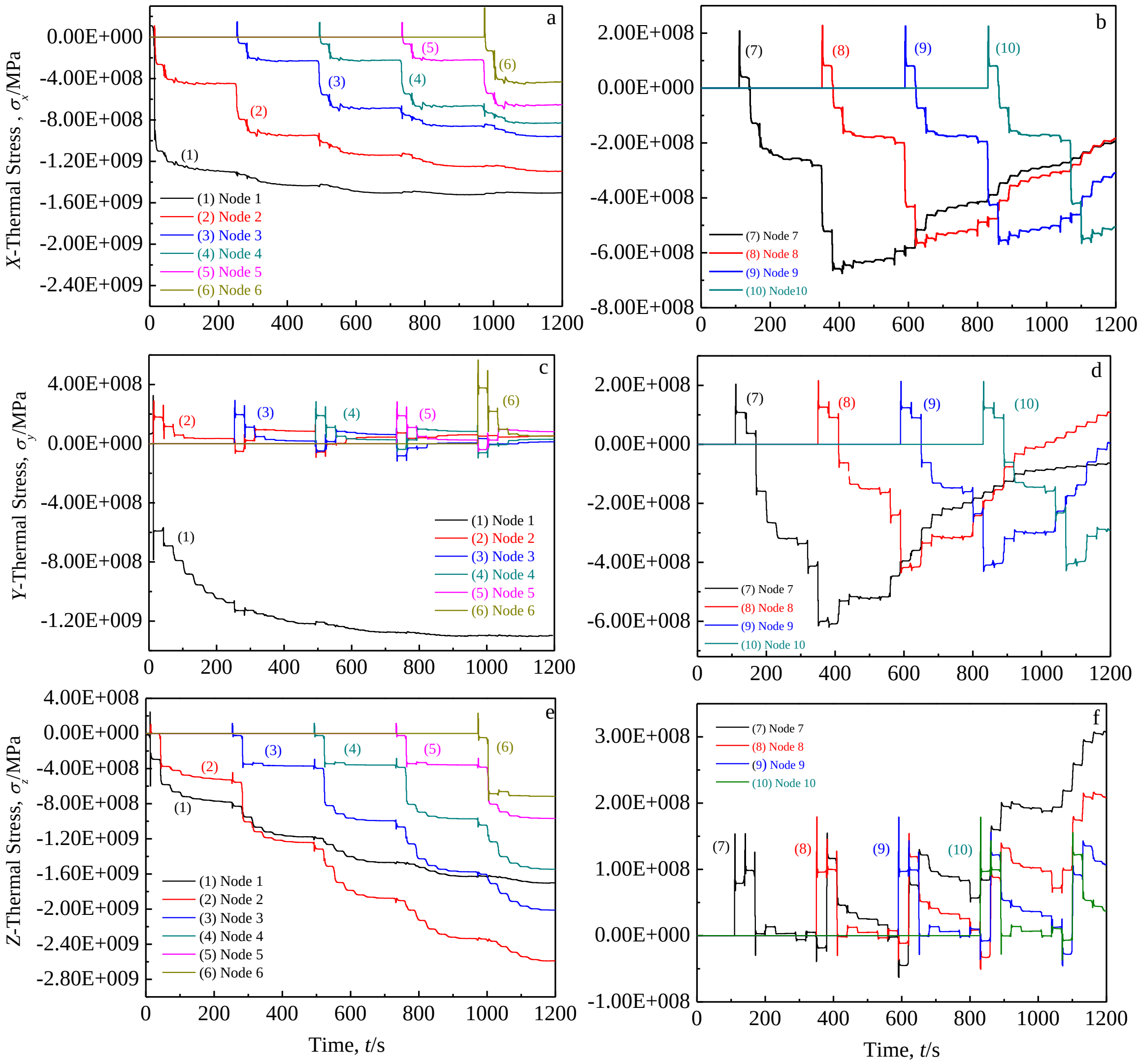

Fig.6 Thermal stress cycle curves of nodes 1~10 in *x* direction (a, b), *y* direction (c, d), and *z* direction (e, f)

4 Experimental Results and Discussion

A series of experiments were conducted for 7075Al alloy droplets under the setting process parameters (same to the initial and boundary conditions) in order to validate the simulation results. Table 2 lists the main process parameters of deposition experiments. Fig.7 shows the thermocouple and the schematic diagram of temperature measurement. A 0.3 mm diameter and 320 ms response time thermocouple was used to measure the temperature of selected position node. The thermocouple could be horizontally inserted into the formed part at any desired position before droplets landed on it. Temperature data were collected in real time by a data acquisition system (national instrument). A 3D component (30 mm×8 mm×5 mm) was fabricated under the process parameters listed in Table 2. The temperature evolution of position node 4 was measured. Fig.8 shows the comparison of node temperature between simulation and experiment for node 4. It is observed that the variation trend of node 4 temperature is basic accordance between simulation and experiment results, validating the correctness of simulation model.

Fig.9 shows the deposition experimental results of 3D component. As shown in Fig.9a, there is the obvious thermal deformation of formed component, the thermal deformation area concentrates mainly on both ends of component and the thermal deformation is upwarping, which are consistent with the simulation result of thermal stress (in Fig.5 and Fig.6). The microstructure of thermal deformation area is shown in Fig.9b, the tiny hot crack is discovered along the stray grain boundaries and the morphology is irregular. Fig.9c shows the surface topography of deposited layer. It can be seen that the deposition droplets have a series of ridges around contact

Table 2 Process parameters of 7075Al alloy deposition experiments

Parameter	Value
Droplet diameter, D/mm	1.2
Deposition frequency, f/Hz	1
Substrate velocity, V/mm s^{-1}	0.95
Solidification angle of droplet, θ/(°)	110
Droplets overlapping ratio, η/%	26.3
Droplet temperature, T_{drop}/ ℃	700
Substrate temperature, T_b/ ℃	450

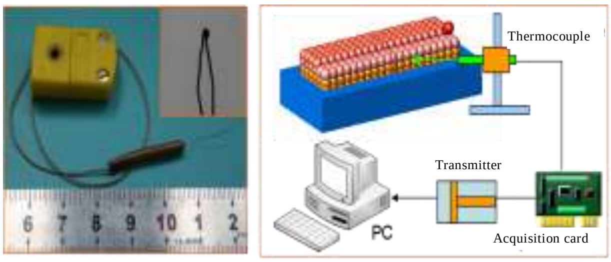

Fig.7 Schematic diagram of temperature measurement

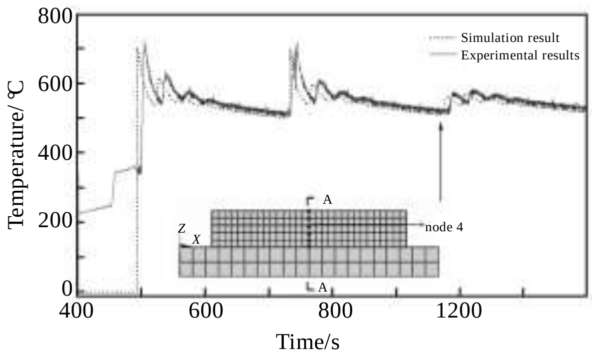

Fig.8 Comparison between simulation and experiment results for node 4

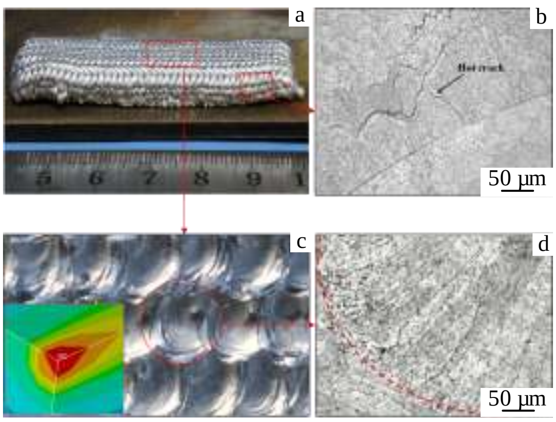

Fig.9 Deposition experimental results of 3D component: (a) the shape of formed component, (b) the microstructure of thermal deformation area, (c) the surface topography of deposited layer, and (d) the grain characteristics of single deposited droplet

interface, which is the direct result of layered solidification and oscillation consisting of alternately spreading and recoiling of the droplets. Fig.9d shows the grain characteristics of single deposited droplet, and the grain nucleation is grown towards columnar morphology along the contrary direction of heat flux in bonding interface, which are consistent with the simulation results of temperature gradients. Based on the above analysis, the experimental results basically agree with the simulation results of thermo-mechanical behavior.

5 Conclusions

1) The high-temperature area of formed component mainly focuses on the droplet deposited position and surrounding local in the whole fabricating stage.

2) The maximum thermal stress concentrates mainly on both ends of formed component and the boundaries of bonding area between deposition droplets and the substrate. The thermal stress cycle curves of position nodes (1~10) display variational compressive stress and tensile stress in x, y and z direction.

3) The experimental results of 3D component are basically in agreement with the simulated results, and the thermo-mechanical behaviors are preferably presented and analyzed in MDDM. The work provides an useful theoretical and experimental guide for optimizing metal droplets deposition manufacture.

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7075 铝合金微滴打印沉积制造中热力耦合 3D 动态仿真分析研究

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摘　要：翘曲、分层、开裂是7075铝合金微熔滴沉积制造过程中常见的缺陷，其原因主要是沉积制造过程中存在较大的温度梯度和热应力集中。为了探究热变形、翘曲和开裂的形成机理，采用有限单元法和单元生死技术，通过APDL (ANSYS)编程，建立了气动按需熔滴沉积成形温度和热应力计算模型，分析了7075铝合金微熔滴逐点、逐层沉积三维制件过程中温度和热应力的动态演变规律。并使用7075铝合金微滴，在相同初始边界条件和工艺参数下进行了沉积试验，模拟结果与7075铝合金制件微熔滴沉积试验结果基本吻合，较好地反映了实际成形过程中零件的温度和热应力场变化规律，为减少或消除铝合金微熔滴沉积制造过程的缺陷提供了理论依据，从而促进了该技术在高熔点合金零件制备中的应用。

关键词：微滴沉积；热力耦合；单元生死技术；热应力

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