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ARTICLE

Process Optimization of Surface Morphology and Internal Quality Based on Metal Droplets Horizontal Lapped Deposition

Li Suli[1, 2], Yang Laixia[1], Lu Bingheng[2]

[1] Xi'an University of Science and Technology, Xi'an 710054, China; [2] State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University，Xi'an 710049, China

Abstract: During horizontal lapped deposition and solidification of an aluminum molten droplet onto an aluminum substrate, the effects of different process parameters on the surface morphology and interior quality of the specimens were studied. By researching the single metal droplet deposition behavior, a numerical model of horizontal lapped deposition was established, and the evolution of morphology and temperature of one, two, three and four molten droplets horizontal lapped deposition impacting a substrate surface at different time was analyzed and multiple droplets successively deposition experiments under the different simulation parameters were carried out. The results indicate that the comparison between numerical simulations and experiments shows a good agreement. The optimal parameters were obtained. This investigation is essential to implement effective process control in metal micro-droplet deposition manufacture and it provides technical support and reference for molten droplets horizontal lapped deposition process of the complex metal parts.

Key words: metal droplets; horizontal lapped deposition; surface morphology; internal quality

Rapid prototyping (RP) technology is applied more and more widely in the building of complex parts. Metal droplet deposition process is a new type of RP technology of metal parts in the early 1990s, and the parts can be manufactured by metal droplets deposition without using any mold or other tooling based on discrete/accumulation principle. Droplet-based 3D printing has the feature of low cost and high efficiency compared with the current mainstream 3D printing technology, including: SLS (selective laser sintering)[1], SLM (selective laser melting)[2], LCD (laser cladding deposition)[3] and EBM (electron beam melting)[4], etc.

In previous studies, a lot of related researches of droplet deposition process were low-melting-point metals. For instance, Fang et al[5] fabricated various thin-walled parts by 0.18 mm tin droplets. Liu et al[6] studied the influence of scanning step on metallurgy bonding among Sn60-Pb40 droplets.

However, when this technique was applied to aluminum which had more practical value in industrial areas, they were much more difficult to apply for aluminum because it has the higher melting point, stronger chemical activity, and larger surface tension than low-melting-point metals. For example, Orme et al[7] who studied the microstructural characteristics of aluminum parts, which were fabricated with rapidly solidified molten aluminum droplets. Zhang et al[8] investigated the inter-impinging of two tin droplets with the diameter of millimeter scale and simulated the lap behaviors of droplets. Furthermore, there are a few reports on the lapped process of aluminum droplets deposition.

The horizontal lapped deposition process of molten aluminum droplets were generated by the DOD (drop-on-demand) jetting onto a horizontally substrate surface in the paper. In order to confirm the implications of the numerical simulations and experiment, a single droplet and multiple

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Corresponding author: Yang Laixia, Ph. D., Professor, College of Mechanical Engineering, Xi'an University of Science and Technology, Xi'an 710054, P. R. China, E-mail: 867368760@qq.com

droplets successively deposition experiments were carried out.

1 Numerical Method

1.1 Calculation model

Fig.1 is a simplified model of the droplets contour[9], where HAFH is the first depositing droplet; EBGE is the latter deposition droplet; HABGH is the cross section of the first depositing droplet and the latter deposition droplet; D is the diameter of metal droplets before depositing; θ is contact angle; S_x is distance of the adjacent droplets center.

In the ideal lapped process, the area of the triangle ABC and the triangle CEF should be equal, according to Fig.1[9]:

$$S_{\triangle \mathrm{ABC}} = S_{\triangle \mathrm{CEF}} \tag{1}$$

The lapped ratio indicates the degree of stack between the adjacent droplets, which can be calculated by Eq.(1):

$$\eta = 1 - \frac{S_x}{D} \tag{2}$$

1.2 Calculation method

The fluid flow during the droplet spreading onto the substrate is modeled using the Navier-Stokes equations for incompressible flows:

$$\rho \cdot \frac{\partial V}{\partial t} + \rho(V\nabla)V = -\nabla P + \nabla \mu[\nabla V + (\nabla V)^T] + \rho g + F_{\mathrm{TS}} + F \tag{3}$$

$$\nabla V = 0 \tag{4}$$

where, V is the velocity, P is the pressure, ρ is the density, ∇ is Laplace operator, μ is the kinematic viscosity, g is the gravitational acceleration, F is the term source corresponding to the occurrence of the droplet solidification and F_{TS} represents the capillary forces given by Eq. (5):

$$F_{\mathrm{TS}} = \sigma m \delta k \tag{5}$$

where, σ, δ and m are the surface tension coefficient, Dirac function and average local slop of the curve at the liquid-gas interface, respectively. k is the normal at the liquid-gas interface. Both fluids are assumed incompressible and Newtonian, and the surrounding air has no effect on the deposition process. Other assumptions are that the liquid is incompressible and the fluid flow is laminar.

To track and follow the evolution of the interface between the two fluids (metal droplet and air), we have used the level set method[10] which has been proven popular in recent years for tracking, modeling and simulating the motion of moving interfaces or boundaries. In this method, the interface is represented by a certain level set or iso-contour of a globally defined function, i.e. the level set function θ. This function θ is a smoothed step function that equals 0 in a domain and 1 in its complementary part. Across the interface, there is a smooth transition from 0 to 1 and the interface is represented implicitly by the 0.5 iso-contour. The interface moves with the fluid velocity v. This is described by the following equation:

$$\frac{\partial \theta}{\partial t} + V\nabla\theta = \eta\nabla[\varepsilon\nabla\theta - \theta(1-\theta)\frac{\nabla\theta}{|\nabla\theta|}] \tag{6}$$

The terms of Eq. (6) give the correct motion of the interface, while those on the right-hand side are necessary for numerical stability. The parameters ε and η determine the thickness of the region and the amount of re-initialization or stabilization of the level set function, respectively. Any property α of the two fluids at the interface such as density, viscosity or thermal conductivity may be expressed as:

$$\alpha = \alpha_{\mathrm{gas}} + \theta(\alpha_{\mathrm{liquid}} - \alpha_{\mathrm{gas}}) \tag{7}$$

The process of spreading and solidification of a molten droplet impinging onto a solid surface involves fluid flow, heat transfer and phase change. Complex phenomena involved are not thoroughly understood yet. For example, the interfaces between the droplet and the surrounding gas and between the liquid and solid phases remain a challenging problem to deal with for scientists and engineers.

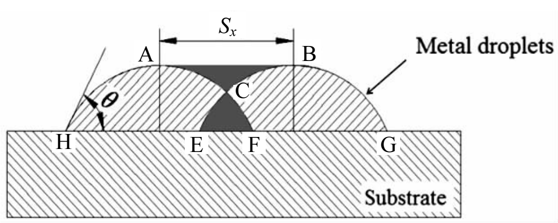

Fig.1 Ideal lapped model[9]

2 Horizontal Lapped Deposition Model

The heat exchange between the droplet, air and substrate is modeled using the energy equation:

$$\rho C_{\mathrm{p}} \cdot \frac{\partial T}{\partial t} + \nabla(-\lambda\nabla T) = -\rho C_{\mathrm{p}} u \nabla T \tag{8}$$

where, u is the spreading velocity of the splat, T, ρ, λ and C_{p} denote the droplet temperature, density, coefficient and specific heat, respectively. The thermal contact resistance is introduced to take into account the discontinuity of temperature at the interface due to the non-perfect contact between the droplet and the substrate. The thermal contact resistance (TCR) is modeled by defining a thin layer of arbitrary thickness L_0. The effective thermal conductivity K_{L} for the splat is related to the TCR by Eq. (9):

$$K_{\mathrm{L}} = \frac{L_0}{\mathrm{TCR}} \tag{9}$$

As the hot droplet spreads on the cold substrate, it cools down and solidifies. Many approaches have been used for modeling solid/liquid transitions. The enthalpy porosity method shows a good ability for modeling some complex problems involving phase change as crystal grow from the melt[11]. The specific heat C_{p} in the energy equation Eq. (9) is replaced by:

$$C_{\mathrm{p}} = C_{\mathrm{P\text{-}solide}} + \frac{\Delta H}{T_{\mathrm{m}}} + \Delta H \delta \tag{10}$$

where, f is a smooth Dirac delta function with nonzero values in a range of temperature equal to ΔT and its integration over temperature is equal to unity, $C_{\mathrm{P\text{-}solide}}$ is the specific heat of solide, ΔH is the latent heat of the transition, T_m is the melting temperature. ΔT is the temperature gap between liquidus temperature ($T_m+\Delta T$) and solidus one ($T_m-\Delta T$), and δ is a Gaussian curve given by Eq. (11):

$$\delta = \frac{\exp[-(T-T_m)^2] \big/ (\Delta T)^2}{\Delta T\sqrt{\pi}} \quad (11)$$

The source term in Eq.(3) is defined in Eq.(12) and serves to slow down the velocity of the fluid at the phase-change interface and eventually arrest its motion as the droplet cools down[11].

$$F = \frac{(1-\beta)^2}{\beta^3+\eta}Cu \quad (12)$$

where, C is the mushy zone constant (should have high value to produce a proper damping), η is arbitrary constant (which should have small value to prevent division by zero), and β is the volume fraction of the liquid phase, given by Eq. (13):

$$\beta = \begin{cases} 0 & T < T_m - \Delta T \\ \dfrac{T-T_m+\Delta T}{2\Delta T} & T_m - \Delta T \le T \le T_m + \Delta T \\ 1 & T > T_m + \Delta T \end{cases} \quad (13)$$

Fig.2 shows the horizontal lapped deposition model. The deposition speed of the Al droplet is V and the substrate moves with a velocity of V_s.

Fig.3 shows the evolution of morphology and temperature of one, two, three and four molten droplets horizontal lapped deposition with a velocity of V=1 m/s impacting a substrate surface at different time and the simulation parameters are shown in Table 1. It is observed that the droplet has been stuck to the substrate and dragged forward in Fig.3a. The spreading diameter shows a trend of increasing, the spreading height h shows a trend of decreasing, and they are all unchanged after 0.06 s, showing that the droplet has been completely frozen. Fig.3b shows the evolution of morphology and temperature of two fusion droplets. When the second droplet deposited on the top right-hand corner of the first droplet is still not fully solidified and continues to spread out after fusion with the second droplet, they are completely frozen until t= 0.08003 s.

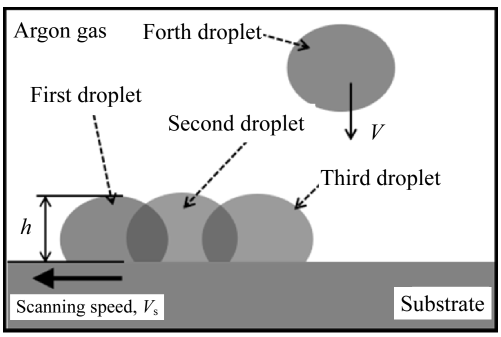

Fig.2 Horizontal lapped deposition model

The third and fourth horizontal lapped droplet closely resembles the second one in morphology and temperature evolution, as shown in Fig.3c and 3d. When the next droplet and the previous droplet begin to fuse, the spreading diameter D increases rapidly, and spreading height h still falls, because the previous droplet is still not fully in contact with the substrate, which is still spreading and fusing. After the previous droplet contacts with the substrate completely, the spreading diameter D and spreading height h are not changed.

The surface tension and viscosity of the metal have a certain influence on the spreading of molten droplets during horizontal lapped deposition. When a molten droplet is fused with the previous one, it will fuse with the next droplet if the first droplet does not solidify completely. Under the same numerical simulation parameters, oxygen levels in the environment under 20 μL/L or less, the experiments of four droplets horizontal lapped deposition were observed, as shown in Fig.4 and the results show good qualitative agreement with experimental photographs at 0.12001 s.

3 Analysis and Discussion

In metal droplet horizontal lapped deposition manufacture, surface and internal quality can be directly reflected in the morphological characteristics and metallurgical defects respectively.

3.1 Influence on the surface morphology

The horizontal lapping of metal droplets refers to the process of piling up in the plane which is parallel to the x-y. A plane is formed by horizontal lapped deposition of many droplets.

When the distance between the adjacent droplets is far away, the insufficiency lap shown in Fig.5a, will decrease the flatness of the surface morphology and then affect the lapped quality of the subsequent layers. However, when the distance is too close, it can lead to excessive lapping (Fig.5c), which not only affects the lapped quality, but also influences the subsequent layers. Therefore, the adjacent metal droplets should be the ideal lap (Fig.5b); and it can be seen that the surface morphology is a flat.

The lapped rate affects not only the surface morphology of the parts, but also the internal quality. Fig.6 shows three different lapping ways of the surface morphology (Fig.6a~6c) and the cross section of the specimen (Fig.6d~6f). The process parameters are shown in Table 2. When the lapping way is inadequate, the gap between the adjacent metal droplets is too large to connect with the entities. When the lapping way is overstretched, the distance is too small and the droplets are easy to be raised. Under different lapping ways, the holes are produced inside the specimen with the inadequate or overstretched lapping way. The optimal distance based on the volumetric invariant method[7] can be used to determine the appropriate lapping distance.

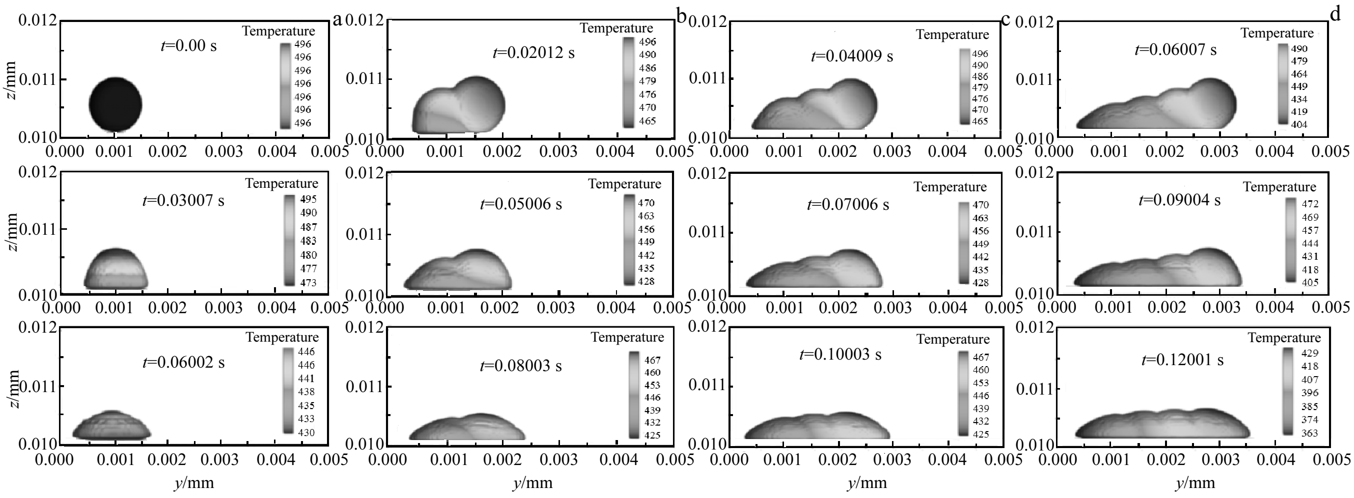

Fig.3 Evolution of morphology and temperature at different time of one (a), two (b), three (c), and four (d) molten droplets horizontal lapped deposition

Table 1 Simulation parameters of horizontal lapped deposition

Parameter	Value
Droplet material	Aluminum
Droplet density, ρ/kg·m^{-3}	2368
Droplet surface tension, σ/N·m^{-1}	0.8
Droplet velocity, V_0/m·s^{-1}	1
Droplet temperature, T_0/K	935
Substrate temperature, T/K	300
Droplet diameter, D_0/mm	1
Inlet pressure, P_s/MPa	0.2
Deposition distance, h_s/mm	10
Solidification angle, θ/(°)	90
Substrate material	Aluminum
Substrate heat capacity, C_P/J·kg^{-1}·K^{-1}	900
Substrate diffusivity/m^2·s^{-1}	9.75×10^{-5}
Substrate thermal conductivity/W·m^{-1}·K^{-1}	237

The distance between two adjacent deposition droplet centers was defined as S_x [7]. When the S_x is 0.914 mm, the distance is larger, and there is a partial lap between adjacent metal droplets; however, the surface morphology of the section is poor and the lapping rate between the droplet is only 8.6%; When S_x is 0.716 mm, the surface morphology is smooth and the overlapping rate is 28.4%; When the S_x is 0.516 mm, because the distance is too small, the droplets grow to the space. The surface morphology is poor and the overlapping rate is 48.4%. So when S_x=0.716 mm, the surface morphology is the best.

The distance between the surface peaks and the trough is H_d, which is shown in Fig.7. These parameters are very important to reflect the surface morphology. The smaller the H_d, the better the surface morphology. The values of H_d, the highest and lowest height of 5 specimens under the condition of the ideal lapping way, insufficiency lapping way and excessive lapping way were measured with KEYENCE VH-8000 micro amplifier for 25 times (Table 3 and Fig.8).

As can be seen from Table 3 and Fig.8, the value of H_d is the biggest with the insufficient and excessive lapping way, and the highest and lowest height of each specimen is more uniform. In ideal lapping way, the value of H_d is the smallest, and the surface smoothness is the highest. It can be seen that the surface is uneven; this affects the forming of the subsequent layers.

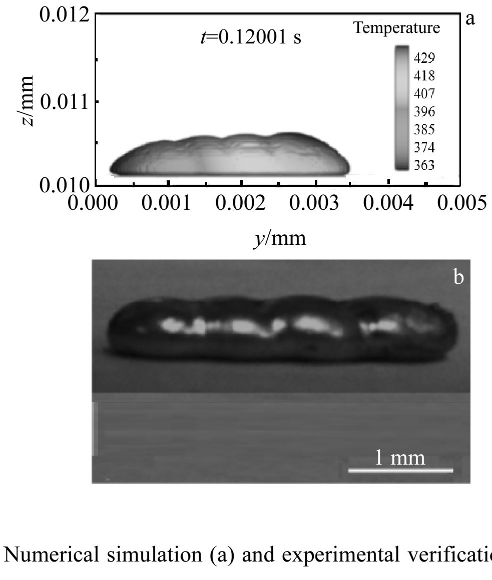

Fig.4 Numerical simulation (a) and experimental verification (b) of four droplets horizontal lapped deposition

Fig.5 Metal horizontal lapped mold: (a) insufficient lapping, (b) ideal lapping, and (c) excessive lapping

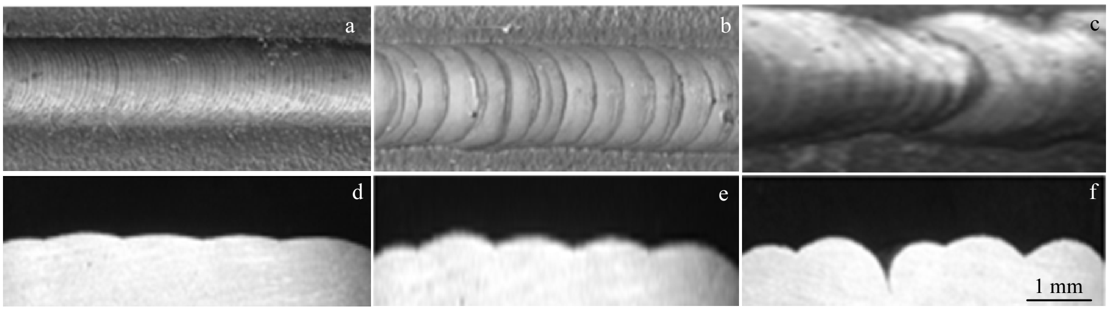

Fig.6 Cross-section surface (a~c) and morphologies (d~f) of a specimen with different lapped way: (a, d) Ideal lapped, (b, e) insufficiency lapped, and (c, f) excessive lapped

Table 2 Experiment process parameters of metal droplet lapping deposition under different S_x

Parameter	Value
Pulse frequency, f/Hz	40
Substrate temperature, T/K	400
Droplet temperature, T_0/K	955
Deposition distance, h_s/mm	5
Pulse pressure, P/MPa	0.40
Nozzle diameter, D_0/mm	0.6
	0.716
Lap center distance S_x/mm	0.914
	0.516
	28.4
Lapping rate, η/%	8.6
	48.4

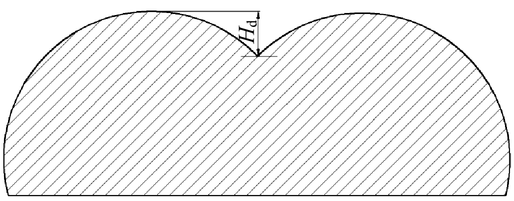

Fig.7 H_d definition

Table 3 Results of H_d, the highest and lowest height of specimens under different lapping ways

Mold	H_d/ mm	The highest value/ mm (from left to right)					The lowest value/mm (from left to right)			
Insufficiency lapping	0.367	0.7	0.8	0.8	0.79	0.8	0.49	0.4	0.42	0.4
Ideal lapping	0.042	0.7	0.8	0.8	0.81	0.8	0.75	0.7	0.78	0.7
Excessive lapping	0.167	0.7	0.8	0.8	0.83	0.8	0.6	0.7	0.6	0.7

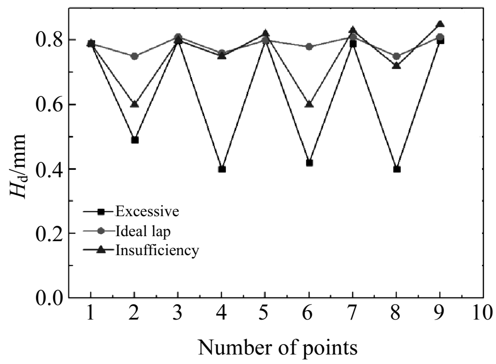

Fig.8 Highest and lowest relationship curves of different lapping molds

3.2 Influence on the internal quality

Microscopic holes and cold isolation are the most common defects in the metal droplet deposition R_P technology[10], because they are mainly affected by Al droplet temperature T_0, substrate temperature T and so on[12]. When T_0 is low, the liquid phase fraction is small, and the lapped gap between the adjacent droplets is difficult to fill completely, so the microscopic holes and cold isolation are easy to form. When T is too low, the droplets will solidify completely in a short time, which influences the spread of the droplets to fill the lapped gap. So the appropriate matching of T_0 and T are necessary to ensure the good remelting and metallurgical bonding between the droplets.

1) Al droplet temperature T_0

The Al droplet temperature T_0 is one of the most important process parameters in metal droplets deposition, which directly determines the energy of the molten metal and its subsequent spreading and solidification behavior.

It can be seen (Table 4) that the surface morphology is poor when T_0 is 935 K (Fig.9a). When the T_0 increases to 955 K (Fig.9b), the surface morphology is greatly improved, and they are completely fused, so the internal quality of metal droplets is better. But it should not be too high, because too

Table 4 Experiment process parameters of metal droplet lapped deposition at different T_0

Process parameter	Numerical value
Substrate temperature, T/K	400
Pulse pressure, P/MPa	0.4
Pulse frequency, f/Hz	40
Substrate distance, h_s/mm	5
Scanning speed, V_s/ mm·s^{-1}	40
Environmental oxygen content/μL·L^{-1}	20
Al droplet temperature, T_0/K	935, 955, 975
Nozzle diameter, D_0/mm	0.5

high T_0 (T_0 =975 K) can cause molten metal to flow and affect the internal quality of parts (Fig.9c).

2) Substrate temperature T

The experimental parameters are shown in Table 5 in the process of metal droplet deposition. When substrate temperature T is 300 K, the time is shorter for the spread of the droplet; therefore, the metal droplets lapped gap can be seen obviously in the specimen section, which can make the poor surface morphology, as shown in Fig.10a. At higher substrate temperature T (T=350 K), the droplet solidification time is longer and sufficient to lap, so the specimen section is relatively flat, and the internal quality can be improved a lot, as shown in Fig.10b. But the substrate temperature T should not be too high; it can also lead to the poor surface morphology.

Due to the mutual influence of each factor, the optimal parameters are achieved through experiments, as shown in Table 6. The metal nozzle is closer to the substrate, the spreading factor of the molten metal droplets and the smaller gradient of the temperature droplets are smaller, so the lapping

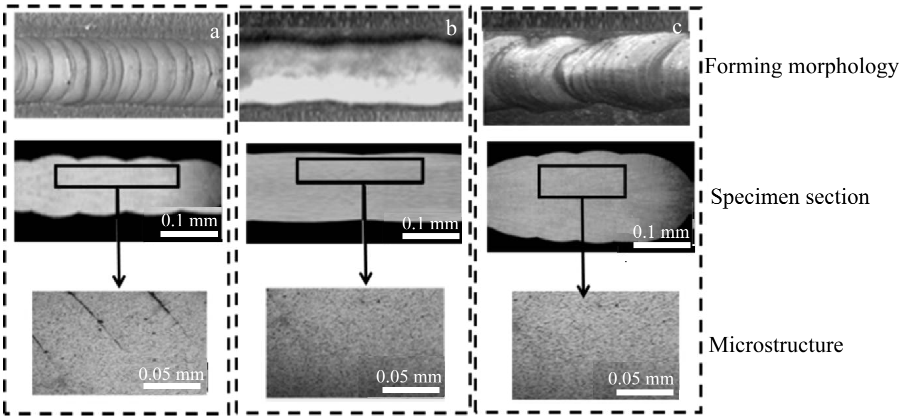

Fig.9 Surface, cross-section morphologies and microstructures of specimen at different T_0: (a) 935 K, (b) 955 K, and (c) 975 K

Table 5 Experiment process parameters of metal droplet lapped deposition at different T

Process parameter	Numerical value
Al droplet temperature, T_0/K	955
Pulse pressure, P/MPa	0.4
Pulse frequency, f/Hz	40
Substrate distance, h_s/mm	5
Scanning speed, V_s/mm·s^{-1}	40
Environmental oxygen content/μL·L^{-1}	20
Substrate temperature, T/K	300, 350, 400
Nozzle diameter, D_0/mm	0.5

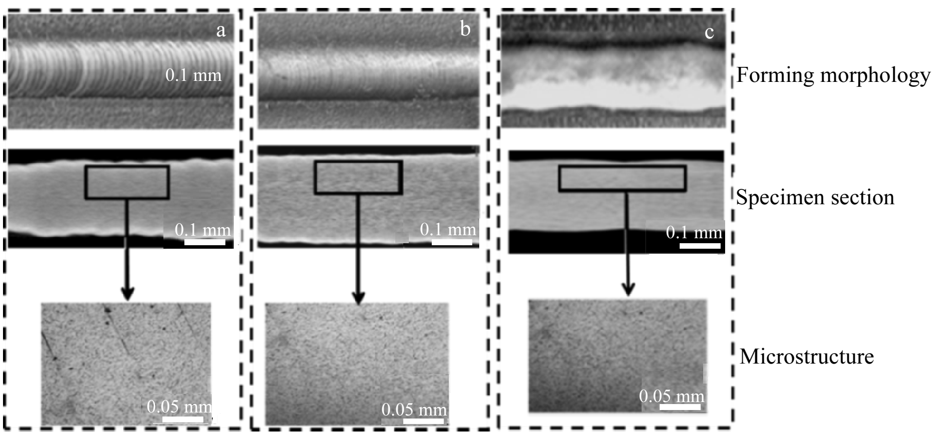

Fig.10 Surface, cross-section morphologies and microstructures of specimen at different T: (a) 300 K, (b) 350 K, and (c) 400 K

Table 6 Optimum experiment parameters off Al alloy

Process parameter	Numerical value
Substrate distance, h_s/mm	5
Al droplet temperature, T_0/K	955
Substrate temperature, T/K	350
Nozzle diameter, D_0/mm	0.5

between the droplets is better, resulting in the improvement of the surface precision. In order to reduce the Al droplet temperature gradient and to fuse with the substrate, it is needed to preheat the substrate. The optimum process parameters (Table 6) are shown in Fig.11a. The track morphology of OLS4000 with confocal microscope is shown in Fig.11b.

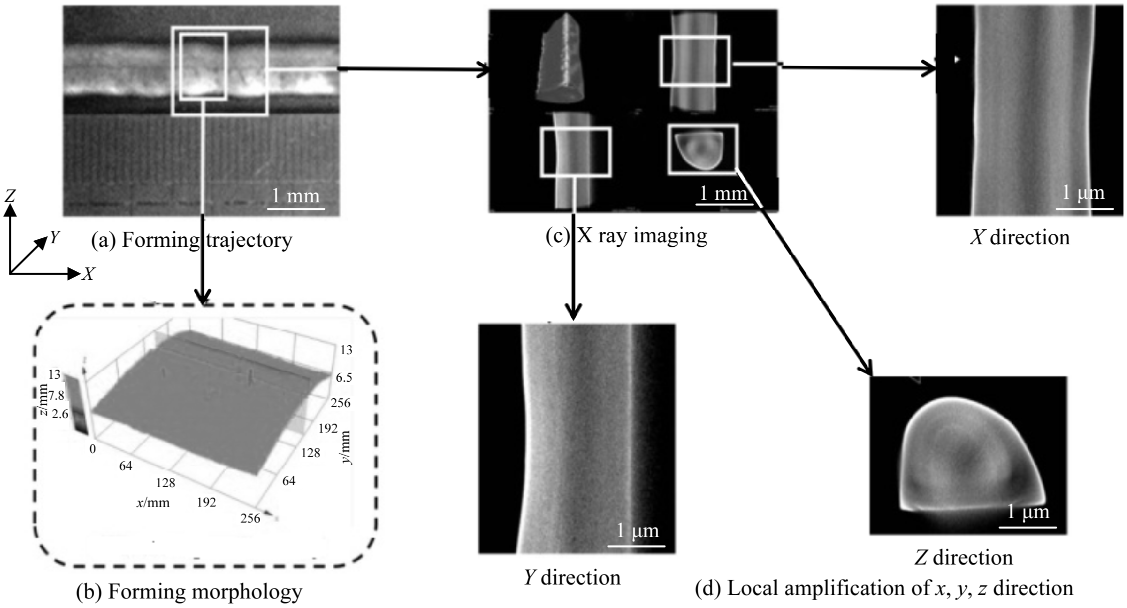

Fig.11 Forming trajectory (a), forming morphology (b), X-ray imaging (c) and local amplification (d) of the metal droplet

And it can be seen that the surface quality is better. The shape and morphology of Fig.11a were analyzed and the internal structure was tested by Y. Cheetah micro X-ray 3D imaging system. It can be seen that under the surface the quality of the metal droplet is high and the inner microstru- cture is dense, as shown in Fig.11c.

4 Conclusions

A 3D model for horizontal lapped deposition of molten Al droplets onto a horizontally moving substrate was developed based on a volume of fluid (VOF) method. The simulations with this model could agree well with the experimental results and provide an insight into the spreading and fusion of molten Al droplets during successive deposition and yield following specific results.

1) In this DOD jetting, both simulated and experimental results demonstrate that deposited droplets have high profile shape, which would be useful for the improvement in the efficiency and accuracy of droplets jetting technology.

2) Through the horizontal lapped deposition droplets spreading and fusing with one and another, it can be seen that the eventual spreading height h after solidification of the four droplets is essentially the same. This explains why the forming process is good, providing favorable conditions for forming the next floor.

3) Through the study of the impact of the morphology and internal quality of the specimens under the different metal droplet deposition parameters, the ideal lapping way, the insufficiency lapping way and excessive lapping way were established and the optimal parameters were achieved through experiments.

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基于金属液滴水平重叠沉积工艺对表面形貌和内部质量优化研究

李素丽[1,2]，杨来侠[1]，卢秉恒[2]

(1. 西安科技大学，陕西 西安 710054)

(2. 西安交通大学 机械制造系统工程国家重点实验室，陕西 西安 710049)

摘　要：铝熔滴在铝基板上沉积、凝固过程中，研究了不同工艺参数下的对成形表面形貌和内部质量的影响规律。通过对单一金属液滴沉积行为研究，建立了横向搭接沉积数值模型，并对 1，2，3，4 个熔融液滴重叠形态的进化和温度变化过程进行分析和实验验证。实验表明：数值模拟与实验结果有良好的一致性，从而得到了最优参数。该研究对实现金属微液滴重叠沉积生产的有效过程控制至关重要，为液滴水平重叠沉积复杂金属提供了技术支持和参考。

关键词：金属液滴；水平重叠沉积；表面形态；内部质量

作者简介：李素丽，女，1981 年生，博士，副教授，西安科技大学，陕西 西安 710054，E-mail: 563456137@qq.com