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ARTICLE

Vertically Lapped Deposition Process of Metal Droplet

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Abstract: During vertically lapped deposition with solidification of an aluminum molten droplet onto an aluminum substrate, the effects of the process parameters on the surface morphology and interior quality of the specimens were studied. By investigating the single metal droplet deposition behavior, the numerical model of vertically lapped deposition was established; the evolution of morphology and temperature of molten droplets vertically lapped and impacting substrate surface at different time were analyzed, and the successive deposition experiments for multiple droplets under different simulation parameters were carried out. The results show that numerical simulation and experiments show a good agreement, and the optimal parameters are obtained. This investigation is essential to the effective process control in the deposition of metal micro-droplet, providing technical support and reference for the molten droplet vertically lapped deposition process of complex metal parts.

Key words: metal droplets; vertical lap; process parameters; internal quality

The rapid prototyping (RP) technology is widely applied in the production of complex parts. Metal droplet deposition process is a new type of RP technology for metal parts in the early 1990s, and the parts can be manufactured by metal droplet deposition without using any molds or other tools 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 [1], including selective laser sintering (SLS) [2], selective laser melting (SLM) [2], laser cladding deposition (LCD)[3], electron beam melting (EBM) [4], etc.

In previous studies, a lot of related researches on droplet deposition process for low-melting-point metals were conducted. For instance, Fang et al [5] fabricated various thin-walled parts by 0.18 mm tin droplets. Cao et al [6] obtained a micro Sn60-Pb40 gear by depositing 0.2 mm droplets on demand. Yi et al [7] studied the influence of scanning step on metallurgy bonding in Sn60-Pb40 droplets.

However, when this technique is applied to aluminum which has more practical value in industrial areas, it is more difficult to eliminate aluminum because it has a higher melting point, stronger chemical activity and larger surface tension than low-melting-point metals. For example, Orme et al[8] studied the microstructural characteristics of aluminum parts fabricated with rapidly solidified molten aluminum droplets. Ghafouri et al [9] investigated the inter-impinging of two tin droplets with the diameter of millimeter scale and simulated the lap behaviors of droplets. However, there are few reports on the lap process of aluminum droplet deposition [10].

The lapped deposition process for molten aluminum droplets was conducted by the drop on demand (DOP) jetting onto a fixed substrate surface in this paper. In order to confirm the numerical simulation and experimental verification, successive deposition experiments for a single droplet and multiple droplets were carried out.

1 Numerical Model

The numerical model was established according to the deposition process of molten metal, as shown in Fig.1. The initial diameter of the droplet is D and the diameter after deposition is D_1. In order to prevent the oxidation of metal, the whole process of deposition was carried out in argon atmosphere

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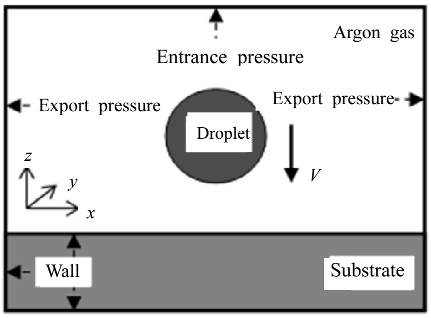

Fig.1 Single droplet deposition model

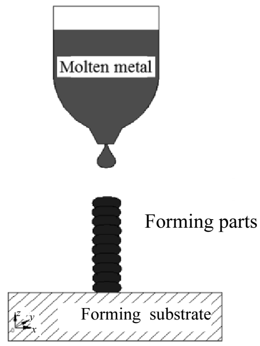

Fig.2 Schematic diagram of vertical lapped process

(less than 20 μL/L). In pulse pressure, the deposition velocity is V. In order to simplify the model, the upper boundary is defined as entrance pressure, the left and right boundaries are defined as export pressure, and deposition substrate surface is defined as a wall.

The vertical lapped deposition refers that the x-y plane (substrate surface) is fixed and the metal droplets deposit along the z direction, as shown in Fig.2.

The vertically lapped metal droplet is accumulated on the previous layer, in addition to the first layer which is accumulated on the substrate, as shown in Fig.3. After the first layer deposition on the substrate, its height is h_1; the second layer refers that the second droplet deposits on the first layer and its height is h_2, and so on and so forth. There is a remelting region between the droplets, as shown in Fig.3b.

For Al droplet deposition, the interface solidification has a great influence on the accuracy and internal quality of parts, so it is essential to analyze the coagulation of droplet deposition process, and to study the influence of metal droplet deposition parameters. Fig.4 is a numerical model of the vertically lapped deposition process of two droplets. The deposited droplets spread on the substrate, and the new droplet is deposited on the former one.

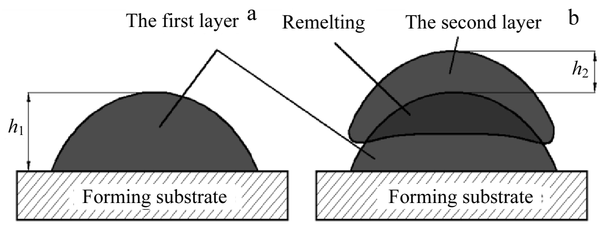

Fig.3 Forming shape of two layers in vertical direction

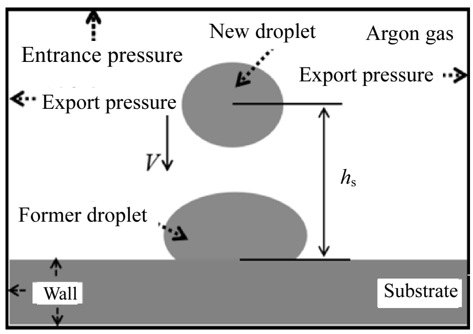

Fig.4 Numerical model of vertically lapped deposition of two droplets

2 Influencing Factors of Vertically Lapped Deposition

2.1 Influence on the surface roughness

Surface roughness is one of the important factors in measuring the accuracy of parts. Therefore, the influence of parameters on the surface roughness of the molten Al droplet is studied in this paper.

With deposition distance h_s and substrate temperature T being determined, if we reduce Al droplet temperature T_d, the spreading factor of metal droplet will get smaller, and the vertically lapped distance between the metal droplets will get larger, and thus insufficient lap will appear, and the lapped surface roughness increases, which in turn affects the surface quality of the parts, as shown in Fig.5a. However, when Al droplet temperature T_d is too high, excessive lap may occur, as shown in Fig.5c, resulting in very low efficiency and poor surface quality. Therefore, under certain other parameters, it is necessary to increase the Al droplet temperature T_d appropriately so that the joint between the droplets can realize an ideal lap, as shown in Fig.5b.

According to the parameters in Table 1, the comparison of different vertically lapping distances was carried out. When the Al droplet temperature was 925, 935 and 945 K, different processes of specimen length (about 50 mm) were compared. Fig.6 shows the surface morphology (left) and the cross section of the corresponding specimen (right) in three different lapped molds.

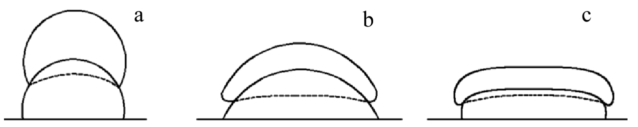

Fig.5 Vertically lapped mold of metal: (a) insufficient lap, (b) ideal lap, and (c) excessive lap

For the ideal lapped specimen, its surface morphology is close to a plane, but it is actually cyclical peaks and troughs, because the liquid metal droplet under the surface tension will shrink and cannot fully spread into the ideal plane, as shown in Fig.6.

The distance between the surface peaks and the troughs is H_D , which is shown in Fig.7. These parameters are very important to reflecting the lapped surface roughness. The smaller the H_D, the smaller the surface roughness. The values of H_D and the highest and lowest height of 3 specimens under the condition of ideal lap, insufficient lap and excessive lap were measured by KEYENCE VH-8000 micro amplifier for 25 times, as shown in Table 2 and Fig.8.

As can be seen from Table 2 and Fig.8, the H_D is the largest when the lapped joint is insufficient. But in ideal lapped deposition, the H_D is the smallest, and the surface roughness is the lowest. When the joint is overlapped, the peak height of subsequent layers increases gradually. Thus, it can be seen that the surface is uneven, which affects the forming of the subsequent layers.

2.2 Influence on the internal and surface quality of the parts

Microscopic holes and cold isolation are the commonest defects in the metal droplet deposition technology [10], because it is mainly affected by Al droplet temperature T_d, pulse pressure P, substrate distance h_s, etc[11]. When other parameters are determined, the Al droplet temperature T_d is low, the liquid phase fraction is small, and the lap between the droplets is difficult to fill completely, so the hole is easily formed. When the pulse pressure P is too low, the droplets will solidify completely in a short time, which will influence the spread of the droplet to fill the lap. When substrate distance h_s is too large, the gap between the metal droplets is too large, and the lap rate is low, so it is difficult to fill completely. In addition to the microscopic holes, shrinkage holes also exist in the final solidification of the droplets, which are usually difficult to completely eliminate. So it is necessary to appropriately match Al droplet temperature T_d, pulse pressure P and substrate distance h_s for ensuring a good remelting and metallurgical bonding between the droplets [12].

2.2.1 Al droplet temperature

The Al droplet temperature T_d is one of the most important

Table 1 Process parameters of experiment

Parameter	Value
Substrate temperature, T/K	400
Deposition distance, h_s/mm	10
Pulse pressure, P/MPa	0.3
Pulse frequency, f/Hz	30
Nozzle diameter, D_0/mm	0.6
Environmental oxygen content, O_c/μL·L^{-1}	≤20
Droplet temperature, T_d/K	925, 935, 945

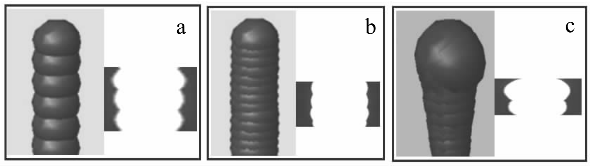

Fig.6 Surface morphology and cross section of 3 lapped specimens: (a) insufficient lap, T_d= 925 K; (b) ideal lap, T_d= 935 K; (c) excessive lap, T_d= 945 K

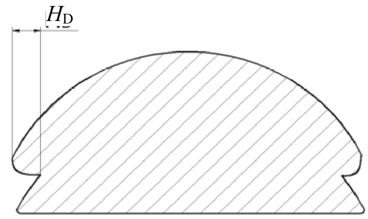

Fig.7 H_D definition

Table 2 Results of the measurement

Project	H_D/mm	The highest value/mm			The lowest value/mm		
Insufficient lap	0.150	1.01	1.02	1.08	0.72	0.78	0.75
Ideal lap	0.037	1.29	1.30	1.30	1.26	1.26	1.27
Excessive lap	0.090	1.40	1.42	1.45	1.33	1.38	1.53

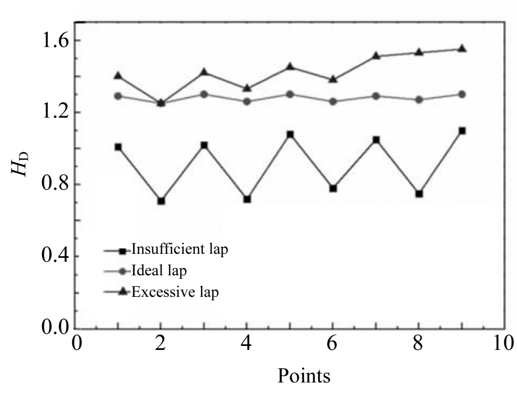

Fig.8 Highest and lowest height curves of different lapped joints

process parameters in metal droplets deposition, which directly determines the energy of the molten metal and subsequent spreading and solidification behavior [13].

In other process parameters (Table 3) under the appropriate conditions, it can be seen that the surface morphology is "fish scale" when the Al droplet temperature is 925 K (Fig.9a). From the specimen section and the partially amplified microstructure, the lapped marks can be seen, and the degree of densification is not high. When the Al droplet temperature increases to 935 K (Fig.9b), the surface morphology is greatly improved, the "fish scale" ripple basically disappears and is completely fused. It can be seen that if the Al droplet temperature is too low, the generation chance of gap and clearance hole will be greatly improved. So the increase in Al droplet temperature T_d can avoid such defects, but don't be too high, because too high T_d (945 K) can cause molten metal to flow, affecting the precision of parts (Fig.9c).

2.2.2 Pulse pressure

The experimental parameters in the process of metal deposition are shown in Table 4. When higher pulse pressure is applied (P=0.5 MPa), metal droplets have larger kinetic energy, and it can inhibit the lapping clearance greatly, and effectively improve the internal and surface quality of parts. However, because the spreading factor of single droplet is too large, there will be excessive lap phenomena, the same as Fig.9c. But when the pulse pressure P is low (P=0.2 MPa), the time of the droplet to the substrate is relatively long, the spreading factor is small, and many lapped region are formed, the same as Fig.9a. So when the pulse pressure P is suitable (P=0.3 MPa), the internal and surface quality of the parts are better. Therefore, under the same parameters, the larger the pulse pressure P, the larger the droplet spreading factor and the denser the internal microstructure. However, the pulse pressure P should not be too high, because it will cause the droplet to spread excessively, and the forming efficiency will decrease.

Table 3 Other process parameters at different Al droplet temperatures

Process parameter	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, O_c/μL·L^{-1}	≤20
Al droplet temperature, T_d/K	925, 935, 945
Nozzle diameter, D_0/mm	0.5

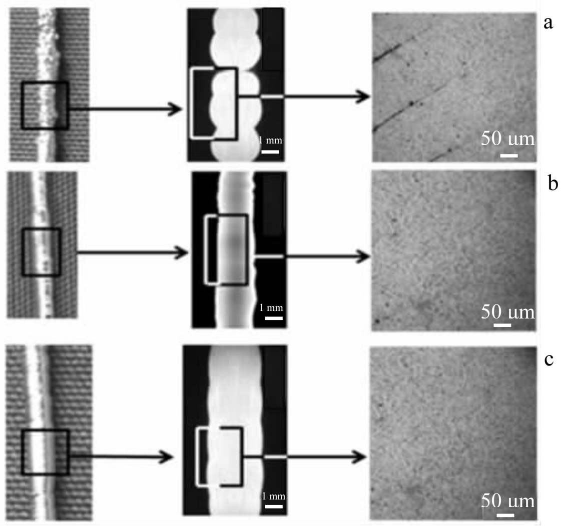

Fig.9 Schematic diagram of the lap of multiple droplets at different Al droplet temperatures: (a) T_d=925 K, (b) T_d=935 K, and (c) T_d=945 K

2.2.3 Substrate distance

When the h_s is too large (h_s=25 mm, Table 5), it takes a long time for molten metal to drop, and the temperature has been greatly reduced before the droplet reaches the substrate, so the internal quality and surface quality of the parts can be significantly decreased because there is no sufficient time for spreading (Fig.10a). When the h_s is 20 mm, the metal droplet spreading factor is smaller, and the temperature gradient of the metal droplets is smaller, so the fusion between the droplets is better, thereby improving the surface accuracy of the parts, as shown in Fig.10b. When h_s=15 mm, the surface morphology and internal quality of the parts are shown in Fig.10c. So the smaller the deposition distance, the higher the accuracy of the parts and the better the internal quality.

Table 4 Process parameters under different pulse pressures

Process parameter	Value
Al droplet temperature, T_d/K	935
Substrate temperature, T/K	400
Substrate distance, h_s/mm	10
Nozzle diameter, D_0/mm	0.6
Pulse frequency, f/Hz	35
Environmental oxygen content, O_c/μL·L^{-1}	≤20
Pulse pressure, P/MPa	0.20, 0.30, 0.50

Table 5 Process parameters under different substrate distances

Process parameter	Value
Al droplet temperature, T_d/K	935
Substrate temperature, T/K	400
Nozzle diameter, D_0/mm	0.6
Environmental oxygen content, O_c/μL·L^{-1}	≤20
Pulse frequency, f/Hz	35
Pulse pressure, P/MPa	0.3
Substrate distance, h_s/mm	25, 20, 15

Through the parameters in Table 6 and analyzing the surface quality of the parts, it can be seen that the above three process parameters can influence the surface morphology, as shown in Fig.11.

With proper T_d, P and h_s, the "fish scales" on the surface of the parts are significantly reduced, which can greatly improve the surface precision. Due to the interaction of each factor, the best experimental parameters are achieved through experiments. The nozzle diameter is 0.6 mm and the environmental oxygen content is below 20 $\mu L \cdot L^{-1}$. In order to reduce the metal temperature gradient and to fuse well with the substrate, it is necessary to preheat the substrate. In this experiment, when the substrate preheating temperature is 400 K, the substrate distance is 20 mm, the Al droplet temperature is 925 K, and the pulse pressure is 0.3 MPa, the metal droplet spreading factor and the temperature gradient are small, and the surface and internal quality of the parts are improved. The vertically lapped parts formed under these parameters are shown in Fig.11c. Using the X-ray 3D imaging system, the surface and internal quality of formed parts (Fig.11c) were analyzed. It can be seen that the Al droplet vertically lapped parts formed under these parameters have high surface quality and dense inner microstructure, as shown in Fig.12.

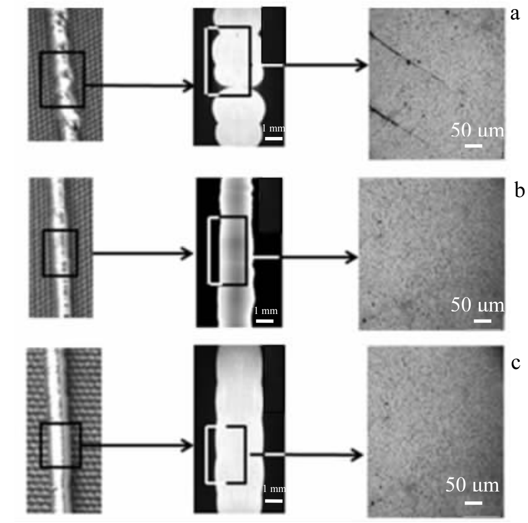

Fig.10 Schematic diagram of the lap of multiple droplets under different substrate distances: (a) h_s=25 mm, (b) h_s=20 mm, and (c) h_s=15 mm

Table 6 Parameters of deposition experiment

Process parameter	Value
Substrate temperature, T/K	400
Nozzle diameter, D_0/mm	0.6
Environmental oxygen content, O_c/$\mu L \cdot L^{-1}$	≤20
Substrate distance, h_s/mm	10, 1, 20, 22, 25
Pulse pressure, P/MPa	0.50, 0.40, 0.30, 0.25, 0.20
Droplet temperature, T_d/K	945, 935, 925, 915, 905

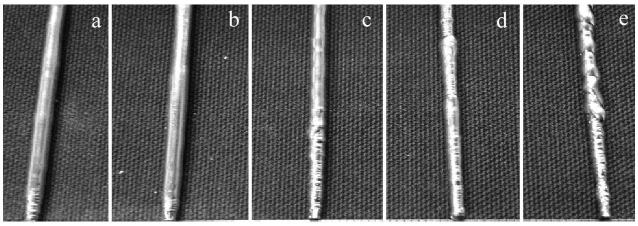

Fig.11 Influence of process parameters on the surface morphology: (a) h_s=10 mm, P=0.50 MPa, T_d=945 K; (b) h_s=1 mm, P=0.40 MPa, T_d=935 K; (c) h_s=20 mm, P=0.30 MPa, T_d=925 K; (d) h_s=22 mm, P=0.25 MPa, T_d=915 K; (e) h_s=25 mm, P=0.20 MPa, T_d=905 K

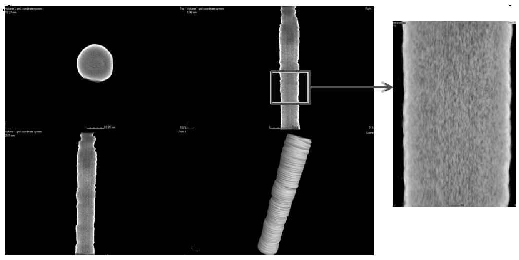

Fig.12 Schematic diagram of droplet by X-ray 3D imaging

3 Conclusions

1) The vertically lapped model is established, and an "equal area method" is put forward to determine the lap distance between adjacent morphologies.

2) By studying the influence of deformation and solidification of droplets under various parameters, and analyzing different forms of the vertically lapped model, optimal methods for improving surface quality and internal quality are obtained. It can be used to guide the selection of process parameters, such as pulse pressure, droplet temperature, substrate distance, and more.

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金属液滴垂直搭接成形工艺

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摘　要: 研究了铝合金熔滴在垂直搭接过程中不同工艺参数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，建立了垂直搭接沉积数值模型，并对多个熔融液滴垂直重叠形态的变化和温度变化过程进行分析和实验验证。结果表明：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垂直搭接的有效过程控制至关重要，为制造复杂金属提供了技术支持和参考。

关键词: 金属液滴；垂直搭接；成形参数；内部质量

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