Molten pool structure, temperature and velocity flow in selective laser melting AlCu5MnCdVA alloy

Pan Lu, Zhang Cheng-Lin, Wang Liang, Liu Tong and Liu Jiang-lin

Abstract

Selective Laser Melting (SLM) has become one of the most promising technologies in Metal Additive Manufacturing (MAM), which is a complex dynamic non-equilibrium process involving heat transfer, melting, phase transition, vaporization and mass transfer. The characteristics of the molten pool (structure, temperature flow and velocity flow) have a decisive influence on the final forming quality of SLM. In this study, both numerical simulation and experiments were employed to study molten pool structure, temperature flow and velocity field in Selective Laser Melting AlCu5MnCdVA alloy. The results showed the structure of molten pool showed different forms (deep-concave structure, double-concave structure, plane structure, protruding structure and ideal planar structure), and the size of the molten pool was approximately 132 μm × 107 μm × 50 μm; in the early stage, molten pool was in a state of deep-concave shape with a depth of 15 μm due to multiple driving forces, while a protruding shape with a height of 10 μm due to tension gradient in the later stages of forming. The metal flow inside the molten pool was mainly driven by laser impact force, metal liquid gravity, surface tension and recoil pressure. For AlCu5MnCdVA alloy, metal liquid solidification speed was extremely fast (3.5 × 10^{-4} S), the heating rate and cooling rate reached 6.5 × 10^7 K s^{-1} and 1.6 × 10^8 K s^{-1}, respectively. Choosing surface roughness as a visual standard, low-laser energy AlCu5MnCdVA alloy optimum process parameters window was obtained by numerical simulation: laser power 250 W, hatching space 0.11 mm, layer thickness 0.03 mm, laser scanning velocity 1.5 m s^{-1}. In addition, compared with experimental printing and numerical simulation, the width of the molten pool was about 205 um and about 210 um, respectively, and overlapping between two adjacent molten tracks was all about 65 um. The results showed that the numerical simulation results were basically consistent with the experimental print results, which proved the correctness of the numerical simulation model.

1. Introduction

AlCu5MnCdVA alloys had high specific strength, high toughness, good machining, fatigue properties, outstanding electroplating and excellent corrosion resistance, which were widely used as structural parts for aviation, aerospace industry [1, 2]. However, only a few works were carried out focusing on the SLM of AlCu5MnCdVA, which is mainly due to the high thermal conductivity (113 W m^{-1} · k^{-1}) [3, 4], too low laser absorption rate reflectivity (27.5% and only 10% after solidification) [3, 4]. Therefore, it is challenging to prepare AlCu5MnCdVA alloy parts by SLM technology. In addition, AlCu5MnCdVA alloys have characteristics as below: ◎ large solidification interval, easy to precipitate low melting point phase; ◎ low viscosity of liquid
aluminum alloy and high thermal expansion coefficient \( (24 \times 10^{-6}/\text{K}) \), very easy to produce cracks;③ high solid solubility of hydrogen element in liquid aluminum alloy, easy to produce holes in hydrogen precipitation during solidification, difficult to obtain high relative density parts. The ability to design free-structure AlCu5MnCdVA parts with high toughness, fatigue properties and corrosion resistance are of great significance, but traditional casting processing is difficult to achieve [5]. Selective Laser melting(SLM) process offers a possibility to fabricate free-structure AlCu5MnCdVA parts.

Metal Additive Manufacturing (MAM) technology has the advantages of fabricating complex free-form geometries directly, which is widely used in aerospace, biomedical, mold manufacturing and other industries in recent years [6–8]. Selective Laser Melting(SLM) is one of the most promising technologies in MAM system. In the SLM process, laser moves up to the speed of 5000 mm s \(^{-1}\) [9], and when laser spot leaves, melt temperature drops sharply in micro-molten pool for less than a few milliseconds, and the cooling rate can reach \( 10^4 \text{ K s}^{-1}\) [10]. The melting and solidification of metal powder in SLM process is less than a few milliseconds [11], and it is easy to produce defects such as balling, pores, bubbles and cracks. Reasonable control of process parameters has become the main way to improve final build quality of SLM. Therefore, it is of great significance to analyze the characteristics of the structure, temperature and velocity flow characteristics of the molten pool during SLM process.

However, the temperature flow, velocity flow and other information are difficult to capture due to the transient nature during SLM process. Numerical simulation has strong flexibility and adaptability, which was an important and effective method to study the evolution law of SLM molten pool. Knoner [12] adopted a self-developed simulation program to consider the heat transfer in the melting-solidification process. By solving the physical equations coupling heat transfer and flow, the formation and mechanism of defects in SLM process of TC4 alloy were simulated, but this paper ignored surface tension gradient caused by the temperature gradient and the recoil pressure caused by the evaporation of the molten metal. The results of the study refute the previously widely accepted view that the balling effect is caused by Due to Plateau-Rayleigh flow instability [13], it was proposed that surface tension drives the spheroidization caused by the molten pool during the forming process. Khairallah et al [14] used the self-developed ALE3D model [15] to simulate the powder melting flow behavior of the 316L stainless steel by SLM. The formation mechanism of defects in the single-pass forming process was simulated, and the mechanisms of powder splashing, hole formation, and powder bed denudation were revealed. Qiu et al [16] used OPENFOAM software to perform the selective melting simulation of TC4 alloy, which revealed the relationship between the holes and the surface roughness during the forming of the molten pool. The flow of the molten pool was related to the splash of the alloy liquid.

In the SLM forming process, the structure of the molten pool is transient and the flow fields (temperature and velocity fields) inside the molten pool are also transient. More importantly, the characteristics of the molten pool (structure, temperature field and velocity field) has a decisive influence on the SLM forming quality (surface accuracy, mechanical properties and internal grain structure). Therefore, it is very important to grasp the evolution law of the molten pool in the SLM forming process.

In this study, based on the determination of the laser source model [17], we perform a systematic study on the evolution of the molten pool throughout the SLM forming process, including the molten pool structure, temperature field and velocity field. On this basis, the relationship between the molten pool structure, temperature field and velocity field was explored. Finally, using the surface roughness as an intuitive standard, the low-laser energy process parameter window of Al–5Cu–Mn alloy by SLM was obtained.

2. Numerical simulation and experimental studies

2.1. Powder properties and chemical composition

Air atomized AlCu5MnCdVA powder were selected for SLM. Metal powder and powder characteristics were provided by Avic Max powder metallurgy technology (Beijing) co. Ltd. Particle size of the powder material was 15–60 μm, with an average diameter of 34 μm, the particle size of 90% powder are below 57.6 μm. And particle size distribution is shown in figure 1.

The morphology of powder is shown in figure 2, there are a small amount of satellite powder, irregular powder and hollow powder. Powder characteristics list as below: the angle of repose is 43°, loose density is 1.44 g cm \(^{-3}\), vibrating density is 1.75 g cm \(^{-3}\), density is about 2.82 g cm \(^{-3}\), and the crystallization temperature range is 544 °C–633 °C. Chemical composition is shown in table 1.

2.2. Finite element model of SLM

As shown in figure 3, the model of SLM in this papers mainly includes substrate (900 μm × 420 μm) and metal powder (15–60 μm), and the calculation domains was 900 μm × 420 μm × 250 μm, using the volume of fluid method (VOF) method with a fine mesh cells dimension size of 5 μm.
2.2.1. Heat transfer mathematical model

SLM process mainly includes three heat transfer methods: heat conduction, heat convection and heat radiation \[18\]. As shown in figure 4, when the high-energy laser heat source acts on the metal powder, the light energy of the laser beam is converted into heat energy. After the powder absorbs the heat, the powder temperature rises,
and part can be transferred to the solidified area or the surrounding powder area by heat conduction. There is also heat transfer inside due to the temperature difference. The energy absorbed by the powder is transmitted or dissipated outward by means of heat conduction and thermal radiation. Therefore, the laser beam, metal powder, solidified solid, molten pool and environment and other parts of the SLM forming process simultaneously transfer heat to each other.

For SLM process, high-energy laser beams was applied on the powder bed. Due to the layer thickness is small (about 0.03 mm), the molten pool area is small, the laser energy is attenuated to zero within a small incident depth, and the material absorbs the laser by surface absorption, so choose the moving Gaussian surface heat source:\[19]\:

\[
q(x, y, t) = \frac{2a(1 - R)}{\pi(K\omega_0)^2} \exp\left(-\frac{2(x - x_0 - vt)^2 + (y - y_0)^2}{(K\omega_0)^2}\right)
\]

Where, \(a\) is laser absorption rate, \(R\) is the reflectivity of the material surface to the laser, \(\omega_0\) is the Gaussian beam waist spot radius, \(K\) is the radius correction factor.

Equations of mass, momentum and energy conservation were applied as below:

(1) The mass continuity equation is:

\[
V_F \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u A_x) + \frac{\partial}{\partial y}(\rho v A_y) + \frac{\partial}{\partial z}(\rho w A_z) + \varepsilon \frac{\rho u A_x}{x} = R_{\text{DIFF}} + R_{\text{SOR}}
\]

Where, \(V_F\) is the fractional volume open to flow; \(\rho\) is the fluid density; \(R_{\text{DIFF}}\) is a turbulent diffusion term; \(R_{\text{SOR}}\) is a mass source. The velocity components \((u, v, w)\) are in the coordinate directions \((x, y, z)\). \(A_x, A_y\) and \(A_z\) are the fractional areas open to flow in the \(x\)-direction, \(y\) and \(z\) directions, respectively.

(2) In the SLM forming process, the heat convection and heat radiation models of the material surface and the surrounding environment are:

\[-\lambda \frac{\partial T}{\partial n} = \eta(T_{\infty} - T) + \sigma \varepsilon (T_{\infty}^4 - T^4)\]

Where, \(\sigma\) is the Stephan-Boltzmann constant, \(\sigma = 5.67 \times 10^{-8} \text{W m}^{-2} \cdot \text{K}^4\); \(\varepsilon\) is the surface emission coefficient, \(\eta\) is the convection exchange coefficient (\(\text{W m}^{-2} \cdot \text{K}\)); \(n\) is the surface normal direction.

(3) For multi-phase flows, the energy equation was written in terms of enthalpy [20, 21]:

\[
\rho \frac{\partial h}{\partial t} + \rho u \frac{\partial h}{\partial x} + \rho v \frac{\partial h}{\partial y} + \rho w \frac{\partial h}{\partial z} = \frac{\partial}{\partial x} \left[k \frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y} \left[k \frac{\partial T}{\partial y}\right] + \frac{\partial}{\partial z} \left[k \frac{\partial T}{\partial z}\right] + q_v
\]

Where, \(\rho\) is density; \(h\) is enthalpy; \(k\) is thermal conductivity; \(q_v\) is volumetric heat source.

(4) Fluid configurations are defined in terms of a volume of fluid (VOF) function, \(F(x, y, z, t)\), which represented the volume of fluid per unit volume and satisfies the equation [20, 21]:
The equations of motion for the fluid velocity components \((u, v, w)\) in the three coordinate directions are the Navier–Stokes equations:

\[
\frac{\partial u}{\partial t} + \frac{1}{V_F} \left[ u A_x \frac{\partial u}{\partial x} + v A_y \frac{\partial u}{\partial y} + w A_z \frac{\partial u}{\partial z} \right] - \frac{\xi A_y v^2}{x V_F} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + G_x + f_x - b_x
\]

\[
-\frac{\partial v}{\partial t} + \frac{1}{V_F} \left[ u A_x \frac{\partial v}{\partial x} + v A_y \frac{\partial v}{\partial y} + w A_z \frac{\partial v}{\partial z} \right] - \frac{\xi A_x v u}{x V_F} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + G_y + f_y - b_y
\]

\[
-\frac{\partial w}{\partial t} + \frac{1}{V_F} \left[ u A_x \frac{\partial w}{\partial x} + v A_y \frac{\partial w}{\partial y} + w A_z \frac{\partial w}{\partial z} \right] = -\frac{1}{\rho} \frac{\partial p}{\partial z} + G_z + f_z - b_z
\]

Where, \(G_x, G_y, G_z\) are body accelerations; \(f_x, f_y, f_z\) are viscous accelerations; \(b_x, b_y, b_z\) are flow losses in porous media or across porous baffle plates.

2.2.2. Thermos-physical properties of AlCu5MnCdVA alloy powder

AlCu5MnCdVA alloy belong to solid solution high strength cast aluminum alloy, 100 MPa higher than that of Casting Al–Si alloy and have good heat resistance and machining properties \([5, 22]\). In this paper, SLM was introduced to fabricate AlCu5MnCdVA alloy parts. Thermos-physical properties of AlCu5MnCdVA alloy was showed in table 2.

| Property and Parameters | Value |
|-------------------------|-------|
| Density Kg m\(^{-3}\)  | 2820  |
| Thermal conductivity W/(m · K) | 113 |
| Specific heat J/(Kg · C) | 133.98 |
| Surface tension coefficient (mN · m\(^{-1}\)) | 890 |
| Liquidus temperature (K) | 906.15 |
| Solidus temperature (K) | 817.15 |
| Latent heat of fusion (J Kg\(^{-1}\)) | 396 000 |
| Temperature sensitivity (mN · m\(^{-1}\) · K\(^{-1}\)) | 0.155 |

2.2.3. Finite element simulation schemes with different laser process parameters

To study the molten pool structure of AlCu5MnCdVA alloy fabricated by SLM, five laser process parameters schemes were selected, shown in table 3.

2.3. Experimental study

2.3.1. SLM forming equipment

All samples were fabricated by desktop metal printer(TB-SLM100S) developed by Anhui Top Additive Manufacturing Technology Co., Ltd As shown in figure 5, the device is equipped with an optical fiber device (wave length 1064 nm), forming platform is 100 mm × 100 mm × 100 mm, the spot diameter is 70–200 um and continuously adjustable. And samples fabricated by SLM were shown in figure 6.
Table 3. Process parameters for FEM.

| Scheme NO. | Hatching space (mm) | Laser Power (W) | Laser canning velocity (m s⁻¹) | Powder preheating (°C) |
|------------|---------------------|----------------|-------------------------------|------------------------|
| 1          | 0.11                | 250            | 15                            | 26.89 °C               |
| 2          | 0.11                | 250            | 1.5                           | 26.89 °C               |
| 3          | 0.11                | 350            | 1.5                           | 26.89 °C               |
| 4          | 0.11                | 60             | 15                            | 26.89 °C               |
| 5          | 0.2                 | 250            | 1.5                           | 26.89 °C               |

3. Results and discussion

Figure 7 the picture showed the three-dimensional structural morphology of Scheme NO.2’s molten pool and molten track. The color indicates the temperature. As shown in figure 7, the front end of the molten track was concave-shape, the width of the molten track reached 200 um, and the depth of the heat affected zone reached 20 um.

Figure 8 showed the velocity field and temperature field of Scheme NO. 2’s molten pool. As shown in figure 8(a), the cross section of the molten pool at 6 us had a protruding shape, and the size of molten pool was about 172 μm × 54 μm, and the protruding height of the molten pool was 36 μm. The maximum temperature of the molten pool center was up to about 1200 K. As shown in figure 8(b), the longitudinal section of the molten pool at 0.5 us has a deep-concave shape, and the size of the molten pool was about 132 μm × 50 μm, with the depth of the molten pool depression 15 μm, and the temperature was up to 3200 K, the maximum speed on the upper surface of the molten pool was 1.9 m s⁻¹. The molten metal at the front end of the molten pool flowed backward and downward, and the molten metal at the rear end of the molten pool flowed upward and backward.
Figure 9 showed the molten tracks in two passes of Scheme NO. 5, molten track B is solidified, and molten track A was near the end of solidification. For molten track B, the size is about 107 μm × 10 μm. In Scheme NO. 5, hatching space was 0.2 mm, which leading too small overlapping between molten tracks and pores appeared.

3.1. Evolution of molten pool structure
Figure 10 showed raw metal powder and molten pool after solidification. According to the molten pool structure, the single molten pool can be divided into five stages: deep-concave structure (figure 11(a)), double-concave structure (figure 11(b)), plane structure (figure 11(c)), protruding structure (figure 11(d)) and ideal plane structure (figure 10(b)).

1. Deep-concave structure
As shown in figure 11(a), when the laser beam irradiated the raw powder, laser energy was absorbed extremely quickly, and the maximum temperature reached 3200 K; the deep-concave structure appeared, the main reasons were listed as below: (1) For the initial stage of laser irradiating on the raw powder, laser beam hit the upper surface of the molten pool; (2) Temperature of the molten pool center reached 3200 K, AlCu5MnCdVA powder boiled and vaporized, forming a recoil force [23] on the surface of the molten pool, resulting in a concave structure of the molten pool.
2. Double-concave structure
As shown in figure 11(b), the central area of the molten pool upper surface was mostly above the liquidus temperature (906 K), and the temperature continued to rise, with a maximum temperature of 3778 K. The double-concave structure of the molten pool structure appeared, mainly due to: (1) The temperature at the molten pool center was the highest, resulting in a small surface tension in the central area but a large surface tension in the periphery [24]. Surface tension gradient driven molten metal from the inside of the molten pool up to the surface in the center both sides; (2) The height difference between center and side appeared, and under the action of gravity, the melt re-flowed again, forming Marangoni Flow [25, 26]. (3) The maximum temperature at this stage rose up to 3778 K, and the area of the high temperature area expanded to both sides of the molten pool. The recoil force on both sides caused the double-concave molten pool structure.

3. Plane structure
As shown in figure 11(c), when the laser beam moved away, the temperature of the molten pool began to drop. The upper surface of the molten pool was mostly between the solidus temperature and the liquidus temperature. The molten pool was in a state of solid-liquid coexistence. As the heat transfer continued, temperature gradient on the surface of the molten pool was reduced, the surface velocity was more uniform, and the surface gradually formed a flat structure. There was a Marangoni Flow effect inside the molten pool, but there was no Marangoni Flow on the surface.

4. Protruding structure
As shown in figure 11(d), the temperature gradient on the upper surface and inside of the molten pool continued to decrease, so Marangoni Flow completely disappeared. However, the temperature at the center of the upper surface of the molten pool was still the highest, and the temperature gradient leaded to surface
tension gradient [27]. Under the effect of surface tension gradient, the molten pool formed a spherical protruding structure to reduce its surface energy [28].

5. Ideal planar structure

For the ideal solidified molten pool, the melt tracks overlapped each other to form a planar structure, which was convenient for the next layer of powder spreading. However, due to the characteristics of rapid heating and rapid cooling in the SLM forming process, the metal flow field of the molten pool changed instantaneously. Therefore, in addition to controlling the laser process parameters, obtaining an ideal planar molten pool required the introduction of other technologies, such as magnetic field [29].
Therefore, there are four main driving forces during the evolution of the molten pool: laser impact force, metal liquid gravity, surface tension, and metal vapor recoil force. In the early stage of the formation of the molten pool, the laser impact force was the main driving force of the molten pool. When the molten pool temperature was above the liquidus temperature, the recoil force and Marangoni Flow were the main driving forces of the molten pool flow; When the molten pool was in solid-liquid coexistence, Marangoni Flow was the main driving force for molten pool flow; In the later stage of molten pool solidification, Marangoni convection disappeared due to the decrease of the temperature gradient inside the surface of the molten pool, and the surface tension gradient caused by the temperature gradient on the surface of the molten pool was the main driving force for the molten pool flow.

3.2. Evolution of velocity field and temperature field in molten pool

Figure 12(a) showed the temperature change curve of the upper surface point of the center in the molten pool. From 0 to Point A, temperature rise rate was extremely fast: the temperature rises rapidly to the maximum temperature of 2500 K at 4 × 10⁻⁵ S, and the temperature rise rate was as high as 6.5 × 10⁷ K S⁻¹. When laser beam moved away (from Point A to Point B), the temperature began to drop to liquidus temperature 906 K at 0.00015 S. From Point B to Point C, temperature dropped to 817 K after 0.0005 S, the cooling rate reached 1.6 × 10⁶ K S⁻¹: This stage is where the molten pool began to solidify until the end of solidification. For AlCu5MnCdVA alloy, from the beginning of solidification (point B) to the end of solidification (point C), it took about 3.5 × 10⁻⁴ S, so the solidification speed of the metal liquid was extremely fast, which promoted the grains refinement [30].

Figure 12(b) showed the velocity change curve of the upper surface point of the center in the molten pool. Similar to the temperature trend, the velocity of the molten metal was mostly in the -x direction. Therefore, during the formation of the molten track, molten metal flowed back. The velocity has the maximum negative velocity in the -x direction (2.2 m s⁻¹). The upper surface of the pool was agitated violently.

Figure 13 showed both temperature and velocity flow of molten track. As shown in figure 13(b), the temperature difference between the isotherms was 306 K, the temperature gradient at the front end of the melt track reached 57 K um⁻¹, and the temperature gradient at the front end of the molten track was greater than that at the rear end. As shown in figure 13(c), the molten metal at the front of the melt track flowed from the front end to the rear end, where the velocity of the front end of the melt channel was greater than the remaining positions, mainly due to greater temperature gradient at the front end, and the surface tension gradient caused by the temperature gradient driven the liquid metal to flow backward.

3.3. AlCu5MnCdVA alloy laser process window and experimental printing

In order to obtain an ideal melt pool structure, the maximum temperature of the melt pool and the length (L), width (W) and depth (H) of the melt pool need to be controlled [31]. In this paper, by optimizing the laser process parameters, the melt pool temperature was guaranteed to exceed the Liquidus temperature to avoid that the metal powder cannot be completely melted (as shown in figure 14(a)), and generate defects such as pores (as shown in figure 14(b)). Optimizing the laser process parameters ensure that the maximum temperature of the molten pool cannot exceed the boiling point (3100 K) to avoid spattering behavior (as shown in figure 14(c)) and ensure that the overlapping rate of the molten pool was around 30% [18, 26] (as shown in figure 14(d)).
Figure 13. Longitudinal 2D slices of molten track: (a) Both temperature and velocity of molten track; (b) Temperature field for molten track; (c) Velocity field for molten track.

Figure 14. Defects: (a) Unmelt defects (Scheme NO.4); (b) Pores defects (Scheme NO.1); (c) Spattering defect (Scheme NO.3); (d) Low overlapping rate defects (Scheme NO.5).
Taking the surface roughness as an intuitive standard \[32\], the experimental printing results showed that the best low-laser energy process parameters window of AlCu5MnCdVA alloy (Scheme NO. 2 in Table 3): laser power 250 W, hatching space 0.11 mm, layer thickness 0.03 mm, scanning speed is 1.5 m s\(^{-1}\). Figure 15 showed the morphology of one layer after solidification: the upper surfaces of the molten track were flat after solidified, which was convenient for the next layer of powder.

Figure 16 showed the cross and side section metallographic diagram of the samples with optimized process parameters (Scheme NO. 2). As shown in figures 16(a) and (b), there were cracks and pores inside, which was the reason why the relative density of AlCu5MnCdVA alloy parts was only 96.1\%: The results showed that it is very challenging to simply adjust the process parameters and use low-power laser power to prepare samples with relative density more than 99\%. Next, adding alloying elements or surface modification for metal powder (such as oxidation) will be explored in order to increase the laser absorption rate of AlCu5MnCdVA alloy, or reduce the thermal conductivity of AlCu5MnCdVA alloy, which is the focus of our next work.

Figure 17 showed two-pass molten track overlapping for Scheme NO. 2 by numerical simulation. Compared with figures 16(b) and 17, the width of the molten pool obtained by experimental printing and numerical simulation was about 205 um and about 210 um, respectively. And overlapping between two adjacent molten tracks was 65 um and about 65 um, with overlapping rate 31.7\% and 30.9\%, which ensured that the overlapping rate of the molten pool was around 30\%\[33, 34\]. The results showed that the numerical simulation results were basically consistent with the experimental print results, which proved the correctness of the finite element modeling.

### 4. Conclusions

This study analyzed evolvement rule of molten pool structure, temperature and velocity flow in Selective Laser Melting AlCu5MnCdVA alloy. The evolution between the structure, temperature and velocity of the molten pool were explored in detail:
(1) The molten pool structure was related to the laser process parameters and metal powder materials. During the SLM forming process, five structural forms (deep-concave structure, double-concave structure, plane structure, protruding structure and ideal plane structure) were presented in this order. Laser impact force, metal liquid gravity, surface tension and recoil pressure driven the flow of metal liquid in stages or together.

(2) In the early stage of laser irradiation, due to the multiple driving forces, the molten pool showed a deep-concave state with a depth of 15 μm. Later, due to the characteristics of the Gaussian heat source, the molten pool turned into a protruding structure with a height of 10 μm.

(3) The temperature gradient at the front of the molten pool is greater than that at the rear end, and the temperature gradient at the front of the molten pool reached 57 K um⁻¹. For AlCu5MnCdVA alloy, the solidification rate of the metal liquid was extremely fast (3.5 × 10⁻⁴ S), and the heating rate and the cooling rate reached up to 6.5 × 10⁶ K S⁻¹ and 1.6 × 10⁶ K S⁻¹, respectively.
Choosing the surface roughness as the quantification standard, the low-laser energy process window for AlCu5MnCdVA alloy by SLM was obtained: laser power \( P = 250 \, \text{W} \), scanning speed \( V = 1.5 \, \text{m s}^{-1} \), hatching space \( H = 0.11 \, \text{mm} \). With the help of a low-laser energy desktop metal printer with independent intellectual property rights, AlCu5MnCdVA alloy was successfully fabricated with a relative density 96.1%.

It should be noted that the content of the research in this article does not involve parameters such as powder characteristics, oxygen content, protective gas, layer thickness and other parameters, and further research is needed in the next step. In addition, using low-power laser to fabricate samples with relative density more than 99.9% is our dream, and technologies such as reducing particle size, adding alloying elements or surface modification for metal powder will be applied to increase the laser absorption rate of AlCu5MnCdVA alloy and reduce the thermal conductivity.

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Author contributions
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Conflicts of interest
The authors declare no conflict of interest.

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