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Mesoscopic numerical simulation and experimental investigation of laser powder bed fusion AlCu5MnCdVA alloys

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Abstract

AlCu5MnCdVA alloys had high specific strength, good machining and fatigue properties, outstanding electroplating and excellent corrosion resistance. However, due to wide crystallization temperature range, it is hard to realize sequential solidification for AlCu5MnCdVA alloy by traditional casting process. Laser Powder Bed Fusion (L-PBF) has become one of the most promising technology in Metal Additive Manufacturing (MAM). In this study, L-PBF was employed to fabricate AlCu5MnCdVA parts, and both mesoscopic numerical element model and experimental printing were applied to study the feasibility of L-PBF Additive Manufacturing AlCu5MnCdVA alloy. Relative densities, phase analysis and micromorphology were investigated systematically by SEM, EDS and XRD. The laser process parameters window for AlCu5MnCdVA were obtained: volumetric energy density 41–51 J mm⁻³, laser power 230–240W, laser scanning speed 1200–1325 mm s⁻¹. And the relative density of parts fabricated by L-PBF reached 96.1%. Besides, AlCu5MnCdVA alloy fabricated by L-PBF was mainly consist of α-Al, little other phase such as Al₂Cu or Al₂Mn₃ was detected.

1. Introduction

AlCu5MnCdVA alloys have the characteristics of 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]. Due to the wide crystallization temperature range, AlCu5MnCdVA alloy is hard to solidify sequentially, which will lead defects, such as shrinkage loose, hot cracking, oxidation slag inclusion and other casting defects [3]. To improve AlCu5MnCdVA mechanical properties and reduce defects, L-PBF was employed to fabricate AlCu5MnCdVA parts in this work.

L-PBF has great potential in strength, precision and compactness, which adopts powder laying mechanism. Metal powder was melted by high energy laser layer by layer in build-up direction. After absorbing laser energy, metal powder temperature rises sharply and reaches melting point, and solidifies sharply after laser moved [4]. L-PBF is suitable for fabrication of complex structures, small sizes and high-precision parts. Besides, due to extreme heating and cooling, L-PBF technology provides a new way to affect the microstructure and properties. So far, very few works have been carried out for AlCu5MnCdVA alloys by L-PBF. Zhang [5] studied microstructure of AlCu5MnCdVA as-cast alloy and the XRD spectra, AlCu5MnCdVA is mainly composed of α (Al), and the reticulated theta (Al₂Cu) phase distributed along the grain boundary. Gong [6] studied the heat
treatment of metal-casting ZL205 alloy T6. The tensile strength of the alloy reached 488.2 MPa. Shu [7] studied sand casting AlCu5MnCdVA alloy, the as-cast tensile strength was 210 MPA. With T6 heat treatment, tensile strength reached 467.5 MPa.

This study was focused on Laser Powder Bed Additive Manufacturing AlCu5MnCdVA alloy. Firstly, the feasibility of preparing AlCu5MnCdVA alloy by L-PBF was studied by mesoscopic numerical simulation, and the metal temperature, velocity and molten pool characteristics of L-PBF were obtained. On this basis, large-scale trial and error experimental printing of AlCu5MnCdVA parts were fabricated by L-PBF to obtain parts with less defects and higher relative densities. In addition, phase analysis and micromorphology were investigated systematically.

Figure 1. AlCu5MnCdVA powder particle size distribution.

Figure 2. AlCu5MnCdVA powder.

Figure 3. Mesoscopic Numerical model of L-PBF.
2. Materials and methods

2.1. AlCu5MnCdVA Powder Properties

Air atomized AlCu5MnCdVA powder is selected for L-PBF. Particle size was 15 μm–53 μm, and the particle size of 90% powder are below 57.6 μm. Particle size distribution is shown in figure 1.

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

To ensure the accuracy of the composition and content of the AlCu5MnCdVA raw material, the chemical composition of the raw material was measured by EDS (Morphology was observed by SEM (Hitachi SU8010), and Oxford instrument EDS (AZtec X-Max50) was used for composition analysis). Chemical composition of both standard and measured by EDS is shown in table 1.

2.2. Mesoscopic numerical model for L-PBF process

Figure 3 showed the mesoscopic numerical model for L-PBF in this study, including laser beam, substrate and metal powder bed. Mesoscopic numerical model for L-PBF process established the melting and solidification process of the metal powder, and the dynamic process of L-PBF formation was obtained by solving the mass, momentum and energy conservation equations\(^8\). The metal powder layer geometry is initialized from DEM simulation, and the melting and solidification process of metal powder after laser irradiation adopts computational fluid dynamics (CFD).

PBF laser process parameters mainly include Laser power, scanning speed, layer thickness, hatching space, contour space. To comprehensively characterize the influence of all laser process parameters (laser power, scanning speed, layer thickness and hatching space) on the density and defects, volumetric energy density \(E\) (J mm\(^{-3}\)) is selected as a comprehensive process parameter:

\[
E = \frac{P}{v \cdot t \cdot h}
\]

where \(P\) is the laser power (W), \(v\) is the scanning speed (mm/s), \(t\) is the layer thickness (mm), and \(h\) is the hatching space (mm).

The relationship between volumetric energy density and defects (pores, bubbles and cracks, etc) of 316L stainless steel has been systematically studied by authors in \([9, 10]\): Too low or too high volumetric energy density will lead to balling. Low volumetric energy density leads to incomplete melting or even no-melting of metal powder, resulting in pores; excessive volumetric energy density resulted in liquid metal splashing, bubbles and even cracks.

Besides, in general, density of AlCu5MnCdVA parts fabricated by L-PBF directly reflects the internal quality and defects, such as pores, bubbles, and affects the mechanical properties. Higher density implies fewer defects such as pores, which is the most direct basis for judging L-PBFed parts quality. Therefore, density is one of the important parameters for L-PBF.

Relative density is introduced as the ratio of actual density to reference density\(^11\):

\[
d = \frac{\rho}{\rho_0} \times 100\%
\]

where \(d\) is the relative density, \(\rho\) is actual density for L-PBFed parts (g cm\(^{-3}\)), \(\rho_0\) is reference density (g cm\(^{-3}\), density of AlCu5MnCdVA is 2.82 g cm\(^{-3}\)).

In this study, Layer thickness was 30 μm, Hatching space and Contour space were 11 μm, and typical process parameters in this study for mesoscopic numerical simulation were shown in table 2.

2.3. L-PBF process parameters for experimental study

On the basis of previous Mesoscopic Numerical simulation (as shown in table 2), to further test the feasibility of using L-PBF to prepare AlCu5MnCdVA, large-scale trial and error methods was used and large-scale experimental printing were performed in this study. Numbers of AlCu5MnCdVA parts (cubic parts, 10

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Table 1. Chemical composition of AlCu5MnCdVA.

| Element | Al | Cu | Mn | Ti | Cd | V | Zr | B | O |
|---------|----|----|----|----|----|---|----|---|---|
| AlCu5MnCdVA BAL | 4.6–5.3 | 0.3–0.5 | 0.15–0.35 | 0.15–0.25 | 0.05–0.3 | 0.05–0.2 | 0.005–0.6 | / |
| EDS BAL | 4.99 | 0.4 | 0.24 | 0.16 | 0.19 | 0.11 | 0.021 | 0.04 |
mm × 10 mm × 10 mm, as shown in figure 4.) were fabricated by desktop metal 3D printer, developed by Anhui Top Additive Manufacturing Technology Co., Ltd, as shown in figure 5.

In this work, laser process parameters for large-scale trial and error experimental printing mainly include laser power, laser scanning speed, layer thickness, hatching space, contour space. And layer thickness (30 μm), hatching space (11 μm), and contour space (11 μm) were fixed factors, laser power and laser scanning speed were variable factors.

For large-scale trial and error experimental printing, laser power range of changes is 140 w–400 w, laser scanning speed range of changes is 1000 mm s⁻¹–2000mm s⁻¹. Large-scale Trial Method was used by random

| Scheme no. | Volumetric energy density (J mm⁻³) | Laser power (W) | Scanning speed (mm s⁻¹) | Layer thickness (μm) | Hatching space (μm) | Contour space (μm) |
|------------|-----------------------------------|----------------|-------------------------|---------------------|---------------------|---------------------|
| NO.1       | 32.63                             | 140            | 1300                    | 30                  | 11                  | 11                  |
| NO.2       | 60.60                             | 240            | 1200                    |                     |                     |                     |
| NO.3       | 50.50                             | 250            | 1500                    |                     |                     |                     |

Table 2. Typical process parameters for mesoscopic numerical simulation.
combination of process parameters to carry out large-scale experimental printing. Laser process parameters in this study for experimental metal 3D printing were shown in Table 3.

### Table 3. Process parameters for experimental study.

| Manufacturing parameters | Value                        |
|--------------------------|------------------------------|
| Laser power W            | 400, 350, 300, 200, 250, 240, 230, 220, 210, 200, 190, 180, 170, 160, 150, 140 |
| Scanning speed mm s⁻¹    | 2000, 1500, 1300, 1200, 1100, 1000 |
| Layer thickness μm       | 30                           |
| Hatching space μm        | 11                           |
| Contour space μm         | 11                           |
| Laser spot diameter μm   | 70                           |

2.4. Characterization

AlCu5MnCdVA parts fabricated by L-PBF for microscopic observation were pre-milled, mechanically polished and chemically etched, and the etchant used for chemical corrosion was Keller reagent (2.5 ml HNO₃, 1.5 ml HCl, 1 ml of HF and 95 ml of deionized water) and the corrosion time was 15 s.

Using Nikon EPIPHOT-300 optical microscope for low-fold microstructure observation. Morphology was observed by SEM (Hitachi SU8010), Oxford, instrument EDS (AZtec X-Max50) was used for composition analysis.

The phase analysis was carried out by Brooke x-ray diffraction (D8 FOCUS). Scanning angle was 30°–90°.

Multifunctional density tester (DAHOMETER, ar-300me) was used to measure the density of printed parts, the precision of density measurement is 0.001 g cm⁻³.

Figure 6. Single-pass molten track morphology of three typical schemes for mesoscopic simulation.

![Image of single-pass molten track morphology](image-url)
3. Results and discussion

3.1. Mesoscopic numerical simulation of L-PBF processes

Figure 6 shows single-pass forming molten tracks structure for Scheme NO.1, 2 and 3, respectively. Molten tracks of all three schemes could be successfully formed, and the surface quality shows well. Therefore, it is feasible to prepare the AlCu5MnCdVA alloy by using L-PBF process with laser process parameters. (1) Figure 6(a) shows the specific process of single pass forming for Scheme NO.1: Metal powder was completely melted, but the upper surface was uneven and wavy. Besides, there were pores defects, and the width of the molten track was small (about 150 μm), which were mainly caused by the lower laser volumetric energy density [11–13]. Therefore, the laser volumetric energy density of the L-PBF preparation AlCu5MnCdVA alloy should exceed 32.63 J mm$^{-3}$.

(2) Figure 6(b) shows the specific process of single pass forming for Scheme NO.2: Metal powder was completely melted, the upper surface was flat and horizontal. Besides, there were no obvious holes and unmelt powder, and the width of the molten track was about 255 μm. However, there were a lot of spatter generated during L-PBF process. This was mainly caused by too high laser volumetric energy density [11–13]. Therefore, the laser volumetric energy density of the L-PBF preparation AlCu5MnCdVA alloy should less than 60 J mm$^{-3}$.
(3) Figure 6(c) shows the specific process of single pass forming for Scheme NO.3: Metal powder was completely melted, the upper surface was flatter, and there was no obvious hole spatter. Therefore, the laser volumetric energy density of 50.5 J mm\(^{-3}\) for L-PBF preparation AlCu5MnCdVA alloy is reasonable.

3.2. Experimental study

3.2.1. Relative density of AlCu5MnCdVA parts

Figure 7 shows the effect of laser power and scanning speed on the relative density of L-PBFed parts. It is observed that the relative density decreased by increasing the scanning speed from 1200 mm s\(^{-1}\) to 1500 mm s\(^{-1}\), and the relative density increased by increasing laser power from 160 W to 240 W. Too low laser power or too high laser power will cause forming failure. In the work, relative density reached 96.1% (Density 2.71 g mm\(^{-3}\)).

To further explore the relationship between laser power, laser scanning speed and the relative density of parts, printing experiments with different laser power and laser scanning speed were performed, and distribution cloud map was plotted in figure 8.

Figure 8 shows the distribution cloud map of laser power, laser speed and relative density: The abscissa represent laser power, and the ordinate represent the laser scanning velocity. The colors of the region in figure 8 represent different relative densities: the blue area is 90.48%–91.09%; the gray area is 95.36%–96.1%; the white area represents printing failure.

As shown in figure 8, the laser process window of AlCu5MnCdVA for L-PBF is red region (Relative density: 94.75%–95.36%): laser power 230 W–240 W, laser scanning speed 1200–1325 mm/s, volumetric energy density 41–51 J mm\(^{-3}\).

3.2.2. Phase analysis

For L-PBF, it is an extremely cooling and hotting non-equilibrium state, therefore, it is necessary to analyze the post-solidification phase composition of aluminum–copper alloy formed by L-PBF.

Choosing laser process parameters in table 4, phase analyses of three optimized parts were performed as showed in figure 9.

![Table 4. Experimental density data of different laser scanning speed.](image-url)

| No. | 1   | 2   | 3   |
|-----|-----|-----|-----|
| Laser power P(W) | 240 | 230 | 220 |
| Scanning speed V(mm s\(^{-1}\)) | 1200 | 1200 | 1200 |
| Volumetric energy density E(J mm\(^{-3}\)) | 60.1 | 58.1 | 55.6 |
| Relative density % | 96.1 | 95.7 | 95.6 |

![Figure 9. XRD patterns of as-fabricated cubes prepared by L-PBF.](image-url)
All XRD patterns peaks were detected as the face-centered cubic (fcc) $\alpha$($\text{Al}$), little other phase such as $\text{Al}_2\text{Cu}$ or $\text{Al}_2\text{Mn}_3$ was detected. The detected $\alpha$($\text{Al}$) peaks slightly shifted to a lower angle, which is attributed to the solid solubility of Cu and Mn in the $\alpha$($\text{Al}$).

The results shows that extreme heating and extreme cooling (up to $10^4 \text{ k s}^{-1}$) by L-PBF will increase the solid solubility limit of Cu and Mn and suppress the precipitation of the second phase.

Table 5 shows lattice parameters of both original powder and L-PBFed parts, lattice parameters of three L-PBFed parts for X-Y internal surface are 4.039 Å, 4.038 Å, 4.035 Å respectively. The lattice parameters shows smaller, which is mainly due to the fact that the atomic radius of Cu is smaller than that of Al, and the radius difference between Cu and Al is about 10.87% [14]. For Al lattice, Cu atom replaces the Al atom and forms the replacement solid solution.

In addition, lattice parameter of L-PBFed parts for Y-Z outside surface is 4.046 Å, which is the same to original powder. So outside surface is covered with unmelted powder.
3.3. Micromorphology and microstructure analysis
Figure 10 shows molten pools both in side section and upper surface. Figure 10(a) presents half cylindrical shape in side section of Scheme NO.3, and width of molten pool reach around 200 μm. Overlapping between half cylindrical molten pools determines the remelting areas, closely stacked to form a good metallurgical bonding between the adjacent molten pools. In this study, overlapping rate was about 25.6%.

As shown in figure 10(a), considering the overlapping between molten pools, width of the molten tracks reaches about 170 μm.

4. Conclusions
In this study, AlCu5MnCdVA alloy parts have been successfully fabricated by both mesoscopic numerical element model and experimental printing. Therefore, L-PBF process has potential for manufacturing AlCu5MnCdVA alloys.

(1) The relationships between relative density, laser process parameters were obtained. The results shows that, the laser process range of AlCu5MnCdVA for L-PBF was laser power 220–240 w, scanning speed 1200–1400mm/s, volumetric energy density 41–51 J mm⁻³.

(2) Because of extreme heating and extreme cooling, L-PBF will increase solid solubility limit of Cu and Mn and suppress the precipitation of the second phase. AlCu5MnCdVA alloys by L-PBF is mainly consist of α-Al, and lattice parameters for L-PBFed parts increase from 4.046 Å to 4.039 Å.

However, relative density below 96% is far from the achievement of an optimal manufacturing, and adjusting laser process parameters cannot meet the requirements of producing parts with relative density above 99%. Therefore, further researches should be carried in the next: the addition of rare elements to AlCu5MnCdVA itself, heat treatment with isostatic pressure, or Green-Laser instead of Infrared-Laser.

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Data availability statement
All data that support the findings of this study are included within the article (and any supplementary files).

Conflicts of interest
The authors declare no conflict of interest.

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