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Letter

Macrosegregation mechanism of primary silicon phase in selective laser melting hypereutectic Al − High Si alloy

A B S T R A C T

Macrosegregation of the primary silicon phase (proeutectic silicon) was observed in the selective laser melting *in-situ* processed Al–50Si alloys. Experimental results show that the Si-rich regions appear in the center and contour region. In contrast, the other region presents a Si-poor microstructure. The temperature field and fluid flow in the molten pool are the two key points for the segregation of the primary silicon phase. This work indicates that the macrosegregation is significantly influenced by the size and temperature of the molten pool, which is controlled by input energy density.

Keywords:
Hypereutectic Al − Si alloy
Selective laser melting
Macrosegregation
Ultra-fine microstructure

1. Introduction

Selective laser melting (SLM) is an additive manufacturing process which can produce three-dimensional (3D) parts with sophisticated shape and fine microstructure [1]. First, the part is designed using CAD software, and then it is built layer-by-layer using a high intensity laser beam which selectively melts the powder. Nowadays, common pure metals (Fe [2], Al [3] and Ti [4]) and their alloys are fabricated via using SLM. Compared with pre-alloyed powders, the use of powder mixture could offer many advantages, such as high level of composition flexibility and cost-saving. Given their high castability, low density, high thermal conductivity and similar thermal expansion coefficient (7–9 $\times$ 10^{-6} °C^{-1}) with pure silicon and GaAs [5], hypereutectic Al − high Si alloys show extensive commercial applications in aircraft, automotive and electronic packaging industries. Olakanmi et al. [6] already reported that Al–Si alloys are suitable candidate materials for SLM, due to their low thermal expansion and uniform surface oxide film distribution.

In this work, a hypereutectic Al − high Si alloy was prepared *in-situ* by SLM processing using ta mixture of Al and Si powders under argon protective atmosphere. The microstructure of the corresponding alloy was then investigated with a focus on the primary silicon phase, the macrosegregation mechanism of which is discussed.

2. Material and methods

An Al powder produced in the laboratory by gas atomization in argon atmosphere (Nanoval process) and a commercial Si powder (Kaiman, China) were used in this study. The average particle sizes of the spherical Al powder and irregular Si powder are 42 μm and 16 μm respectively. A commercial SLM machine MCP-realizer SLM 250 equipped with YLR-100-SM single-mode CW ytterbium fiber laser (MCP-HEK Tooling GmbH, Germany) was employed. The spot size and maximum power are 40 μm and 400 W respectively. Small cube samples (8 $\times$ 8 $\times$ 8 mm) were fabricated using a zigzag scanning mode. An Al substrate was sandblasted before process, and heated to 400 K during the process. According our previous works, the macrosegregation appears in the SLM processed sample with high laser power. Therefore, laser power, laser scanning speed, hatch distance and layer thickness were fixed at 320 W, 500 mm s^{-1}, 45 μm and 50 μm respectively. Experiments were performed under a high-purity argon atmosphere containing less than 0.2% oxygen. The porosity and size distribution of the primary silicon phase was determined by image analysis (NIH Image J, Software, USA). Each reported value is an average corresponding to a set of 10 measurements performed 3 times. The microstructure of the specimens was observed using optical microscopy (OM) (Nikon, Japan) and scanning electron microscopy equipped with X-ray energy dispersive spectroscopy (SEM) (JEOL JSM 7800F, Japan). X-ray Diffraction (XRD) was performed with a Cobalt anticathode (λ = 1.78897 Å) operated at 35 kV and 40 mA.

3. Results and discussions

The XRD analysis spectra of the SLM processed samples and powders mixture are presented in Fig. 1(a). Fig. 1(b) reminds the binary phase diagram of Al and Si [7]. It is observed that the main phases in the XRD spectra are α − Al and silicon for the composition of Al–50Si, which shows a good consistency with the Al–50Si composition of the binary diagram at room temperature. No other peak is detected. However, when compared with the powder mixture, the main peak (2θ) of Al (1 1 1) of the SLM processed alloy moves to right. According to Bragg's Law, a larger θ value indicates a smaller lattice constant. Bendijk et al. [8] reported a linear correlation between the lattice parameter of α − Al and the atomic fraction

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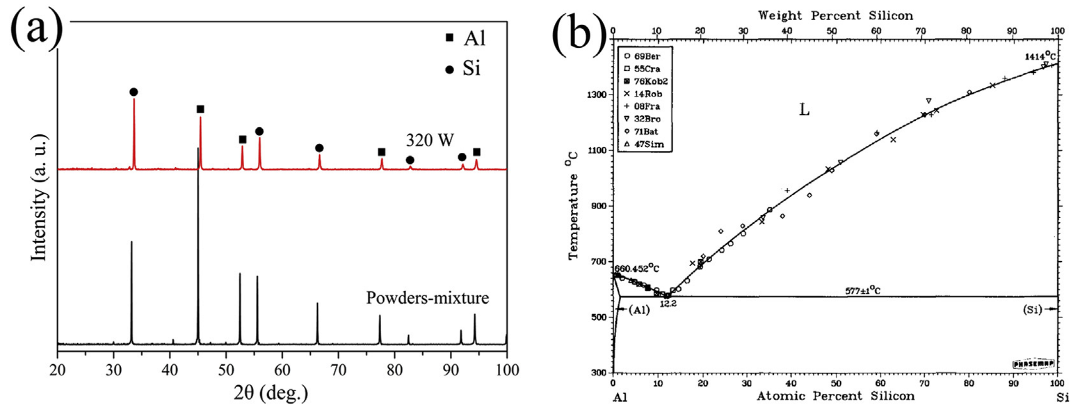

Fig. 1. (a) XRD pattern of SLM processed sample and powder mixture and (b) phase diagram of Al–Si.

of silicon (X_{Si}):

$$a = 0.40491 - 0.0174X_{Si}^2$$

So that, it can be concluded that the SLM processed alloy shows a supersaturated Al (Si) solid solution (about 5 wt. %), due to its high cooling rate.

The microstructures of the SLM processed hypereutectic Al–Si alloys are shown in Fig. 2. It is observed that the SLM processed sample clearly presents a macrosegregation behavior of the primary silicon phase. For A and B facets of the cubes as indicated in Fig. 2(a), the minimum primary silicon phase content is detected in the middle region. For the A-side (Fig. 2(b)), the primary silicon phase content in the middle region is about 43.7 vol. % while the contour and center regions present higher value about 53.4 and 51.4 vol. % respectively. EDS analysis confirms these results. It shows that the silicon content is about 60 vol. % in the contour and center region, which is higher than that of the middle region (50 vol. %). For B-side (Fig. 2(c)), the primary silicon phase presents the same distribution. In addition, the center and contour region present fewer pores than that of the middle region.

Fig. 3 shows the microstructures (top view) and size distributions of the primary silicon phase at higher magnification of the SLM processed sample. The primary silicon phase in the contour region presents a fine microstructure (Fig. 3(a)) with mean particle size of 2.58 μm (Fig. 3(d)). In the middle region, a large irregular primary silicon particles (8.45 μm) appear (see in Fig. 3(b and e)), which are surrounded by the eutectic structure. Fig. 3(c and f) show a primary silicon phase with an average diameter of 6.10 μm in the center region.

It is obvious that macrosegregation occurs in SLM processed sample. Depending on the geometry of the part, a schematic illustration of the macrosegregation of the primary silicon phase is shown in Fig. 4. The scanning mode is illustrated in Fig. 4(a). Several authors, for example, Dai et al. [9] and Zhao et al. [10] reported that a fluid flow appears in the molten pool, which can be attributed to the temperature gradient between internal and external molten pool. Indeed, this temperature gradient induces variations of the surface tension and of the density which produces a shear force and causes the fluid flow. As reported by Levich [11], the Marangoni convection occurs when an inhomogeneous temperature distribution exists in the liquid for the 2D model according to the formula.

$$\eta \frac{\partial u}{\partial y} = \gamma \frac{\partial T}{\partial x}$$

Where η is the dynamic viscosity, γ is the temperature derivative of surface tension (N/(m × K)). Dai et al. [12] investigated the influence of oxidation of Al based alloy on the surface tension and Marangoni flow. They showed that the molten pool with oxidation presents a fluid flow similar to that of Fig. 4(b). According to the

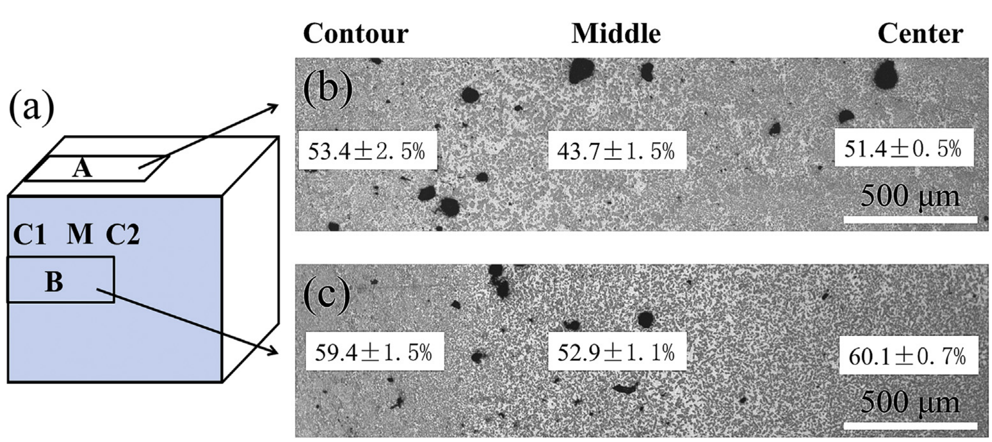

Fig. 2. (a) Schematic illustration of SLM-processed sample (C1: contour, M: middle, C2: center), the microstructure and primary silicon content (vol. %) of (b) A-side, (c) B-side.