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High-strength silicon brass manufactured by selective laser melting

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ABSTRACT

Generally, metallic alloys adaptive to selective laser melting (SLM) need to meet three basic physical properties, i.e. relatively high laser absorptivity, relatively low thermal conductivity, and especially non-containing low boiling point volatile elements. In this work, high-strength Cu-12.5Zn-2.9Si silicon brass, which does not meet these three requirements, was manufactured by SLM from gas-atomized powder. Interestingly, the SLM-manufactured silicon brass has high relative density (98.8%) thereby exhibiting higher strength than that for cast counterpart. Accordingly, this work substantiates, for the first time, the feasibility by SLM to manufacture high-strength metallic alloys with special physical properties.

1. Introduction

Because of its distinctive feature of additive layer-by-layer strategy, selective laser melting (SLM) has demonstrated several advantages compared to conventional manufacturing processes [1,2], such as flexibility associated to realize parts with complex geometries, refined microstructure resulted from non-equilibrium rapid solidification in SLM therefore improved properties [3]. Generally, to ensure high enough energy input for obtaining nearly full density and excellent properties, metallic alloys adaptive to SLM should meet the following three basic requirements with regard to physical properties [4]: (1) relatively high laser absorptivity, (2) relatively low thermal conductivity, and especially (3) without volatile elements with low boiling point. Undoubtedly, alloy systems widely studied by SLM so far, including stainless steel [5], titanium alloys [6], nickel alloys [7], and aluminum alloys [8], *etc*., meet these three requirements.

For the alloy systems failing to meet the requirements (1) and (2), considerable endeavors have been made recently on SLM of pure copper and its alloys, for example, Cu–4.3Sn alloy [9] and Cu–Cr–Zr–Ti alloy [10], *etc*. It is well accepted that vaporization phenomenon stemmed from volatile elements with low boiling point is detrimental to achieving nearly full density for SLM-produced alloys. Especially, as a typical volatile element with low boiling point of 900 °C, Zn brings about more difficulty in manufacturing Zn-containing alloys by melting-related technologies, especially by SLM. Reasonably, studies on Zn-containing alloys manufactured by SLM, for example Mg–5.2Zn–0.5Zr alloy [11], suffer from low relative density (94.0%). Typically, compared with Mg–5.2Zn–0.5Zr, more special physical properties such as higher Zn content, higher melting point of base element, and/or smaller temperature difference between the melting point of base element and the boiling point of Zn, can coexist in some specific alloy system, for example brass. This scenario raises an interesting and important question. For a specific alloy system failing to meet the aforementioned three requirements, can it be manufactured by SLM to obtain near full density therefore high strength?

Motivated by this question, we report on formation of high-strength Cu-12.5Zn-2.9Si silicon brass manufactured by SLM from gas-atomized powder. The manufactured silicon brass has high density and exhibits enhanced yield strength compared to cast counterpart. To the best of our knowledge, this is the first time that a specific alloy failing to meet the aforementioned three requirements is manufactured successfully by SLM.

2. Experimental

The Cu-15.5Zn-2.8Si spherical powder (called silicon brass hereafter) was gas atomized via a close-coupled gas atomization system (HERMIGA) with the following parameters: an atomization temperature of 1150–1200 °C, a liquid-metal flow velocity of

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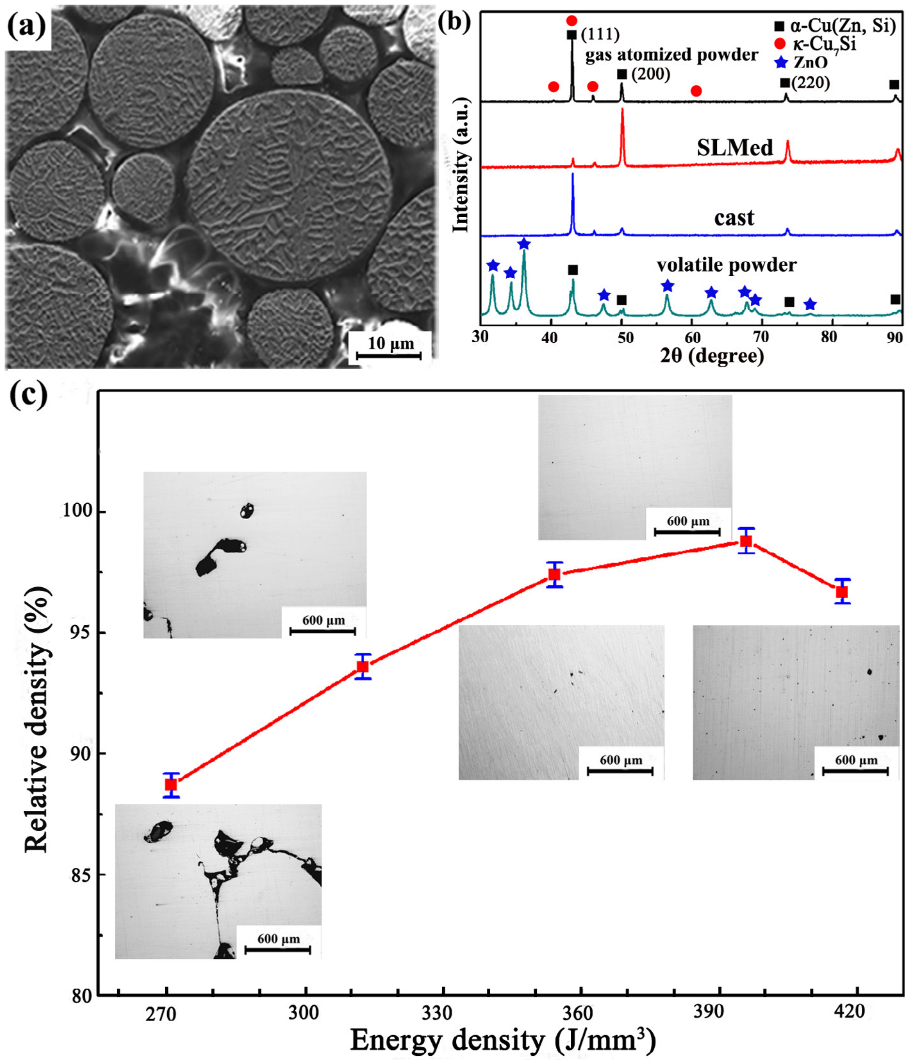

Fig. 1. (a) Cross-section morphology of the atomized powder. (b) XRD patterns of atomized powder, SLM-produced and cast specimens, and volatile substance. (c) Relative density and corresponding optical images of the SLM-produced samples.

6 kg/min, and a nitrogen gas pressure of 2.5 MPa. Mesh sieving and air classification were adopted to select spherical-shape silicon brass powder with particle size of about 15–53 μm for SLM processing. Bulk silicon brass specimens were manufactured by SLM in a Dimetal-280 SLM system, which had a SPI fiber laser with wavelength of 1090 nm and maximum laser power of 200 W. The following SLM processing parameters, i.e. laser power P altering from 130, 150, 170, 190 to 200 W, laser scanning velocity $v = 200$ mm/s, layer thickness $t = 30$ μm and hatch spacing $h = 80$ μm, were taken into account by varying laser energy density inputs (E), which is described as $E = P/(v{\cdot}h{\cdot}t)$ [12]. As such, the E value corresponded to 270, 312, 354, 395, and 416 J/mm^3, respectively. Two kinds of bulk specimens perpendicular to the building direction, $8 \times 8 \times 8$ mm^3 cubes and cylindrical rod specimens with 42 mm long and 8 mm in diameter, were built for microstructure characterization and tensile testing, respectively. For comparison, cylindrical rod samples having the same composition were prepared by copper mold casting from high purity raw materials.

The relative density of the SLM-produced specimens was averaged from five measurements by Archimedes' principle. The phase constituents and microstructure features were examined by X-ray diffraction (XRD, D/MAX-2500/PC) with Cu Kα radiation and scanning electron microscopy (SEM, Philips XL-30 FEG) with energy dispersive X-ray spectrum (EDX). Moreover, the chemical compositions of the gas-atomized powder and SLM-produced silicon brass specimens were analyzed by wet chemical and gas analysis, respectively. Tensile tests for the cylindrical specimens with a 15 mm gauge length and 3 mm in diameter were performed by a universal testing machine (Instron 5569) equipped by a laser extensometer under quasi-static loading at a strain rate of 1 mm/min.

3. Results and discussion

The atomized powder displays a nearly spherical shape with size distribution of 15–53 μm (Fig. 1a). The particles consist of cellular and dendrite structure with two constituent phases, i.e. predominant face-centered cubic (fcc) α-Cu(Zn, Si) solid solution and minor hexagonal close-packed (hcp) κ-Cu_7Si phase (Fig. 1b). EDX analyses indicate that the chemical compositions of different powder particles are almost identical, indicating no significant segregation in chemical composition.

Fig. 1c displays the relative density and corresponding optical microstructure of the SLM-produced silicon brass at different laser energy densities. Apparently, with increased laser energy density,