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J. Mater. Sci. Technol., 2014, 30(4), 417–422
www.JMST.org

Mechanical Properties of a Low-thermal-expansion Aluminum/Silicon Composite Produced by Powder Metallurgy

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[Manuscript received May 1, 2012, in revised form November 12, 2012, Available online 9 November 2013]

Al matrix composite containing high volume fraction silicon has been promising candidate for lightweight and low-thermal-expansion components. Whereas, optimization of its mechanical properties still is an open challenge. In this article, a flexile powder metallurgy processing was used to produce a fully dense Al–4.0Cu (wt%) alloy composite reinforced with 65 vol.% Si particles. In this composite, Si particles were homogenously distributed, and the particle size was refined to the range of 3–15 μm. Tensile and flexural strength of the composite were 282 and 455 MPa, respectively, about 100% and 50% higher than the best properties reported in literature. The measured fracture toughness of the composite was 4.90 MPa $m^{1/2}$. The improved strength of 65%Si/Al was attributed to the optimized particle characteristics and matrix properties. This investigation is expected to provide a primary understanding of the mechanical behaviors of Si/Al composites, and also promote the structural applications of this low-thermal-expansion material.

KEY WORDS: Aluminum matrix composite; Powder metallurgy; Mechanical properties; Coefficient of thermal expansion; Fracture

1. Introduction

Aluminum alloys containing highly loaded silicon (Si/Al composite) are of special importance in terms of thermal management applications owing to their low density, high thermal conductivity and tailorable coefficient of thermal expansion (CTE)[1,2]. Besides the attractive physical properties, the strength and elastic modulus of Si is markedly higher than Al[3], so that highly loaded Si/Al composite may be effectively strengthened and has superior mechanical properties. This proposal is supported by the extensively accepted strengthening theory for particle reinforced Al matrix composites (AMCs)[4–8]. Besides, appropriate strength–toughness combinations will enable the structure–function integrated applications of this lightweight material.

Typically, high volume fraction Si/Al composite often contains 50–75 vol.% Si inclusions in manner of closely packed particles or semi-continuous network within Al matrix[9–12]. In such kind of AMCs, the coordinated deformation of matrix and particle is difficult because of the intense constraint of reinforcement framework[10,13,14]. As a result, these composites are brittle and their mechanical properties become highly sensitive to flaws, such as porosities[11], particle defects[15] or abnormally coarsened Si particles. Most of the available investigations on Si/Al composites revealed poor mechanical properties and machinability. Particularly, strength of composites reinforced with more than 50% Si is often comparable or even lowered than the non-reinforced Al alloys, and further degrades with increasing Si content[9–12]. In a word, the mechanical behaviors of this composite are highly dependent on the fabrication processing which now is not well controlled.

Mechanical properties of particulate AMCs have been well documented. Generally, superior strength together with appropriate toughness requires proper particle–matrix strength matching, ductile matrix, well bonding particle–matrix interface, homogenously distribution of particles etc[4–8,13–16]. Unfortunately, controlling of above factors was particularly difficult for high volume fraction Si/Al composite in comparison with traditional SiC_p/Al, Al_2O_3/Al or low volume fraction Si/Al. The composites are difficult to be fully densified by using solid-phase processing. On the other hand, in liquid-phase processing like stir casting or pressure infiltration, excessive liquid phase of Al–Si eutectic would favor the coarsening of the highly loaded Si particles. These shortages exist in most of the reported Si/Al composites prepared by powder hot-pressing (porosities containing), melting-metal infiltration or spray forming techniques (porosities and coarsened particles). These defects lead to poor

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http://dx.doi.org/10.1016/j.jmst.2013.11.003

machinability and inferior mechanical properties. Besides, most of existing Si/Al composites employ pure-Al or Al−Mg−Si alloy as matrix, so the strengthening effect is limited. As a result, high volume fraction Si/Al composite was less considered as a candidate for structural application. And the open challenge for mechanical observation of Si/Al composite is achieving fully dense material with controllable microstructural features like matrix composition, size and spatial distribution of Si reinforcement.

In the present research, well controlled powder metallurgy (P/M) route was used to produce fully dense and porosity-free 65 vol.%Si/Al composite with optimized microstructure. The composite was designed to have refined silicon reinforcement that homogeneously distributed in Al alloy matrix. The P/M processing including the following steps: blending of elemental Al powder, Cu powder and Si powder, cold-isostatic pressing (CIP) of powders mixture, degassing and hot-isostatic pressing (HIP) consolidation. Our purpose is to provide a controllable producing method and a primary understanding on the mechanical properties of high volume fraction Si/Al composites as a potential structural material.

2. Experimental

Air atomized Al powder and Cu powder with similar mean particle diameter of 15−18 μm, and commercially crushed silicon powder with mean particle size of 10 μm were used as starting powders. All powders have purity higher than 99.9%. The three powders were mixed according to Si weight fraction of 60.8% and Cu weight fraction of 4.0% of Al−Cu matrix, and were mechanically blended in a rotary mixer for 24 h to achieve homogenous mixture. The powder mixture was subsequently CIPed (under pressure of 150 MPa for 15 min) into a compact with relative density of about 70%. The compact was canned and degassed at 500 °C. After degassing, the compact was HIP consolidated using the following parameter: temperature at 545 °C, pressure of 90−100 MPa and holding time of 3 h. As HIPed billet was sampled and solution treated at 500 °C for 2 h, and then quenched in cold water and artificial aging (T6, 180 °C/4 h).

The microstructure and fractography were characterized by optical microscopy and scanning electron microscopy (SEM, 20 kV, JEOL). Tensile test was carried out on dog bone-shape circular specimens with a gauge diameter of 5 mm and gauge length of 10 mm. Three-point flexural strength was measured on specimens with dimensions of 3 mm × 4 mm × 40 mm. Both tensile and flexural tests were conducted at an initial strain rate of 10^{-4} s^{-1}. Fracture toughness was measured using compact-tensile specimens. The specimen thickness (*B*) is 10 mm and a specimen width (*W*) is 30 mm, and other sizes were determined according to ASTM-E399. Since this composite is too brittle for pre-cracking using fatigue method, the specimens were notched using an electrical discharge machining, without pre-cracking. The notch has a width of 0.25 mm. Besides, the CTE of the composite (20−100 °C) was measured on a dilatometer at heating rate of 3 °C/min, by using machined cylinder samples (6 mm × 15 mm).

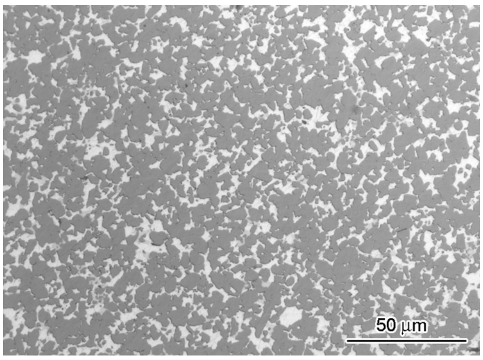
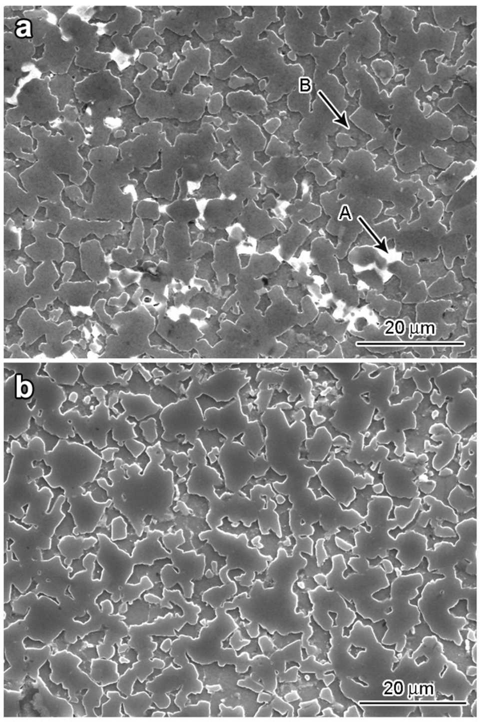


Fig. 1 Optical micrograph of HIP processed 65%Si/Al composite.

3. Results and Discussion

3.1. Microstructure characterization

The density of the 65%Si/Al composite measured by Archimedes method is slightly higher than the theoretical density, which indicates the composite is fully dense. Fig. 1 is a representative optical micrograph of as prepared 65%Si/Al composite, showing very fine and homogenous microstructure. Fig. 2(a) and (b) shows typical SEM micrographs of the polish-and-etched surface of the composite specimen before and after solution treatment, in which no pore or micro-crack was found. Most of the Si particles are interconnected and a few small particles are mono-dispersed. In spite of the locally connected Si particle, no closed Al region forms and the matrix are spatially continuous. Particularly, continuous Al phase is needed for diffusion of alloying element during solution heat treatment, which enables



c

Element	A	B	C
Al K	67.70	98.83	95.42
Si K	–	1.17	2.22
Cu L	32.30	–	2.36

Fig. 2 Microstructure of 65%Si/Al composite before (a) and after (b) T6 heat treatment, together with an inset (c) showing composition of pointed area of Al matrix, measured by EDS (in at.%).