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Effect of copper content on microstructure and mechanical properties of Al/Sip composites consolidated by liquid phase hot pressing

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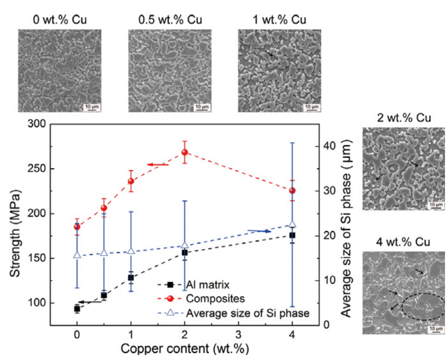
HIGHLIGHTS

- Cu addition effectively strengthens the Al matrix after heat treatment.
- Composites show similar microstructure other than by adding 4 wt.% Cu.
- Extensive clustering and coarsening of Si phase occur by adding 4 wt.% Cu.
- Mechanical properties increase with Cu content from 0 to 2 wt.% and then decrease.

GRAPHICAL ABSTRACT



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ABSTRACT

Aluminum (Al)-based composites reinforced with 50 wt.% silicon (Si) were prepared by liquid phase hot pressing. Elemental copper (Cu) powder was mechanically mixed with gas-atomized Al—Si alloy powder to form partial liquid phase during sintering, and its effect on densification, microstructure and mechanical properties was investigated. The results indicate that the amount of precipitated Al_2Cu (θ) phase increases gradually as the Cu content increases from 0 to 2 wt.%. Accordingly, it promotes solid solution hardening along with precipitation hardening, and leading to an enhancement of mechanical properties. However, the presence of too much brittle Al_2Cu phase and large Si phase caused by Si—Si clustering in the Al-4 wt.%Cu/Sip composite debase the mechanical properties remarkably. Cu addition reduces the melting point and results in the formation of Al_2Cu phase, thus reducing the consolidation temperature and enhancing the strength of Al matrix. Therefore, the addition of minor elemental Cu powder is an effective approach to promote the preparation and the performance of Al/Sip composites by powder metallurgy.

1. Introduction

Aluminum (Al) matrix composites (AMCs) with high content of reinforcement exhibit superior mechanical and thermo-physical properties. This is related to the good combination of strength attained from reinforcement and toughness due to the underlying Al matrix [1–3]. AMCs are good candidates for high performance power and microelectronics applications in thermal management as a result of their high thermal conductivity and low coefficient of thermal expansion (CTE) [4]. On the other hand, AMCs always show a high potential for structural applications, e.g., automotive engineering and aerospace industry, in which low weight, high

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strength and excellent damage tolerance are required [5]. Recently, AMCs reinforced with silicon (Si) particles have attracted increasing interest in the application of thermal management and automotive engineering due to their excellent properties and environmental friendliness [6–8]. Additionally, the solution ability of Si in Al matrix and the absence of interfacial reactions enhance the interface bonding strength, which is a great challenge in the traditional AMCs reinforced with ceramics [9,10].

Generally, pressureless sintering of Al alloy powder can hardly be achieved due to the presence of surface oxide layer with high negative enthalpy associated with the oxide formation [11,12]. Such thermodynamically stable ceramic layer prevents solid state diffusion among powder particles. Heard et al. [13] performed a comprehensive assessment on sintering behavior of Alumix-231 (Al-15Si-2.5Cu-0.5Mg) alloy. A relative density of 98% and an UTS of 330 MPa were received after sintering at 560 °C for 60 min. Liquid phase sintering is known to be an effective way in increasing the sintering rate. With the presence of liquid phase, it can pull and braze the powder together by a capillary force and it also acts as a quick diffusion channel among the powder, thus increasing the sintering density and inter-particle bonding strength [1]. However, too much liquid phase could lead to the extensive coarsening of Si phase or even phase segregation in the Al/Sip composites [14]. Zhou and Duszczyk [15] reported that with 19%Si added to Al—Cu elemental powder and liquid phase sintered at a proper temperature, few dimensional or shape change were observed, and further hot extrusion for densification is necessary. Therefore, the pressure assisted consolidation processes are commonly employed in fabricating Al/Sip composites, such as powder forging [16] and powder extrusion [17] at solid state and thixocasting [12] and pressure infiltration [18] at liquid state.

As a matter of fact, Al/Sip composites usually contain Si reinforcement in a manner of large closely packed particles or semi-continuous network structure, which results in poor mechanical properties. Liquid phase hot pressing is often employed in various powder systems to improve the sintering behavior and the performance of bulk materials [11, 19,20]. It is known that copper (Cu) is an alloying element widely used in Al alloys, and the addition of Cu leads to the formation of semi-coherent precipitates (Al_2Cu, θ) after solution treatment and subsequent aging [21]. Furthermore, the liquid-solid zone is enlarged according to the Al—Cu binary phase diagram. These facts will strengthen the Al matrix and decrease the consolidation temperature. However, too much Al_2Cu phase or other intermetallic compounds could significantly reduce the elongation, and even strength of the composites [21]. Such secondary phase may act as failure initiation sites when pressure is applied. Additionally, the presence of secondary phase may have negative effects on thermo-physical properties. Therefore, the content of elemental Cu powder should be controlled in a reasonable range.

In this respect, hot pressing route provides some opportunities, as it involves relatively high pressure, low temperature (about 500–650 °C), near-full density, and high productivity [20,22]. Such processing also allows for the synthesis of AMCs along with the application of various matrix alloys to tailor properties for the needs of particular applications. However, there is few information concerning the effect of alloying elements on microstructural characteristics and mechanical properties of Al/Sip composites. In this work, Al/Sip composites were prepared by hot pressing of rapidly solidified Al—Si alloy powder mixed with different amounts of elemental Cu powder. The present work aims at providing a contribution to identify the effect of Cu addition on densification, microstructure and mechanical properties of Al/Sip composites. Therefore, the effect of Cu content on the microstructural characteristics, hardness, bending and tensile properties, and fracture behavior of the composites were evaluated and compared with the unalloyed reference composite.

2. Experimental procedures

2.1. Materials

Gas-atomized Al-50 wt.%Si alloy powder and electrolytic Cu powder with an average size of 49 and 40 μm, respectively, were used. Both the powder have a purity of higher than 99.8%. Fig. 1a and b shows the scanning electron microscope (SEM) micrographs of the irregular Al—Si alloy powder and the dendritic Cu powder, respectively. The microstructure of Al—Si alloy powder is presented in Fig. 1c, which shows suppressed Si phases distribute homogeneously in Al matrix. The Al—Si alloy powder and Cu elemental powder (from 0 to 4 wt.%) were mixed mechanically in a V-blender at 50 rpm for 4 h. After that, the mixed powder was compacted using a steel die under a pressure of 400 MPa for 2 min. The green compacts have relative densities of about 83%.

2.2. Preparation

During the hot pressing, the compacts were firstly placed in a graphite mold with its inner walls coated with BN slurry, and then a pressure of 20 MPa was applied. After the mold was heated to 560 °C with a rate of 15 °C/min, the applied pressure was increased to 45 MPa. The compacts were hot pressed at 560 °C for 60 min in vacuum. The pressure on the samples was not released until the consolidation was finished and the samples were cooled down to 200 °C. After hot pressing, the as-prepared samples were cooled in furnace to room temperature with a cooling rate of about 10 °C/min. The samples were solution treated at 510 °C for 4 h and quenched in water, and then artificially aged at 150 °C for 24 h (T6).

2.3. Characterization

The hot pressed samples were cut and polished to examine the microstructure. Kellers' reagent was used for metallographic etching.

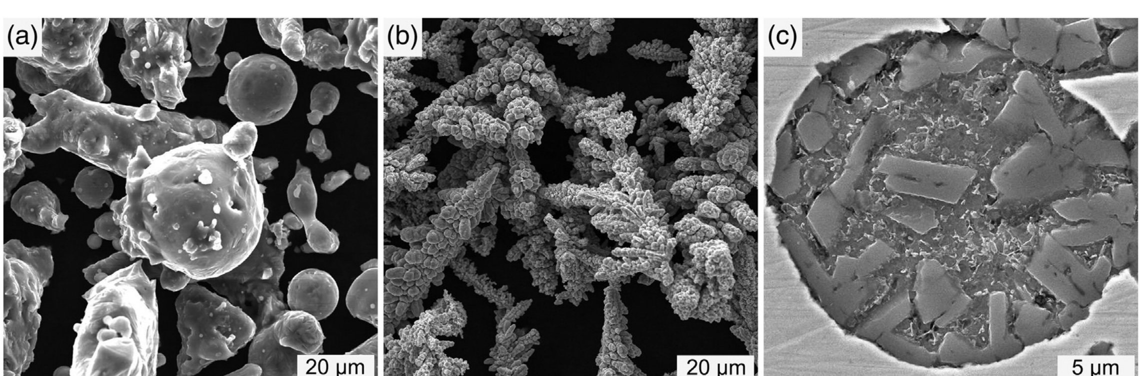

Fig. 1. SEM images of the Al—Si alloy powder (a), Cu powder (b), and microstructure of the Al—Si alloy powder (c).