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Enhanced precipitation hardening in an alumina reinforced Al–Cu alloy matrix composite

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Abstract

An alumina reinforced Al–Cu alloy matrix composite was prepared by reaction sintering of Al and CuO powders. Precipitation hardening by further aging the composite at 250 °C was studied. In situ formed micron-sized alumina particles were present in the Al(Cu) matrix of the un-aged composite, while additional nanometer-sized Al_2Cu rods were obtained in the matrix of the aged composite. Both hardness and bending strength were enhanced after the composite was aged. In the bending test, the sample was plastically deformed before fracture. Microstructural analysis revealed that the size of dimples found in the fracture mouth of the un-aged composite was micron-sized, and that in the aged composite was much smaller. It was evident that when the composite was subjected to stress, micron-sized alumina particles were responsible for the formation of cracks in the un-aged sample, while in the aged sample, Al_2Cu nano-rods were the dominant nucleation sites for crack growth.

Keywords: A. Metal-matrix composites (MMCs); B. Hardness; B. Strength; E. Powder processing; Precipitation hardening

1. Introduction

Recently, more and more aluminum-based metal matrix composites (Al-MMCs) are fabricated by the in situ methods [1–5], in which the reinforcements are synthesized by chemical reactions during sintering rather than by directly adding and mixing reinforcing agents into the molten matrix. The in situ formed reinforcements are finer in size, thermodynamically stable and distributed uniformly. At the same time, the composites possess contaminated-free reinforcement–matrix interfaces. Thus, mechanical properties of the in situ products are usually superior to those made by reinforcement–matrix mixing [6]. One commonly adopted in situ method involves the displacement reaction between Al and selected metal oxides, such as NiO [7], TiO_2 [8], MoO_3 [9], Fe_2O_3 [10], CuO [11] and ZnO [12]. In many of these systems, Al_2O_3 reinforcements in various physical forms are produced. Among the used metal oxides, CuO and ZnO are the most widely used ones, because Cu and Zn are two important additional elements to Al alloys. Previous studies showed that reduced Cu [11] and reduced Zn [12] formed solid solution with Al and produced an alloy matrix in the Al-based MMC. Using Al(Cu) or Al(Zn), instead of pure Al as a matrix of the MMC, had improved the mechanical properties of the composite products. It is well known that the precipitation hardening is a standard technique used in the production of Al alloys to enhance their mechanical properties [13]. In this work, we found that aging the Al–Cu alloy based MMC could further enhanced its strength. We will discuss the mechanism of precipitation hardening in this composite.

2. Experiments

A powder, containing 95 wt.% high-purity Al and 5 wt.% CuO, was mixed and cold-pressed under 500 MPa

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to form green compact samples. A series of samples were sintered in argon atmosphere in a tube furnace at 1000 °C for 0.5 h before they were cooled rapidly to room temperature by water quenching. The time for each quenching was less than 2 s. One of the sintered and quenched samples was kept as a reference, while the others were further aged at 250 °C for 0.5, 1, 2, 4, 8 and 16 h respectively. The hardness values (VHN) of the samples were determined by a Vickers microhardness indenter (Buehler 2013). Their corresponding microstructures were studied by scanning electron microscopy (SEM, LEO-1450VP) and transmission electron microscopy (TEM, Philips CM-120). Elemental and compositional analyses were performed by using energy dispersive X-ray spectrometry (EDS). In order to evaluate the bending strength of the sintered and aged products, six bar samples (50 mm × 5 mm × 3 mm) were also prepared by similar heat treatments. The three-point bending tests were conducted to the un-aged and the aged specimens. Morphologies of the fracture mouths of the samples were studied by SEM.

3. Results and discussion

3.1. In situ reactions

Fig. 1a and b was the SEM micrographs of a green sample and a sample sintered at 1000 °C, respectively. In Fig. 1a, the dark background was composed of Al grains with size of about tens of microns. The light patches were the CuO particles. They were distributed randomly in the green sample. One of our previous works [11] was to study the reactions between Al and CuO (20–40 wt.%). It was determined that the displacement reaction between Al and CuO took place in the temperature range from 580 °C to 700 °C, and Al_2O_3 particles were in situ formed. The study also revealed that in the temperature range from 800 °C to 870 °C, the reduced Cu dissolved into the molten Al to form Al–Cu liquid solution. In this work, the possible reactions between Al and CuO (5 wt.%) can be described by the following equations:

$$2Al_{(l)} + 3CuO_{(s)} \xrightarrow{\text{firing}} Al_2O_{3(s)} + 3Cu_{(s)} \quad (1)$$

$$Al_{(l)} + Cu_{(s)} \xrightarrow{\text{firing}} (Al, Cu)_{(l)} \quad (2)$$

$$(Al, Cu)_{(l)} \xrightarrow{\text{water-quenching}} Al(Cu)_{(s)} \quad (3)$$

where *l* and *s* indicated that the reactant or the product was in the form of liquid or solid. As the liquidus Al–Cu was cooled to room temperature by water quenching (reaction 3), an Al(Cu) solid solution was formed. As a result of the reactions between Al and CuO, the microstructure of the sintered Al–CuO samples was quite different from the green one. The SEM image of the sintered sample was shown in Fig. 1b, which revealed the existence of Al_2O_3 particles (bright) and the uniform Al(Cu) solid solution matrix (dark) in the quenched sample. The in situ formed alumina particles had grain size of 5–10 μm, they tended to segregate along the grain boundaries of the Al(Cu) matrix.

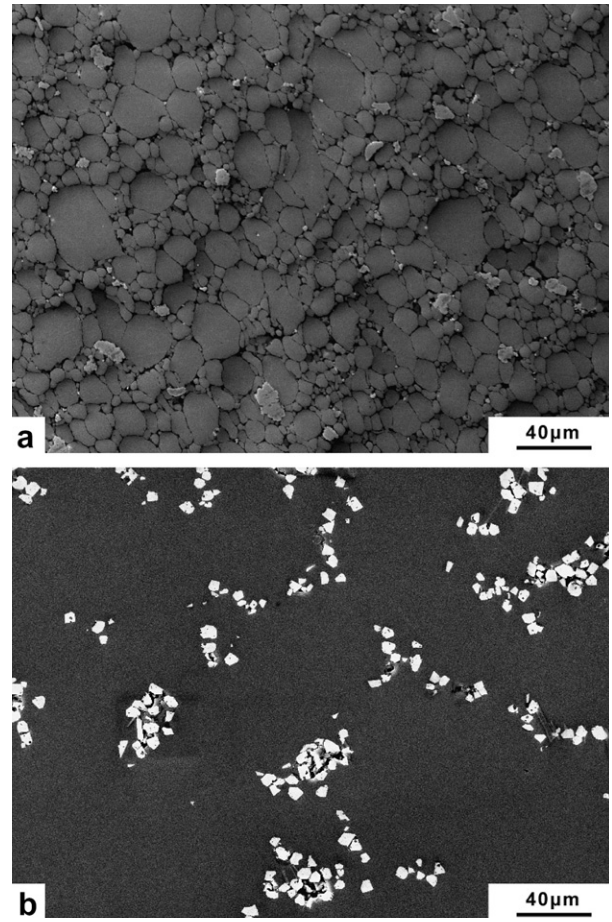

Fig. 1. SEM micrographs of (a) a green sample, and (b) a water-quenched sample after it was sintered at 1000 °C.

Knowing the starting composition of CuO in the green sample was 5 wt.%, we calculated that the volume fraction of the alumina particle in the sample after the displacement reaction (reaction 1) was about 1.5 vol.%. The image analysis on Fig. 1b indicated that the apparent volume fraction of alumina particle in the sample was about 3 vol.%, which suggested that some of the Al matrix was also oxidized by oxygen from the atmosphere during sintering. We also calculated that the Cu content in the Al(Cu) solid solution matrix should be ~4.5 wt.% for this as-sintered Al–5 wt.% CuO sample. In our work, the EDS analysis on the Al(Cu) matrix which showed that the sample contained about 2 at.% of Cu, which was equivalent to ~4.5 wt.% of Cu. According to the Al–Cu binary phase diagram [14], the solubility of Cu in Al can be as high as 5.7 wt.% at the eutectic temperature (548 °C). However, the solubility decreases sharply with temperature, and the solubility of Cu in Al at room temperature is less than 0.1 wt.%. Therefore, the Al(Cu) matrix in the water-quenched sample was a supersaturated solid solution, which was metastable and tended to transform to a more stable form upon further heat treatment.