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Intermetallic-reinforced aluminum matrix composites produced in situ by friction stir processing

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Abstract

Friction stir processing (FSP) is applied to produce intermetallic-reinforced aluminum matrix composites from elemental powder mixtures of Al–Cu and Al–Ti. The intermetallic phases are identified as Al_2Cu and Al_3Ti, which are formed in situ during FSP. The volume fraction of the intermetallic phases in the in situ composites may reach as high as ~ 0.5. The composites produced by FSP are fully dense with high strength, and the composite strength increases with the reinforcement content.

Keywords: Metal matrix composites; Friction stir processing; Intermetallic compounds; Hardness

1. Introduction

The friction stir welding (FSW) technique, developed at The Welding Institute (TWI) of UK [1], is a solid-state joining technique and has been extensively applied in aluminum alloys. In FSW, a non-consumable rotating tool with a specially designed pin and shoulder is plunged into the interface between two plates to be joined and traversed along the line of joint. Localized heating is produced by the friction between the rotating tool and the workpiece to raise the local temperature of material to the range where it can be plastically deformed easily. As the rotating tool traversed along the joint line, metal is essentially extruded around the tool before being forged by the large down pressure [2]. Based on the principles of FSW, Mishra et al. [3] developed friction stir processing (FSP) for the microstructural modification of materials, mainly refining the microstructure [3–9]. Recently, FSP has been successfully applied to produce ultrafine-grained Al–Al_2Cu in situ composite from Al–Cu elemental powder mixture [10].

It is widely recognized that the mechanical properties of metal matrix composites (MMCs) are controlled by the size and volume fraction of the reinforcements as well as the nature of the matrix–reinforcement interface. Superior mechanical properties can be achieved when fine and stable reinforcements with good interfacial bonding are dispersed uniformly in the matrix. Conventionally, reinforcing particles in metal matrix composites (MMCs) are formed ex situ and then added to the matrix metal. A possible alternative is to synthesize the reinforcement in situ in the metal matrix [11]. The advantages of in situ MMCs are more homogeneous in microstructures and thermodynamically more stable. Moreover, they also have a strong interfacial bonding between reinforcements and the matrices.

The objective of this study is to produce fully dense intermetallic-reinforced aluminum composites by the use of the FSP technique. The basic idea is to combine the hot working nature of FSP and the exothermic reaction between aluminum and transition metals. The FSP is utilized to provide the following functions: (a) severe plastic deformation to promote mixing and refining of constituent phases in the material, (b) elevated temperature to facilitate the formation of intermetallic phase, and (c) hot consolidation to form fully dense solid. In this paper, we will present the microstructure and mechanical properties for friction stir processed composites based on Al–Cu and Al–Ti systems.

2. Experimental

The starting materials used are aluminum powder (99.7% purity, − 325 mesh), copper (99.5% purity, − 320 mesh), and

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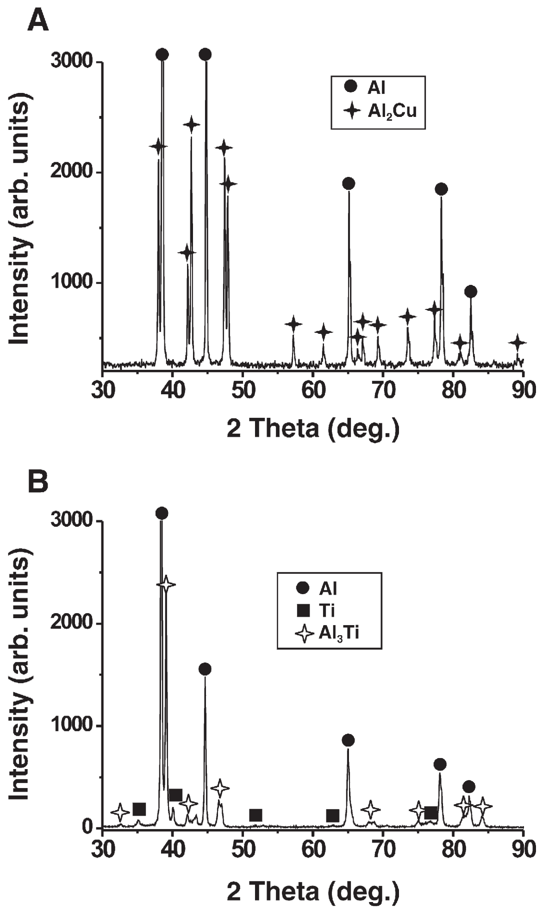

Fig. 1. The XRD patterns for (A) Al–10Cu, and (B) Al–10Ti alloys.

titanium powder (99.1% purity, − 325 mesh). The alloying elements (Cu or Ti) of 5, 10, 15 at.% were pre-mixed with aluminum powder. The pre-mixed alloy powders were cold compacted to 12 × 20 × 88 mm billet in a steel die set by using a pressure of 225 MPa. To improve the billet strength for easier handling in FSP, the green compact was sintered. The sintering temperature for Al–Cu and Al–Ti systems was 773 K and 823 K, respectively, and the sintering time was 20 min for both systems.

The tool pin used in FSP is standard M1.2*6 (metrication, with pitch height and diameter of 1.2 mm and 6 mm, respectively). A counterclockwise tool rotation speed of 700 rpm was used, and the rotating tool was traversed at a speed of 45 mm/min along the long axis of the billet. To enhance the reaction, two and four FSP passes were applied to Al–Cu and Al–Ti specimens, respectively.

X-ray diffraction (XRD, Cu K_α) was utilized to identify the phases present in the specimens. Scanning electron microscope (SEM, JSM-6400, and JSM-6330) and transmission electron microscope (AEM, JEOL 3010) operated at 200 kV were used to study the microstructure. The Vickers microhardness of the stir zone (SZ) was measured with 300 g load for 15 s. Mechanical properties of specimens machined from SZ were evaluated. Rectangular specimens with dimensions of 4 × 4 × 6 mm^3 were used for compression tests. The stress direction was aligned along the traverse direction of the FSP. The tests were carried out on an Instron 5582 universal testing machine with an initial strain rate of 1×10^{-3} s^{-1}.

3. Results and discussion

For all the Al–Cu systems, Cu is fully reacted to form Al_2Cu after two FSP passes. Fig. 1A shows a typical XRD pattern for Al–Cu alloy after FSP, which indicates the presence of only Al and Al_2Cu. For the Al–Ti system, Ti is reacted with Al to form Al_3Ti but some Ti remains unreacted after four FSP passes as indicated by the XRD pattern (Fig. 1B). The microstructure of the FS processed material is revealed by SEM backscattered electron image (BEI) in Fig. 2. The typical microstructure of Al–Cu alloys is shown in Fig. 2A, where the bright particles are Al_2Cu and the dark matrix is Al. Unreacted Cu was rarely observed in SEM, which is consistent with the XRD results. Therefore, Cu is considered to be fully reacted with Al to form Al_2Cu. The typical microstructure of Al–Ti alloys is shown in Fig. 2B. The white particles of micrometer size are pure Ti, which has been verified by EDS (energy dispersive spectroscopy), and the very fine gray particles (<100 nm) are Al_3Ti particles. From microscopic observations, the FSP materials of both alloy systems were found to be free of porosity. In addition, the measured density agrees well with the theoretical density for all the FSP materials. These evidence indicate that the FSP materials are fully dense.

A typical microstructure of Al–Cu alloys observed by TEM is shown in Fig. 3A. The grain sizes of both phases (Al and Al_2Cu) were

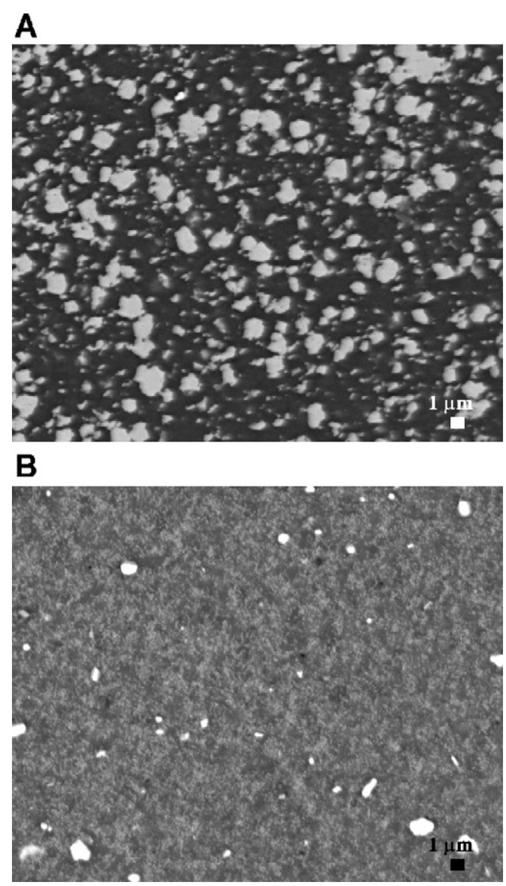

Fig. 2. SEM/BEI micrographs showing (A) the dispersion of fine Al_2Cu particles (white contrast) in Al–10Cu alloy and (B) the presence of residual Ti particles (normally larger than 1 μm) along with the dispersion of fine Al_3Ti particles in Al–5Ti alloy.