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Fabrication, microstructure and mechanical properties of Al–Fe intermetallic particle reinforced Al-based composites

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ABSTRACT

In this paper, Al-based composites reinforced by Al–Fe intermetallic compounds have been successfully fabricated by powder metallurgy technique. The reinforcements were generated in the aluminum matrix by in situ solid state reaction between commercial pure Al and pure Fe powders. The effects of sintering temperature and Fe content on the microstructure and mechanical properties of the composites were systematically studied by scanning electron microscopy, energy dispersive X-ray spectroscopy, X-ray diffraction analysis and compressive tests. New core–shell structured particles were dominant reinforcements in the composites after sintered at 560 °C for 5 h. It has been shown that the yield strength of the composites remains almost the same, while the ultimate compressive strength and ductility decrease with increasing the sintering temperature and Fe content.

1. Introduction

Particulate reinforced aluminum matrix composites have been widely used in automobile, aviation and aerospace industries due to their promising properties such as low cost, easy fabrication, isotropic property, and high stiffness-to-density and strength-to-weight ratios [1–3]. In general, ceramic particles such as SiC, Al_2O_3, TiB_2, and B_4C, which are of high strength, elastic modulus, wear resistance and fatigue resistance, are used as the reinforcements to fabricate the particulate reinforced Al matrix composites [1]. It should be noted that although the strength of the materials can be improved by introducing the ceramic particles, the ductility will be severely decreased, which substantially restricts the wide applications of the composites. The decreased ductility results from a couple of reasons. First, the existence of intrinsic defects (such as microcracks) within the ceramic particles introduced during their fabrication process will nucleate cracks during the deformation of the composites [4]. In general, larger ceramic particles have a greater statistical probability of containing defects that are apt to form flaws during deformation [5]. Second, the residue porosity at the interface between the matrix and reinforcements, the formation of brittle phases resulted from the chemical reaction during the fabrication process, and the poor wettability and significant difference in the thermal expansion coefficient between the matrix and the reinforcements might induce crack nucleation and propagation during plastic deformation.

It is widely recognized that the mechanical properties of metal matrix composites are controlled by the size and volume fraction of the reinforcements, as well as the nature of the matrix-reinforcements interface bonding strength [1]. The good interfacial bonding between the matrix and reinforcement makes a significant contribution to the achievement of superior mechanical properties. It is known that intermetallics have high modulus and strength, which can substantially increase the strength of the composites if used as reinforcements. Thus, an alternative method to improve the interfacial bonding strength is in situ fabrication of intermetallic compound reinforced composites by chemical reaction between the elements or between elements and compounds during sintering process. Al_3Ti [6], $AlNi_3$ [7] and Al_3Fe [8] in situ formed Al matrix composites have been reported in recent decades. Many in situ methods have been utilized to produce these composites such as friction stir processing [9–12], hot pressing [13–16] and plasma synthesis method [17]. The in situ methods have the advantages including: (a) more thermodynamically stable reinforcements in the matrix, resulting in less degradation in elevated-temperature services, (b) cleaner interfaces between the reinforcements and matrix, leading to a good interfacial bonding, (c) finer reinforcing particles in size and homogeneous distribution in the matrix, and better mechanical properties [18].

In this study, intermetallic particles reinforced Al matrix composites were successfully fabricated by an in situ powder metallurgy technique. During the fabrication process, a novel

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core–shell structured particulate reinforced Al matrix composite was presented. In the composites, the matrix is the soft commercial pure Al, and the reinforcements (with a core–shell structure) are comprised of a soft core (commercial pure Fe) and a hard intermetallic shell formed by the solid reaction between the Al matrix and the Fe core. The soft Al matrix and soft Fe core can effectively inhibit the crack propagation once cracks are nucleated from the intermetallic shell during plastic deformation, resulting in the preservation of the ductility as well as the improved strength. The new composites have the potential applications in some load bearing conditions, such as in automobile transportation industries to replace the heavy parts, and in aviation or aerospace industries due to their light weights and low fabrication costs.

2. Experimental

The starting materials were gas atomized Al powder (99.8% in purity, average size of 40–60 μm) and commercially pure Fe powder (99.5% in purity, average size of 40–60 μm), with the Fe contents being 1, 3 or 5 vol.% (denoted Al–1Fe, Al–3Fe, and Al–5Fe). The mixed Al and Fe powders, added by pure ethanol as the liquid medium, were blended for 10 h using a planetary powder rotator mixer with the rotation speed of 300 rotation per minute (rpm), with the ball to powder weight ratio of 5:1. Then the mixed powders were dried in a vacuum oven at 75 °C for 5 h and die-pressed at room temperature under a pressure of 400 MPa in a cylindrical steel die with a diameter of 15 mm. To enhance the density of the green specimen, all the die-pressed specimens were further compressed under an isostatic pressure of 200 MPa for 5 min. Subsequently, the green compacts were sintered in a vacuum furnace under argon atmosphere (pressure of 10 MPa) at 560, 570, and 580 °C, respectively, with a heating rate of 10 °C per minute. At 560, 570 and 580 °C, all the compacts were sintered for 5 h.

The bulk densities of the composites were measured by standard Archimedes method. D/max2550pc X-ray diffraction (XRD) with Cu Kα radiation (k = 0.154 nm) was utilized to identify the phases in the sintered specimens. The microstructures of the sintered specimens were analyzed by a FEI nano230 field emission scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectroscope (EDX). The strength and ductility of the composites were measured by compressive tests. The compressive properties of the cylindrical samples, with diameter of 3 mm and height of 5 mm, were tested using an Instron 3369 universal testing machine at a cross head speed of 1 mm per minute. The yield strength was determined as the 0.2 pct offset.

3. Results

3.1. X-ray diffraction

Fig. 1 shows the XRD patterns of the composites with 5 vol.% Fe content sintered at (a) 560 and (b) 570 °C. It can be seen that three phases (Al, Al_5Fe_2 and Fe) exist in the composites sintered at 560 °C, while only two phases (Al and $Al_{13}Fe_4$) exist in the composites sintered at 570 °C. Comparing Fig. 1a and b, it shows that the intensity of Al peaks decreases, the peaks of Al_5Fe_2 disappear and the peaks of $Al_{13}Fe_4$ appear when the sintering temperature increases from 560 to 570 °C. It should be noted that all the peaks of the XRD results sintered at the same temperature are similar no matter what Fe content is, except for the difference of the intensity. In addition, when the sintering temperature changes from 570 to 580 °C, the type of the phases does not change.

According to the Al–Fe binary phase diagram, increasing the Al content could result in the formation of five stable intermetallics, Fe_3Al, FeAl, $FeAl_2$, Al_5Fe_2 and Al_3Fe in a solid diffusion couple. However, only one detectable intermetallic phase $Al_{13}Fe_4$ or Al_5Fe_2 was detected from XRD in this work. According to the principle of kinetics, the Al–Fe intermetallics including $FeAl_2$, Al_5Fe_2 and $Al_{13}Fe_4$, which are rich of Al, will firstly precipitate from the solid interface between Al and Fe. From the literature [19], the main intermetallic compound formed in Al–Fe system in the range of Fe contents in this work should be Al_5Fe_2 during the solid reaction because of the lowest Miedema formation enthalpies. $Al_{13}Fe_4$ can only be formed via the eutectic reaction in the Al matrix, indicating that it is hard for the formation and growth of $Al_{13}Fe_4$ during the solid reaction. Thus, under the driving force of kinetics and thermodynamic, Al_5Fe_2 will firstly precipitate from the solid interface, and only Al_5Fe_2 can grow to a certain thickness via the solid diffusion along the interface between Al and Fe. Because the Fe amount in the Al is less than 10 at.%, the last phase existed in the Al matrix will be $Al_{13}Fe_4$ according to the Al–Fe binary phase diagram. Some researchers [20,21] have also demonstrated this phenomenon.

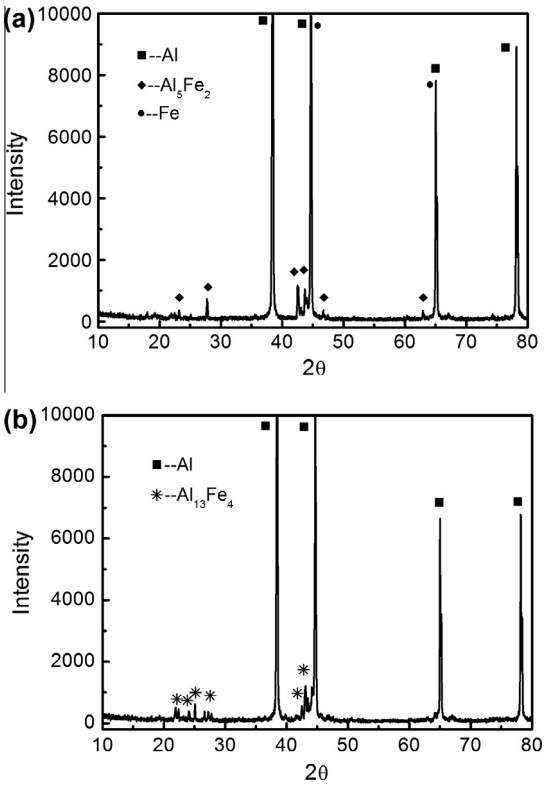

Fig. 1. XRD patterns for Al–5Fe composite sintered at (a) 560 and (b) 570 °C for 5 h, respectively.

3.2. SEM microstructures

Figs. 2–4 show the SEM microstructures of the Al–1Fe, Al–3Fe and Al–5Fe composites sintered at 560, 570 and 580 °C, respectively. It can be seen from Fig. 2 that three phases, differing in contrast, exist in three different Fe contents composites sintered at 560 °C. Using EDS analysis (as show in Fig. 5b), the continuously distributed dark matrix is identified as Al, the bright phase is Fe and the light gray phase surrounding the Fe core or dispersing in the Al matrix is Al–Fe intermetallic compound. From Fig. 2, it can be seen that the core–shell structured particles are the dominant reinforcements, although some complete intermetallic particles can also be observed in the matrix. It should be noted that a few small sized pores are presented in the matrix and at the interface between the Al matrix and intermetallics when the composites were sintered at 560 °C, as shown in Fig. 2b, d and f (arrowed). Fig. 3 shows that two main phases, differing in contrast, exist in three different Fe contents composites sintered at 570 °C. By EDS analysis, the continuously distributed dark matrix is identified as Al and the light gray phase dispersing in the Al matrix is Al–Fe intermetallic compound. The little bright phase surrounded by the intermetallic particle is Fe core. It can be seen from Fig. 3a, c and e that the intermetallic particles disperse homogeneously in the matrix when the Fe content is 1 vol.%. When the Fe content increases to 3 vol.%, the intermetallic particles begin to cluster