Materials and Design 56 (2014) 405–408

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Short Communication

In situ formed core–shell structured particle reinforced aluminum matrix composites

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ARTICLE INFO

Article history:
Received 27 September 2013
Accepted 17 November 2013
Available online 25 November 2013

ABSTRACT

Particulate reinforced metal matrix composites (PRMMCs) have high strength but their plasticity and toughness are usually low. Here in this paper a new PRMMC with both high strength and plasticity was successfully developed. The composite is composed of three distinct phases, including ductile matrix, ductile core phase and in situ formed hard intermetallic shell. The strength can be substantially improved by transferring the applied stress from the soft matrix to the hard shell. The propagation of the cracks in the shell during deformation can be inhibited since both tips of each crack become blunt due to the high ductility of the matrix and core phases. The designed structure provides guidance for developing new PRMMCs with high strength and plasticity.

1. Introduction

Particulate reinforced metal matrix composites (PRMMCs) have widely been used as structural materials nowadays due to their excellent mechanical properties such as high strength and elastic modulus [1–6]. The increased strength of the PRMMCs can be explained by the shear lag model based on the soft matrix transferring the applied stress to the hard reinforcements [7,8]. Up to now, ceramic particles such as SiC and Al_2O_3 are the most commonly used reinforcements to fabricate PRMMCs. However, it should be noted that although the addition of ceramic reinforcements improves the strength, it substantially decreases the plasticity and toughness of the composites due to two reasons [9–13]. First, the interfacial bonding strength between the externally added ceramic particles and matrix is generally weak due to unwetting or possible interfacial reactions. Thus, cracks with the size of the ceramic particles can easily be nucleated along the weak interfaces during deformation. Second, even if the interfacial bonding is strong, cracks might also be easily nucleated due to the fracture of the ceramic particles. It is known that ceramics are very brittle and easily cleavage fractured during deformation once the externally applied stress is transferred from the matrix to the ceramic particles [9–13]. Recently, to solve the weak interfacial bonding problem, in situ formed intermetallic compounds reinforced PRMMCs were developed with strong interfacial bonding between the matrix and reinforcements, such as Al_3Ti, $AlNi_3$ and Al_3Fe reinforced aluminum alloy composites [14–18]. Intermetallics have high strength and modulus, and can substantially increase the strength of the composites. Particularly, the PRMMCs reinforced by in situ formed intermetallic compounds have clean reinforcement-matrix interfaces, better compatibility and higher bonding strength between the reinforcements and the matrix [19]. It should be noted, however, although in situ formed intermetallic compounds reinforced PRMMCs have strong interfacial bonding between the reinforcements and matrix, the plasticity and toughness of the composites might also be low since the intermetallics are also very brittle. During deformation, cracks with the size of the intermetallic particles might be nucleated due to the fracture of the intermellics since the externally applied stress is transferred from the matrix to the intermetallics.

To improve the plasticity and toughness of the PRMMCs, a new PRMMC — in situ formed core–shell structured particle reinforced metal matrix composite was developed in this article. In the PRMMC, the matrix is soft metal/alloy (such as Al or Al alloy) and the reinforcements are composed of hard intermetallic shell and soft metal/alloy core (such as Fe, Ni or Ti), with the hard intermetallic shell being formed by in situ reaction between the matrix and core metals/alloys. This special matrix–shell–core structure can substantially decrease the size of the cracks because the in situ formed interfaces are very clean and strong, and the thickness of the brittle intermetallic shell is thin. The structure can also effectively inhibit crack propagation since both soft matrix and core metals/alloys can effectively inhibit crack propagation once cracks are nucleated from the intermetallic shell during deformation.

2. Experimental details

The raw materials were gas atomized Al powder (99.8% in purity and the average size of 1.47 μm) and commercial Fe powder

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0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.11.030

(99.5% in purity and the average size of 54.98 μm), with the volume fractions of the Fe powder being 10% and 20%, respectively. The mixed Al and Fe powders, combined with pure ethanol as the liquid medium, were ball-milled for 8 h in a 4 planetary ball mill under an argon atmosphere with a rotation speed of 300 rpm. The ball to powder weight ratio was 5:1. Subsequently, the composite powders were dried in a vacuum oven at 85 °C for 5 h, and then pressed under a pressure of 200 MPa in a cylindrical steel die to compacts with 45 mm in diameter at room temperature. The compacts were further compressed under an isostatic pressure of 120 MPa for 10 min to enhance the density. The specimens were then heated in a vacuum furnace (pressure of 7×10^{-3} Pa) to 610 °C with a heating rate of 10 °C per minute. At 610 °C, the specimens were sintered for 5 h under a pressure of 25 MPa. Part of the sintered specimens were then hot extruded to rods at 420 °C with an extrusion ratio of 9:1.

The bulk densities of the composites were measured by standard Archimedes method. The strength and ductility of the composites were measured by compressive testing method. At room temperature, the cylindrical specimens, having a gage size of 6 mm in diameter and 12 mm in height, were served in the compressive test at a constant strain rate of 1.67×10^{-5} s^{-1} on an Instron 3369 testing machine, based on the standard GB 7314-87 [20]. The yield strength was determined as the 0.2 pct offset. The D/max2550pc X-ray diffractometer with Cu Kα radiation (k = 0.154 nm) was used to identify the phases in the materials. The microstructures of the composites were studied using a FEI Nova Nano230 scanning electron microscope (SEM) equipped with an EDAX energy dispersive spectroscopy (EDS) system.

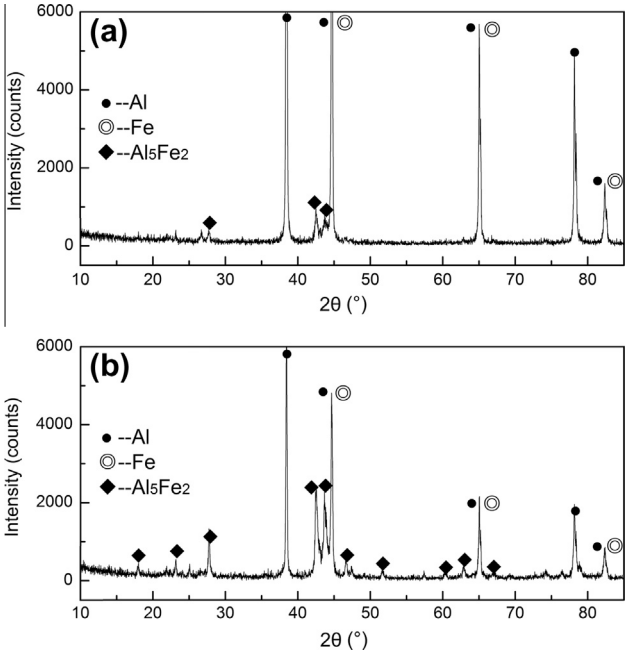

Fig. 1. XRD patterns of the composites after sintering under a pressure of 25 MPa at 610 °C for 5 h, with the volume fraction of Fe particles being (a) 10% and (b) 20%, respectively.

3. Results and discussion

Fig. 1 shows the X-ray diffraction (XRD) patterns of the composites with 10 vol.% and 20 vol.% Fe after sintering. It can be seen from Fig. 1 that both the sintered composites with different Fe concentrations have three phases, including Al, Fe and intermetallic compound Al_5Fe_2 phases, indicating that intermetallics were formed during the fabrication of the composites. Comparing Fig. 1a and b, it can be seen that the intensity of Al_5Fe_2 peaks increases, while the intensities of Al and Fe peaks decrease with increasing the Fe volume fraction from 10% to 20%, indicating that the amount of Al_5Fe_2 increases with the Fe volume fraction increasing from 10% to 20%.

Fig. 2a and b shows the back scattered SEM images of the sintered composites with 10 vol.% and 20 vol.% Fe before extrusion, and Fig. 2c shows the back scattered SEM image of the composite with 20 vol.% Fe after extrusion. It can be seen from Fig. 2a–c that all the specimens consist of three different phases, including dark matrix, white core and grey shell. EDS analysis indicates that the dark matrix and white core are Al and Fe (as shown by Fig. 3d and f), respectively, while the grey shell are composed of 71.6 at.% Al and 28.4 at.% Fe, in consistent with the XRD results in that the in situ formed intermetallic compound was Al_5Fe_2 phase. All the testing results show that the shell contains only one type of the intermetallic compound (Al_5Fe_2), instead of a series of intermetallic compounds such as Al_3Fe, AlFe, and $AlFe_3$. This phenomenon was also observed previously during fabricating composites from not only Al–Fe system, but also in Al–Ni and Al–Ti systems [14,15]. However, Torres et al. found that a series of the intermetallic compounds including Al_3Ni and Al_3Ni_2 are formed during fabricating aluminum alloy matrix composite reinforced with Ni_3Al powder particles [16]. Abbasi Chianeh et al. indicated that transformation of different intermetallics to each other would be faster than pure metal to intermetallics [15]. As a result of that, only one intermetallic compound will thus be formed.

It should be noted that although the intact core–shell structured reinforcements were presented, a few small sized pores can be observed on the side of Al–Al_5Fe_2 interface. It has been shown that the relative density of the composites with 10 vol.% and 20 vol.% Fe before extrusion are ~92.8% and ~92.1%, respectively. Three possible reasons might result in the pores. First, oxide layer might exist at the surface of the aluminum powder. The oxide layer can substantially degrade the solid-phase-sintering ability through inhibiting the elements diffusion, a phenomenon being also observed previously [18,19]. Second, during the solid-phase-sintering process, the interdiffusion coefficients between Al and Fe are different, and result in the generation of pores on the side of Al/Al_5Fe_2 interface, a phenomenon called Kirkendall effect [21]. Third, the volume changing during the formation of Al_5Fe_2 phase might also be another possible reason. It should be noted that extrusion can greatly improve the density and decrease the pores of the composites, since the relative density of the composites with 20 vol.% Fe after extrusion is ~99.7%. Song et al. indicated that externally applied stress can break up the oxide layer, and thus improve the solid-phase-sintering ability and decrease the volume fraction of the pores [22].

Fig. 3a and b shows the compressive strain–stress curves of the sintered composites with 10 vol.% and 20 vol.% Fe before extrusion. Compared to the mechanical properties (33.1 MPa in yield strength, 52.7 MPa in ultimate compressive strength and 14.7% in ductility) of the matrix alloy fabricated using the same process, the average yield strength, ultimate compressive strength and ductility of the composites with 10 vol.% and 20 vol.% Fe are 217.2 MPa, 260.5 MPa and 13.2%, and 227.1 MPa, 273.0 MPa and 12.1%, respectively. It can thus be concluded that the in situ formed core–shell structured particle reinforced composites have high strength, without much expense of the plasticity. Fig. 3c shows the compressive strain–stress curves of the sintered composites with 20 vol.% Fe after extrusion. It can be