



Al-based matrix composites reinforced with short Fe-based metallic glassy fiber



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ABSTRACT

Novel lightweight composites consisting of an Al matrix reinforced with short Fe-based metallic glassy fibers have been fabricated by powder metallurgy. A detailed microstructural characterization was carried out along with the analysis of their mechanical properties. The results reveal that the strength of the composites is greatly enhanced by the addition of the short glassy fibers, while maintaining good ductility. The yield strength increases by two and three times, with respect to pure Al matrix, for the composites reinforced with 20 and 40 vol.% of glassy fibers, respectively. The investigation on the fracture behavior reveals that the strengthening effect is strongly dependent on the fiber orientation and length.

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1. Introduction

Al-based metal composites (AMCs) reinforced with discontinuous reinforcements have attracted considerable attention in many areas, such as aerospace and automotive industry, owing to their high specific strength, high specific stiffness, high wear resistance, relatively low cost of the raw materials and easy of production [1]. Typical discontinuous reinforcements used in AMCs are ceramics, which can effectively improve the matrix mechanical properties [2]. Recently, the AMCs with non-ceramic reinforcements, such as intermetallic [3,4], quasicrystalline [5–7], nanocrystalline [8,9] and metallic glassy particles [10–26], have been the focus of intense research. In particular, the metallic glassy particles stimulated significant interest as they have been proven to create good bonding with the metal matrix and can effectively improve the mechanical properties of the matrix [10]. Varied metallic glassy particles have been successfully used as reinforcement in metal matrix composites; these include Mg- [11,12], Al- [13], Fe- [14–17], Zr- [18–21], Cu- [22,23] and Ni-based [24–26] metallic glassy particles. Recently,

Gupta M et al. [10,27] have summarized the ongoing advances in the field.

Most prior studies on AMCs strengthened with metallic glasses have focused on particulate reinforcements. Metallic glassy fibers have been successfully produced recently [28–30]. The results show that the metallic glassy fibers not only have high strength similar to the bulk glassy counterparts, but also show improved ductility. More importantly, it is found that metallic glassy fibers can be produced by gas-atomization, which can greatly reduce the production costs. In addition, comparing to the particulate-reinforced AMCs, short fiber-reinforced AMCs are also very important owing to their effectively improved properties and to the facility of production [1]. Therefore, the research on production and characterization of short metallic glassy fiber reinforced AMCs is important and may chart a new direction on developing of AMCs.

In this study, Al-based composites reinforced with Fe-based metallic glassy fibers (Fe-MG fibers) have been produced by powder metallurgy (PM). The Fe-MG fibers were selected because of their ultrahigh strength, good corrosion resistance, high glass-forming ability and low cost, and also because it has been proven that the Fe-based glassy particles have good bonding with Al or Al alloy based matrixes [14–17,31]. The selection of P/M as producing method was dictated by the fact that P/M allows the production of

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bulk samples at low temperatures, which can effectively avoid crystallization of the metallic glassy fibers and interface reactions.

2. Experimental

$\text{Fe}_{74}\text{Mo}_4\text{P}_{10}\text{C}_{7.5}\text{B}_{2.5}\text{Si}_2$ (at.%) metallic glass fibers (Fe-MG fibers), which were selected as the reinforcement, were made using the containerless gas-atomization process by TLS Technik GmbH & Co. Spezialpulver KG, Germany, in Ar atmosphere. Due to the high viscosity of the master alloy, typical for glass-forming alloys, the very fine parts of molten alloy jet tends to solidify forming fibers instead of round particles with small diameters. This is a process-related result and it was observed that there exists a powder dimension threshold above which the formation of fibers is not anymore possible. Therefore, the atomization product was dry sieved under Ar and only those fibers were selected. The fiber diameters exhibit several hundred nanometer and their lengths may be very different, ranging from microns to millimeters (Fig. 1). In addition, some micron scale particles were also observed. In order to achieve the homogeneous distribution of the reinforcement, mixtures consisting of 10, 20 and 40 vol. % of Fe-MG fibers and pure Al powders (particle size $\leq 44\ \mu\text{m}$) were prepared by ball milling. Ball milling was performed at room temperature using a Retsch PM400 planetary ball mill with hardened steel balls and vials. The milling time was 4 h and the rotational speed 100 rpm. Bulk samples were prepared by uniaxial hot pressing under Ar atmosphere. During hot pressing, the powders were heated up to 673 K at a heating rate of 40 K/min and then a pressure of 600 MPa was applied on the powders for 10 min; after that, the pressure was removed and the sample was cooled down to room temperature using air cooling. The microstructure was studied by scanning electron microscopy (SEM), using a Gemini 1530 microscope equipped with an energy dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD) using a D3290 PANalytical X'pert PRO diffractometer (Co-K α radiation, $\lambda = 0.17889\ \text{nm}$). Uni-axial compression tests were performed at room temperature at constant loading rate of $1 \times 10^{-3}\ \text{s}^{-1}$ using an Instron INSTRON 8562 testing facility and at least 3 specimens were tested for each material.

3. Results

Fig. 2 shows the morphology of the composite powders of the mixture 10 vol. % of Fe-MG fibers and 90 vol. % of pure Al powders after milling. The Fe-MG fibers and Al powders are subjected to severe plastic deformation resulting from the high intensity collisions between the balls during milling. Due to the plastic deformation, the pure Al powders are agglomerated and the Fe-MG fibers are broken into many short fibers and inserted into the

soft Al powders. As a result of the agglomeration of Al, the final composite particles display irregularly-spherical shape with an average diameter of about 600 μm . The severe plastic deformation also can be seen in the big Fe-MG fibers (Fig. 2c), where shear bands and cracks are observed and highlighted with red arrows.

The XRD patterns of the hot pressed bulk composites reinforced with 20 and 40 vol.% of Fe-MG fibers ($f = 20$ and $f = 40$), and Fe-MG fibers are presented in Fig. 3. The XRD pattern of the Fe-MG fibers exhibits the typical broad diffraction maximum of amorphous materials, indicating the amorphous structure of the Fe-MG fibers. Meanwhile, several tiny sharp peaks are observed which are likely due to the existence of the micron scale particles among the glassy fibers. For the same master alloy, the large size particles may have relatively low cooling rate and some of them may show partially crystalline amorphous structure. Bragg peaks corresponding to the fcc-Al and a broad diffraction maximum corresponding to the amorphous phase are observed in the composite reinforced with 40 vol.% of Fe-MG fibers. In contrast, the composite reinforced with 20 vol.% of Fe-MG fibers only shows fcc-Al Bragg peaks without a clear amorphous peak owing to the small amount of glassy phase. The XRD patterns of the composites suggest that no crystallization of the glassy fibers occurred during hot pressing. In addition, no diffraction peaks belonging to additional phases can be detected, implying that no reaction occurs between the matrix and reinforcement during consolidation.

Fig. 4 shows the SEM micrographs of the cross-section of the composites with $f = 20$ and 40. Only very few pores are observed, indicating high densification of the materials. The SEM micrographs display a microstructure consisting of bright areas (the glassy reinforcement) distributed homogeneously in the Al matrix (the dark phase). EDX analysis of the composites (not shown here) shows that the bright areas are rich in Fe, Zr and Mo corresponding to the Fe-MG fibers, and the dark area is rich in Al corresponding to the Al matrix. No pores or new phase layer are observed at the interface between the glassy reinforcement and Al matrix, indicating good interface bonding.

Typical room temperature uni-axial compressive stress–strain curves for the composites are shown in Fig. 5 together with the curve for the unreinforced pure Al matrix. The yield strength σ_y (0.2% offset) increases from $\sim 40\ \text{MPa}$ for pure Al to ~ 81 and $\sim 115\ \text{MPa}$ for the composites reinforced with 20 vol. % and 40 vol. % Fe-MG fibers. Similarly, the compressive strength increases from $\sim 132\ \text{MPa}$ for pure Al to ~ 184 and $\sim 245\ \text{MPa}$ respectively for the composites with $f = 20$ and 40. The yield strength of the composite with 20 vol. % Fe-MG fibers is almost 2 times of the unreinforced pure Al, and the yield strength for the composites with $f = 40$ goes up to nearly 3 times than the pure Al. The strength for the composite reinforced with 10 vol. % Fe-MG fibers is between the

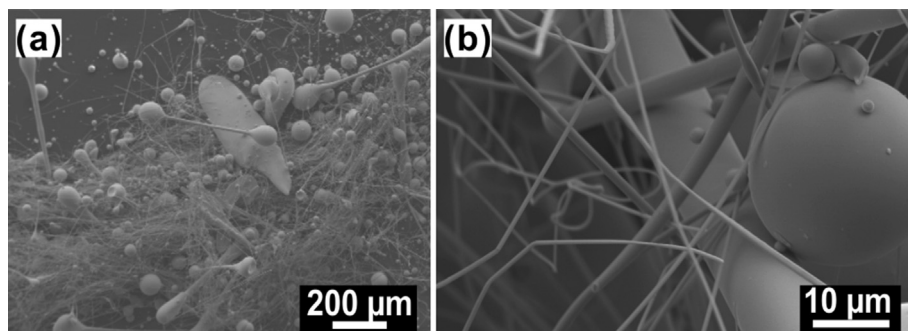


Fig. 1. SEM micrographs for the as received $\text{Fe}_{74}\text{Mo}_4\text{P}_{10}\text{C}_{7.5}\text{B}_{2.5}\text{Si}_2$ (at.%) metallic glass fibers fabricated by gas atomization.

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