Materials Science and Engineering A 532 (2012) 325–330

Contents lists available at SciVerse ScienceDirect

Materials Science and Engineering A

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

Strong and light metal matrix composites with metallic glass particulate reinforcement

M. Aljerf[a], K. Georgarakis[a,b,*], D. Louzguine-Luzgin[b], A. Le Moulec[a], A. Inoue[b], A.R. Yavari[a,b]

[a] *Euronano (SIMaP-CNRS-INPG), Grenoble-Université, 38402 Saint-Martin d'Hères Campus, France*
[b] *WPI-AIM Research, Tohoku University, Aoba-Ku, Sendai 980-8577, Japan*

ARTICLE INFO

Article history:
Received 17 June 2011
Received in revised form 15 October 2011
Accepted 20 October 2011
Available online 3 November 2011

Keywords:
Aluminium alloys
Composites
Bulk amorphous alloys
Sintering
Hardening
Micromechanics

ABSTRACT

A new Al 6061 alloy composite reinforced with $[(Fe_{1/2}Co_{1/2})_{75}B_{20}Si_5]_{96}Nb_4$ metallic glass was produced by sintering at a temperature between the glass transition (T_g) and crystallization temperature (T_x) of the metallic glass and close to the melting temperature of the Al alloy. At this temperature range ($\Delta T_x = T_x - T_g$), the metallic glass particles exhibit viscous behavior, resulting in composites with low or zero porosity. The use of the glassy particles as reinforcement led to significant strengthening of the Al matrix alloy while retaining a plastic strain before fracture of about 13% leading to a remarkable combination of high strength and plasticity. Because metallic glasses are much harder than Al matrix alloys, when strain is applied to the composite, plastic deformation occurs in the matrix while the glassy particles deform only elastically.

1. Introduction

The potential of metal matrix composites (MMC) to provide tailored mechanical properties such as high specific strength and stiffness make them attractive for applications in the aerospace, defense and automotive industries [1–3]. In conventional metal matrix composites, the reinforcements are typically ceramic materials in the form of continuous or discontinuous fibers, flakes or particulates. Often, issues of low wetability, agglomeration, porosity and detrimental interfacial interactions are difficult to be resolved [4–6]. Metallic glasses have been recently proposed as a novel type of reinforcement in metal matrix composites, able to overcome the disadvantages of conventional ceramic reinforcing phases [7–12].

Metallic glasses are metastable materials with disordered structure and unique properties. They exhibit exceptional mechanical properties, such as high strength, fracture toughness and high elastic limit at ambient temperature [13–17]. Between their glass transition T_g and crystallization T_x temperatures, metallic glasses exhibit a technologically attractive Newtonian flow regime where their viscosity drops drastically and they behave like liquids. In fact, this behavior of metallic glasses makes them a unique reinforcement possibility for metal matrix composites. By properly choosing a matrix alloy and a metallic glass so that the sintering process can be made within the supercooled liquid region ($\Delta T_x = T_x - T_g$), the metallic glass can act as a soft binder resulting in removing porosity. After compaction to full density and cooling down to room temperature, metallic glass particles recover their very high mechanical strength and become the hard reinforcing phase [11,12]. However, the limitation of metallic glasses as a unique reinforcement lies in their metastability as they crystallize above a certain temperature T_x. Thus, metallic glass particles would be particularly suitable for reinforcing low melting temperature alloys, such as Al and Mg alloys.

Using the above guidelines, we have recently shown the cases of a Mg alloy reinforced with Zr based metallic glass particles [11] and an Al 520 alloy reinforced with Cu based glassy particles [12], in which significant strengthening was achieved while retaining noticeable plasticity over 10%. In the present work a new composite has been produced using a much stronger FeCo-based metallic glass reinforcement in an Al6061 matrix alloy, in order to examine the effect of the hardness of the glassy reinforcements on the mechanical behavior of the composites and improve our understanding on the design of these composites.

2. Experimental

Melt-spun glassy ribbons of $[(Fe_{1/2}Co_{1/2})_{75}B_{20}Si_5]_{96}Nb_4$, 25 μm thick, were milled in a ceramic vibratory mill for 6 h using a

---

[*] Corresponding author at: Euronano, SIMaP – Institut Polytechnique de Grenoble (INPG), 1130, rue de la Piscine 38402, Saint-Martin d'Heres, France. Tel.: +33 0 47682 6641; fax: +33 0 47682 6641.
E-mail addresses: georgara@minatec.inpg.fr, georgarakis@gmail.com (K. Georgarakis).

0921-5093/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2011.10.098

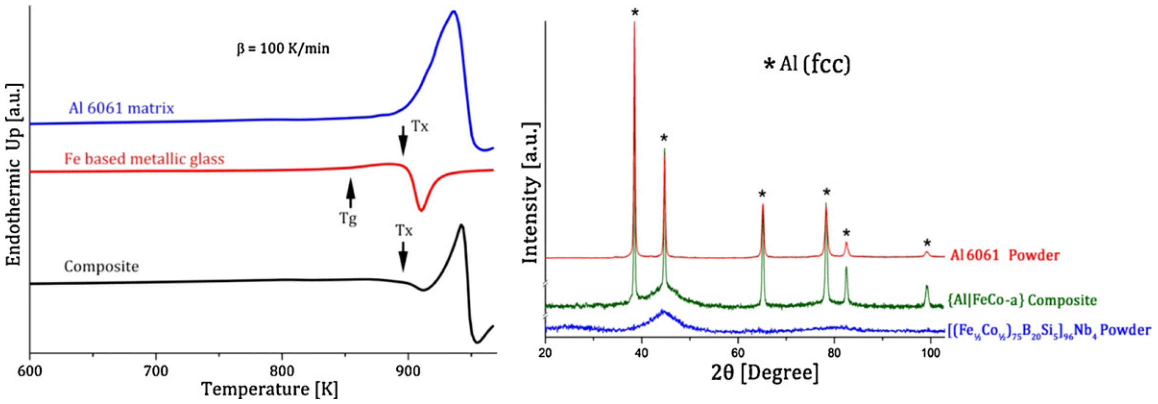

Fig. 1. DSC thermograms (a) and X ray diffraction patterns (b) of the two initial materials (Al 6061 alloy and FeCo based metallic glass) and the composite.

single ceramic (zirconia) ball of 5 cm in diameter. The ball to powder ratio weight ratio was of the order of 10^3; few drops of ethanol were added as process control agent. Ceramic mills and balls were used in this case, because FeCo-based metallic glass is harder than the conventional stainless steel vials and balls, and thus inappropriate for milling FeCo-based metallic glasses. The glass transition temperature (T_g) of this alloy is 821 K and the crystallization temperature (T_x) 861 K, resulting in a supercooled liquid region of about 40 K [18]. The commercial Al6061 alloy with a melting range of 855–935 K was chosen to be the matrix material. Ribbons of this alloy with thickness of about 30 μm were prepared by melt spinning on a rotating Cu wheel. The ribbons were cut in small pieces and milled in a stainless steel vibratory mill for 48 h to produce fine powder. Then the Al alloy powder was mixed together with the glassy FeCo-based powder in an analogy of 15 vol % metallic glass and 85 vol % Al alloy and milled for 3 h in order to obtain a homogeneous mixture of powders.

Consolidation of the composite powder was performed under vacuum using induction heating sintering. Stainless steel punches and dies with an inner diameter of 10 mm were used. A pressure of 70 MPa was applied during the entire heating cycle. The sintering temperature, 828 K, was chosen to be within the supercooled liquid region ($\Delta T_x = T_x - T_g$) of the metallic glass and close to the melting temperature of the Al alloy. The holding time at maximum temperature was 120 s and the average heating rate about 1.6 K s^{-1}. The sintering conditions (temperature and time) were properly chosen in order to avoid crystallization of the metallic glass during processing [19,20].The produced samples were examined by X-ray diffraction (XRD) using a Panalytical X'Pert Pro diffractometer with CuK_α radiation. The microstructure of the composite was studied by Electron Microscopy using a LEO S440 Scanning Electron Microscope (SEM) equipped with an energy dispersive spectrometer (EDS). Uniaxial compression tests were carried out on a Zwick 1455 machine at a strain rate 10^{-3} s^{-1}. Samples with 2×2 mm^2 cross section and 4 mm length were used for this purpose.

3. Results

A comparative presentation of Differential Scanning Calorimetry (DSC) thermograms of the two initial materials (Al 6061 alloy and FeCo based metallic glass) and the composite, Fig. 1a, reveals schematically the idea of the processing procedure of the metallic glass reinforced composites. The supercooled liquid region of the metallic glass (between glass transition T_g and crystallization temperature T_x), within which is the sintering temperature, lies just below the melting temperature (T_m) of the Al matrix alloy. Therefore, both the Fe-based metallic glass and the Al alloy are expected to be very soft at the sintering temperature T_s, leading to full densification of the composite and thus eliminating porosity. The exothermic peak on the DSC curve of the composite corresponding to the crystallization event of the metallic glass phase clearly indicates that the Fe-based particles remained amorphous during sintering.

Fig. 1b shows the X-ray diffraction (XRD) patterns of the $[(Fe_{1/2}Co_{1/2})_{75}B_{20}Si_5]_{96}Nb_4$ powder obtained by milling of the glassy ribbons. The diffuse peak observed around $2\theta = 45°$ manifests the amorphous nature of the powder. This diffuse peak is also observed in the XRD pattern of the composite, indicating the existence of the FeCo-based amorphous phase in the composite, in agreement with the DSC results of Fig. 1a. In addition, the XRD pattern of the composite shows sharp Bragg peaks which correspond to the Al matrix alloy.

The morphology of the Al 6061 alloy and the FeCo based metallic glass powders is shown in Fig. 2a and b respectively. The particle size of the Al alloy powder, as observed with the SEM, spans in the range of 10–50 μm, whereas in the case of the metallic glass particles is of the order of 1–2 μm. After milling together the two powders, Fig. 2c, the size of the particles did not change drastically; however the metallic glass particles (light colored particles) were observed to be attached on the surface of the Al alloy particles (dark colored particles).

Fig. 3 shows the microstructure of the Al alloy matrix composite reinforced with FeCo-based metallic glass. As confirmed by EDS analysis, the bright phase corresponds to the metallic glass, whereas the darker phase to the Al matrix alloy. Interestingly, no detectable pores could be seen during extensive microscopical examination, indicating successful densification during sintering. Although the presence of nano-pores cannot be completely ruled out, the detrimental effect of nano-pores on the mechanical behavior of the composites is expected to be much less severe compared to that of macro-pores. The metallic glass particles have been agglomerated along the grain boundaries of the Al alloy matrix. As observed in Fig. 2c, during milling together the two initial powders, metallic glass particles have been attached on the surface of the Al alloy particles. During consolidation, the glassy particles remained on the surface of the Al alloy particles thus revealing their boundaries (Fig. 4) as in the case of intergranular precipitates in many metallic alloys, thus acting as fingerprints of the grain boundaries. It should be noted, however, that the Al alloy particles after milling are not necessarily single crystals and therefore the "grains" revealed by the glassy phase in the composite (Fig. 4a) may consist of more than one crystallite, thus having further grain boundaries which are not revealed by the glassy particles. The size of the majority of the glassy particles in the composite is of the order of 1–2 μm or smaller. However, few particles with bigger size (∼10–100 μm) are also present.