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Tensile deformation behavior of two Ti-based amorphous matrix composites containing ductile β dendrites

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ABSTRACT

In this study, two Ti-based amorphous matrix composites containing Nb and Ta contents were fabricated by a vacuum arc melting method, and deformation mechanisms related to improvement of strength and ductility were investigated by observing the initiation and propagation of deformation bands, shear bands, or twins occurring at ductile dendrites and hard amorphous matrix. The two composites contained 60–66 vol.% of coarse dendrites sized by 42–73 μm had excellent tensile properties of yield strength over 1 GPa and elongation over 5%. In the composite having higher Ta content, shear bands were formed first at the amorphous matrix, while dendrites were hardly deformed. With further deformation, dendrites were deformed in a band shape as a considerable number of twins were formed inside some dendrites. According to the EBSD analysis result of this composite, parts of β phases were transformed to α phases during the tensile deformation, and twins were formed at phase-transformed α phases. In this composite mixed with α and β phases, β phases could play a role in interrupting the twin formation at α phases, which resulted in the increase in stress required for the twin formation and consequently the increase in yield and tensile strengths.

1. Introduction

Since bulk amorphous alloys have liquid-like atomic structures, unlike in crystallized conventional alloys, they show excellent characteristics such as strength, stiffness, hardness, magnetism, and corrosion resistance [1]. However, they have shortcomings of poor ductility and toughness as they are fractured in an abrupt shear type by the formation of shear bands under tensile or compressive stresses. To overcome this shortcoming, active studies have been conducted to fabricate composites by dispersing ductile crystalline particles or phases in the amorphous matrix. There are several methods to fabricate amorphous matrix composites, including one in which crystalline particles or phases are added into a molten amorphous alloy before casting [2–6], and another one in which ductile dendrites are generated *in situ* from a molten amorphous alloy during casting [7].

In recently developed Zr- and Ti-based amorphous matrix composites containing ductile dendrites, the tensile ductility is improved by forming deformation bands at dendrites and multiple shear bands in the amorphous matrix simultaneously [7–10]. For example, a Zr-based amorphous composite containing ductile dendrites of crystalline β phases (structure; bcc), *i.e.*, an 'LM2' alloy (commercial brand name of the Liquidmetal Technologies, Lake Forest, CA, USA, composition; $Zr_{56.2}Ti_{13.8}Nb_{5.0}Cu_{6.9}Ni_{5.6}Be_{12.5}$ (at.%), dendrite size; 6–7 μm, dendrite volume fraction; 35–40%) showed the tensile strength of 1470 MPa and ductility of 2.5–3%, which were improved by the formation of more shear bands than those formed in a monolithic Zr-based amorphous alloy, *i.e.*, an 'LM1' alloy (commercial brand name of the Liquidmetal Technologies, Lake Forest, CA, USA, composition; $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10.0}Be_{22.5}$ (at.%)). In Ti-based amorphous composites, where the Ti content was higher than the Zr content, the volume fraction of β dendrites increased up to 70%, which led to the improvement of tensile ductility up to 10% [9]. These results on Zr- and Ti-based amorphous matrix composites indicate that the increased Ti content works for increasing the volume fraction of β dendrites, which generally results in the improvement of tensile ductility, although the tensile strength is largely varied with the fabrication conditions and composite compositions. In order to further improve tensile properties of these composites, effects of alloying elements such as Nb and Ta working as a stabilizer of a β phase in titanium alloys [11–15] on tensile properties need to be sufficiently investigated since the stability of β dendrites can affect tensile properties. In addition, elucidation of deformation mechanisms in relation with microstructure and stability of β dendrites is essentially needed.

In this study, thus, two Ti-based amorphous matrix composites containing Nb and Ta contents were fabricated by a vacuum

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arc melting method, and effects of the increased Ta content were investigated by comparing the two composites. Microstructures of the fabricated composites were analyzed, and their tensile properties were evaluated. Tensile deformation mechanisms related to improvement of strength and ductility were investigated by observing the initiation and propagation of deformation bands, shear bands, or twins occurring at ductile dendrites and hard amorphous matrix.

2. Experimental

Two Ti-base amorphous matrix composites used in this study were $Ti_{48}Zr_{27}Ni_6Nb_4Ta_1Be_{14}$ and $Ti_{48}Zr_{27}Ni_6Nb_2Ta_3Be_{14}$ (at.%) ones. These two composites are referred to as 'A' and 'B', respectively, and effects of the increased Ta content, while the total contents of Nb and Ta were fixed at 5 at.%, were investigated by comparing the A and B composites. Ni acts as an important element for composing elements of amorphous phases, together with Ti and Zr. When the amount of Ni exceeds 10 at.%, the formation of dendrites is interrupted, whereas properties of amorphous phases are deteriorated when the amount of Ni is less than 3 at.%. Be works for improving the amorphous forming ability and for controlling properties of dendrites and amorphous phases [16]. The composites were fabricated by a vacuum arc melting method, held at 800–900 °C for 1 h to remove inhomogeneous cast structures, and quenched to obtain the amorphous matrix.

The two composites were polished, etched by a solution of 40 ml HF, 20 ml HNO_3, 40 ml HCl, and 200 ml H_2O, and observed by a scanning electron microscope (SEM, model; JSM-6330F, Jeol, Japan). Phases present in the composites were identified by X-ray diffraction (Cu radiation, scan rate; 2° min^{-1}, scan step size; 0.02°), and their size and volume fraction were measured by an image analyzer (model; SigmaScan Pro ver. 4.0, Jandel Scientific Co., USA). Electron back-scatter diffraction (EBSD) analysis (resolution; 0.2 μm) was conducted by a field emission scanning electron microscope (FE-SEM, model; Helios Nanolab™, FEI, USA). The data were then interpreted by orientation imaging microscopy (OIM) analysis software provided by TexSEM Laboratories, Inc.

Plate-type tensile specimens having a gage length of 11.4 mm, gage width of 2.0 mm, and gage thickness of 1.2 mm were prepared, and were tested at room temperature at a strain rate of $1.59 \times 10^{-4}\ s^{-1}$ by a universal testing machine of 10,000 kgf capacity (model; 4202 Load Frame, Instron, USA). In order to investigate the tensile deformation processes, the deformed area near the fracture surface was observed by an SEM.

3. Results and discussion

3.1. Composite microstructure

Fig. 1(a) and (b) are SEM micrographs of the A and B composites, respectively. The microstructures of both composites consist of dendrites and amorphous matrix. Dendrites having irregularly spherical shapes are relatively homogeneously dispersed in the amorphous matrix. The volume fractions of dendrites are 66% and 60% in the A and B composites, respectively, and the sizes are 11.4 μm and 14.8 μm, respectively. The XRD data are shown in Fig. 2. Sharp peaks of bcc β phases are observed, together with broad halo patterns of amorphous phases. This indicates the existence of dendrites of β phase in the amorphous matrix.

The EBSD analysis data are shown in Fig. 3(a)–(d). In inverse pole figure (IPF) color maps, dendrites having same or similar orientations are presented in the same color, and are generally considered to be effective ones (Fig. 3(a) and (c)). The sizes of dendrites shown in Fig. 1(a) and (b) are estimated to be 10–15 μm, but the actual (or effective) sizes shown in Fig. 3(a) and (c) are much larger because dendrites having same or similar orientations are connected. The effective dendrite sizes measured from the IPF color maps are 73 μm and 42 μm for the A and B composites, respectively. All dendrites consist of β phase (green-colored) as shown in phase maps of Fig. 3(b) and (d).

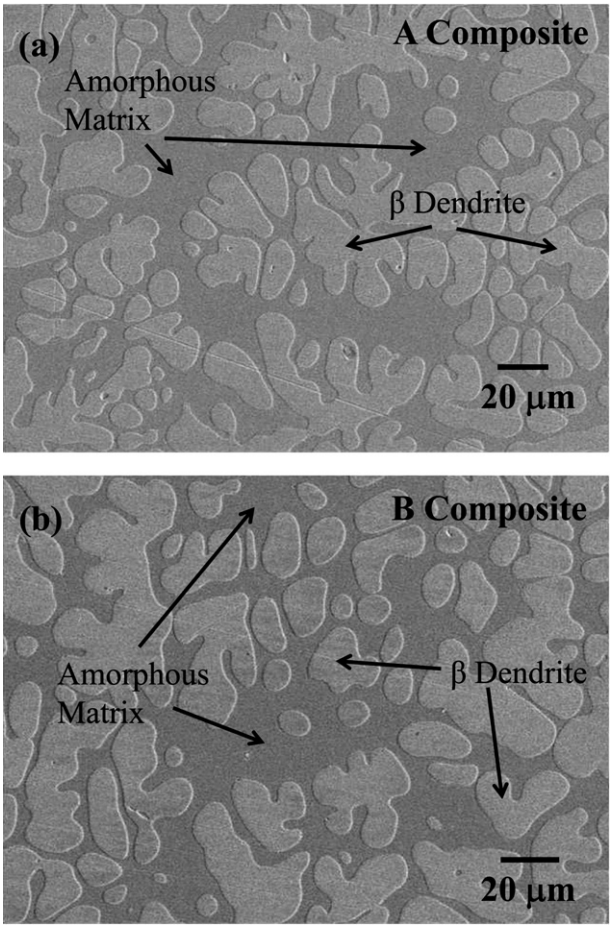

Fig. 1. SEM micrographs of the Ti-based amorphous matrix composites: (a) A composite and (b) B composite. Dendrites having irregularly spherical shapes are relatively homogeneously dispersed in the amorphous matrix.

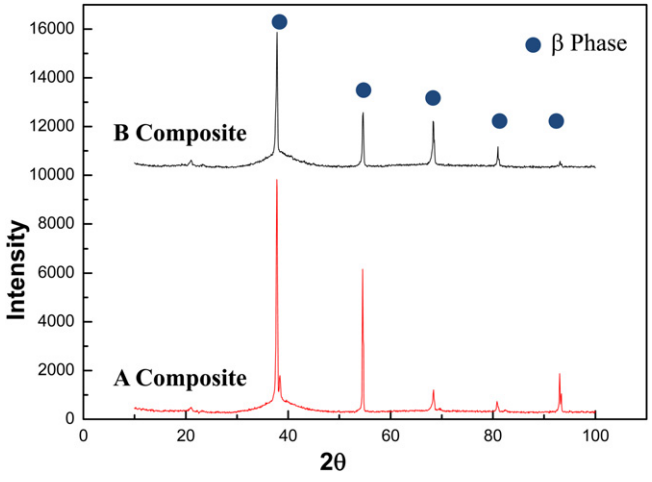

Fig. 2. X-ray diffraction results of the Ti-based amorphous matrix composites.