

High tensile ductility of Ti-based amorphous matrix composites modified from conventional Ti–6Al–4V titanium alloy

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Abstract

Three Ti-based amorphous matrix composites containing ductile dendrites were fabricated by adding alloying elements of Ti, Zr, V, Ni, Al and Be into a conventional Ti–6Al–4V alloy, and the deformation mechanisms related to the improvement of tensile ductility were investigated by focusing on how the effective size of ductile dendrites affected the initiation and propagation of deformation bands or shear bands. The composites contained ~73–76 vol.% dendrites ~63–103 μm in size, and had excellent tensile properties with a yield strength of over 1.3 GPa and an elongation of over 7%. In the composite containing very large dendrites, deformation bands were formed at dendrites in the same direction. In the composite containing small dendrites, however, many deformation bands were actively formed inside dendrites in the several directions, and cross each other to form widely deformed areas. This wide and homogeneous deformation in both dendrites and amorphous matrix enhances the tensile ductility, resulting in high strength and elongation occurring simultaneously. In order to theoretically explain the enhanced tensile ductility, a finite-element method (FEM) analysis based on the real microstructures considering dendrite crystal orientations was performed. The FEM simulation results of deformation bands or shear bands were in good agreement with the experimental findings. The reasons for such a good match between the simulation and experimental results are discussed in detail.

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Keywords: Ti-based amorphous matrix composite; Dendrite; Ti–6Al–4V alloy; Ductility; Deformation band

1. Introduction

Amorphous alloys possess excellent strength, stiffness and corrosion resistance because of their distinctive liquid-like structure [1–5]. However, their manufacturing cost is still high because of the relatively high expense of alloying elements and the need for a vacuum environment during casting, and moreover the size and shape of fabricated products are quite restricted [6,7]. In addition, problems such as brittle fracture need to be solved in order to expand the applications of amorphous alloys [8–10]. Thus, if a fabrication method for amorphous alloys by utilizing conventional alloys such as Ti–6Al–4V alloy and by forming a sufficient amount of ductile dendrites in the amor-

phous matrix can be developed, the principal problems of amorphous alloys could be solved.

To improve the low ductility and toughness of monolithic amorphous alloys, intensive studies have been conducted using composites by dispersing ductile crystalline particles in amorphous alloy matrix. In amorphous matrix composites, where ductile dendrites are formed in situ in the amorphous matrix, the formation of deformation bands at dendrites and multiple shear bands in the amorphous matrix can favorably affect the ductility since it works as an important deformation mechanism in amorphous alloys [11,12]. In order to further improve the tensile ductility of these amorphous matrix composites, the size and volume fraction of dendrites should be optimized; however, the effects of dendrite size on tensile properties have not been sufficiently investigated, although a trend of increased ductility with increasing volume fraction of

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dendrites is generally accepted [13]. Elucidation of the deformation mechanisms in relation to the microstructure is needed as well, since conflicting explanations for the effects of dendrite size and volume fraction have been proposed by different investigators [14]. In addition, an economical fabrication method of Ti-based amorphous matrix composites needs to be developed by adding alloying elements to enhance the amorphous-forming ability in conventional Ti alloys such as a representative ($\alpha + \beta$) Ti–6Al–4V alloy, whose major elements are also beneficially utilized for forming amorphous phase or β dendrites [15,16]. This fabrication approach is quite appealing as it enables the production costs of amorphous alloys with excellent tensile strength and ductility to be seriously reduced, while taking full advantage of the properties of amorphous alloys.

In this study, therefore, three Ti-based amorphous matrix composites containing ductile dendrites dispersed in the amorphous matrix were fabricated by adding alloying elements of Ti, Zr, V, Ni, Al and Be into a conventional Ti–6Al–4V alloy. This composite design offers economical fabrication of Ti-based amorphous matrix composites as well as simultaneous improvement in their tensile strength and ductility. The microstructures of the fabricated composites were analyzed, and their mechanical properties were evaluated by conducting tensile tests. Deformation mechanisms related to the improvement in tensile ductility were investigated by focusing on how the effective size of ductile dendrites affected the initiation and propagation of deformation bands or shear bands. In addition to the experimental approach, a finite-element analysis based on real electron backscatter diffraction (EBSD) microstructural morphologies, and taking dendrite crystal orientations into consideration, was performed to theoretically explain the deformation mechanisms.

2. Experimental

The Ti-based amorphous matrix composites used in the present study were fabricated by adding Ti, Zr, V, Ni, Al and Be to a Ti–6Al–4V alloy (composition: Ti–6Al–4V–0.1O–0.02N–0.04C). The proportion of Ti–6Al–4V alloy was 18 wt.% (20 at.%), and the amount of Ti, Zr, V, Ni, Al and Be added to the Ti–6Al–4V alloy varied as shown in Table 1 to achieve the overall chemical compositions given in Table 2. Since dendritic β phases are stably formed when the Ti + Zr content is higher than 70 at.% [16,17], the Zr content is higher than 16 at.%. The element V dissolves in the β phase (body-centered cubic (bcc) structure), and works as a stabilizer of β phase in Ti alloys as it lowers the $\beta/(\alpha + \beta)$ transformation temperature [18]. The element Al dissolves in the α phase (hexagonal close-packed structure), and works as a stabilizer of α phase in Ti alloys because it raises the $\beta/(\alpha + \beta)$ transformation temperature and expands the α phase region. The elements Ni and Be improve the amorphous-forming ability of the amorphous matrix, and control the properties of dendritic and amorphous phases [16,19,20]. The element Ni, together with Ti and Zr, is an important constituent of amorphous phases. The formation of dendrites is interrupted when the amount of Ni exceeds 10 at.%, but the properties of amorphous phases are deteriorated when the amount of Ni is smaller than 3 at.% [15–17,21]. The formation of the amorphous matrix can be obstructed when the amount of Be is larger than 20 at.% or smaller than 8 at.% [13,15]. In the present alloy design of the Ti-based amorphous matrix composites, the amount of V is relatively high and hence they may contain β phase dendrites [17,22]. The D1 composite has the basic composition of the Ti–Zr–V–Ni–Al–Be composite, and the D2 and D3 composites have smaller amounts of Al and Be than the D1 composite. The composites were

Table 1
Chemical compositions of the Ti-based amorphous matrix composites modified from a conventional Ti–6Al–4V alloy.

| Composite | | Ti–6Al–4V | Ti | Zr | V | Ni | Al | Be |
|-----------|------|-----------|------|------|---|-----|------|------|
| D1 | wt.% | 18 | 37.1 | 29.9 | 9 | 3.5 | 0.5 | 2 |
| | at.% | 20 | 39 | 16.8 | 9 | 3 | 0.9 | 11.3 |
| D2 | wt.% | 18 | 37.4 | 30 | 9 | 3.5 | 0.3 | 1.8 |
| | at.% | 20 | 40.5 | 17 | 9 | 3 | 0.5 | 10 |
| D3 | wt.% | 18 | 37.7 | 30.2 | 9 | 3.5 | 0.1 | 1.5 |
| | at.% | 20 | 41.9 | 17.1 | 9 | 3 | 0.15 | 8.85 |

Table 2
Overall chemical compositions of the Ti-based amorphous matrix composites.

| Composite | | Ti | Zr | V | Ni | Al | Be |
|-----------|------|------|------|-----|-----|------|------|
| D1 | wt.% | 53.7 | 29.9 | 9.8 | 3.5 | 1.1 | 2 |
| | at.% | 57 | 16.8 | 9.8 | 3 | 2.1 | 11.3 |
| D2 | wt.% | 53.9 | 30 | 9.9 | 3.5 | 0.9 | 1.8 |
| | at.% | 58.4 | 17 | 9.9 | 3 | 1.7 | 10 |
| D3 | wt.% | 54.1 | 30.2 | 10 | 3.5 | 0.7 | 1.5 |
| | at.% | 59.6 | 17.1 | 10 | 3 | 1.45 | 8.85 |

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