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# Dendrite size and tensile ductility in Ti-based amorphous alloys containing ductile dendrites

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ABSTRACT

Three Ti-based amorphous alloy sheets containing ductile dendrites were fabricated by varying cooling rate, and deformation mechanisms related with improvement of tensile ductility were investigated by observing initiation and propagation processes of deformation bands at dendrites. The alloy sheets contained many dendrites (volume fraction; 64∼68%, size: 2.1–9.4 μm), and showed the yield strength of 1.5 GPa and the elongation up to 5%. According to the observation of tensile deformation behavior of the 3-mm-thick alloy sheet, many deformation bands were formed inside dendrites in several directions, and deformation bands met crossly each other to form widely deformed areas. Since the wide and homogeneous deformation in this alloy sheet beneficially worked for the tensile strength and ductility simultaneously, the optimum size of dendrites and thickness of the alloy sheets were about 3.1 μm and 3 mm, respectively.



## 1. Introduction

Bulk amorphous alloys have excellent combinations of strength, hardness, stiffness, and corrosion resistance [1–6], which makes them ideal for structural applications. However, their widespread applications have been limited mainly by the brittle failure resulting from shear localization and shear band formation, particularly under a tensile loading condition [7–12]. This brittle fracture acts as an obstacle against the life and reliability of high-performance structural parts. In order to solve the brittle fracture problem and to improve the tensile ductility, studies on fabricating amorphous alloys in which ductile dendrites are formed *in situ* from the amorphous melt have been actively made [13–19]. In recently developed Zr- or Ti-based amorphous alloys containing ductile dendrites, the tensile ductility is improved by forming deformation bands at dendrites [15–19]. According to Ha et al. [15], the tensile strength and ductility can be increased by increasing the volume fraction of dendrites (β phase, structure; bcc) up to about 70% in Ti-based amorphous alloys. These Ti-based amorphous alloys show the better tensile ductility because of the higher volume fraction of dendrites than the Zr-based amorphous alloys, and have merits of light weight. In order to further improve the tensile ductility of these alloys, the size and volume fraction of dendrites need to be optimized. In this study, thus, three Ti-based amorphous alloy sheets having different thickness were fabricated by varying cooling rates after a vacuum arc melting in order to obtain different dendrite sizes. Deformation mechanisms related with ductility improvement were investigated by observing the initiation and propagation processes of deformation bands at dendrites.

## 2. Experimental

A master alloy of a Ti-based amorphous alloy ($Ti_{48}Zr_{27}Ni_6Nb_5Be_{14}$, at%) was fabricated by arc-melting in a water-cooled copper crucible under a Ti-gettered argon atmosphere. Since dendritic β phases are stably formed when the content of (Ti+Zr) is higher than 70 at% [15,16], the content of Zr is higher than 25 at%. The elements of Ni and Be improve the amorphous forming ability, and control properties of dendritic and amorphous phases [19,20]. Ni acts as an important element for composing amorphous phases, together with Ti and Zr [14–16]. Nb works as a strong stabilizer of a β phase in Ti alloys [13,14]. In the present amorphous alloy design, the amount of Nb is relatively high (5 at%) so that they may have sufficient dendrites of β phase [14,15,17]. Three alloy sheets, whose thicknesses were 1, 3, and 5 mm, were produced by using a sheet forming apparatus composed of two water-cooled copper plates, in which alloy melts were pressed by both plates. For convenience, the sheets having thicknesses of 1, 3, and 5 mm are referred to as T1, T3, and T5 alloys, respectively. During the rapid cooling process of the alloy sheets, a β phase, which was stable at high temperatures [14,15], was readily formed in a form of dendrite.

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The arc melting and suction casting were conducted in a vacuum chamber, and the direct measurement of cooling rate was not easy because of the high heat generated during the arc melting. However, the cooling rate ($R$) can be obtained approximately by the calculation using the following equation [21]:

$$\text{Coolingrate, } R = 40(K_t/C_p)T_1/d^2$$

where $K_t$, $C_p$, $T_l$, and $d$ are the thermal conductivity, specific heat, liquidus temperature, and thickness, respectively. The $K_t$, $C_p$, and $T_l$ of a Zr-based '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%)) are 0.06 W/cm K, 5 J/cm$^3$ K, and 1000 K, respectively [22]. The specific heat of titanium is about twice higher than that of zirconium, while its thermal conductivity is almost same to that of zirconium [23–25]. Considering the $K_t$, $C_p$, and $T_l$ of the LM2 alloy, titanium, and zirconium, thus, the cooling rates of the T1, T3, and T5 alloys are calculated to be about $2.4 \times 10^4$, $2.5 \times 10^3$, and $1.0 \times 10^3$ K/s, respectively.

The alloys were polished in diamond pastes (size; 0.25 μm), etched by a solution of 40 ml HF, 20 ml $HNO_3$, 40 ml HCl, and 200 ml $H_20$ for 3 s, and observed by a scanning electron microscope (SEM, model; JSM-6330F, Jeol, Japan). Crystalline phases and amorphous matrix were analyzed by X-ray diffraction (XRD, Cu radiation, scan rate; 2 deg min$^{-1}$, scan step size; 0.02°), and their average size and volume fraction were measured by an image analyzer. They were machined into flat tensile specimens, and room-temperature tensile tests were conducted on these specimens at a strain rate of $5.2 \times 10^{-4}$ s$^{-1}$ by a universal testing machine (model; 8862, Instron Corp., Canton, MA, USA) with capacity of 10,000 kg. Since the specimen size was very small to attach a strain gage, the precise measurement of strain was difficult. During the tests, thus, strains were measured by a vision strain gauge system (model; ARAMIS v6.1, GOM Optical Measuring Techniques, Germany), which could detect 3-dimensional coordinates of the deforming specimen surface on the basis of the digital image processing delivering 3-dimensional displacement and strain. This ARAMIS system recognized the surface structure of the measuring specimen in digital camera images, and allocated coordinates to image pixels. The first image in the measuring specimen represented the undeformed state, and further images were recorded during or after the deformation. Then, the ARAMIS system compared the digital images, and calculated the displacement and deformation. Tensile stress–strain curves could be drawn by matching time–strain values obtained from this ARAMIS system with time–strain curves experimentally obtained from the testing machine.

## 3. Results

### 3.1. Microstructure

SEM micrographs of the T1, T3, and T5 alloys are shown in Fig. 1(a) through (c). A dendritic structure is well developed, and dendrites are evenly distributed in the amorphous matrix. The average size and volume fraction of dendrites were measured, and the results are shown in Table 1. The present T1, T3, and T5, alloys have similar microstructures composed of dendrites in the amorphous matrix, but the size of dendrites changes as a function of cooling rate during fabrication of alloy sheets. The volume fraction of dendrites is almost same (64∼68%) in the three alloys.

Fig. 2 shows the X-ray diffraction (XRD) data. Sharp diffraction peaks of crystalline phases (bcc β phase) as well as broad and diffused patterns of amorphous phase are found, indicating the presence of crystalline phases in the amorphous matrix. Since the alloys have peaks of β phase, they contain dendrites of β phase in the amorphous matrix. These XRD results are matched with the microstructural results of Fig. 1(a) through (c).

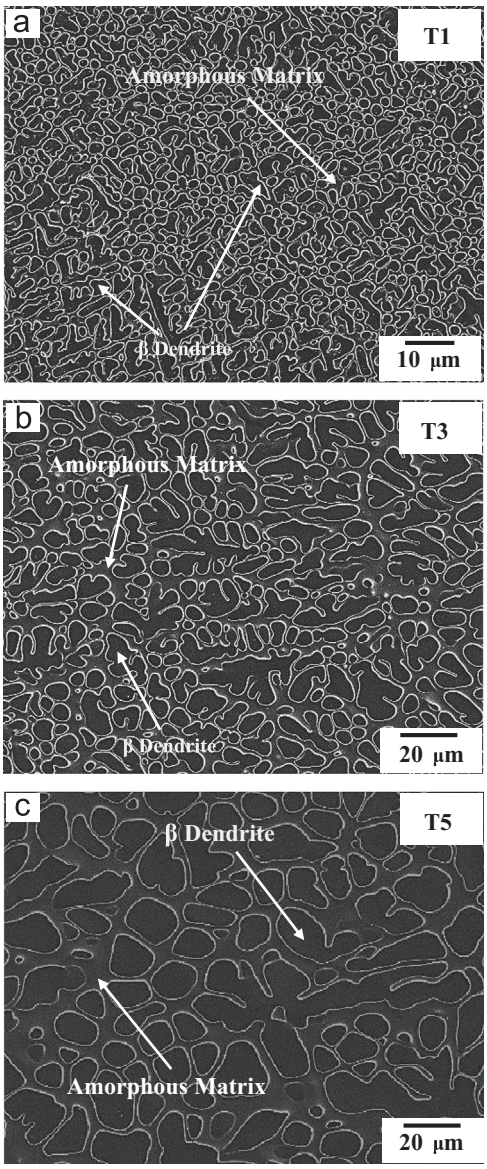


**Fig. 1.** SEM micrographs of the T1, T3, and T5 alloys.

**Table 1**
Volume fraction and size of dendrites of the Ti-based amorphous alloys.

| Alloy | Volume fraction of dendrites (%) | Size of dendrites* (μm) |
|---|---|---|
| T1 | 68.7 ± 3.2 | 2.1 ± 1.1 |
| T3 | 64.7 ± 3.9 | 3.2 ± 2.2 |
| T5 | 66.8 ± 3.8 | 9.4 ± 6.5 |

* Size of dendrites measured from SEM micrographs of Fig. 1(a) through (c).

### 3.2. Tensile properties

Fig. 3 presents tensile stress-strain curves drawn by matching time–strain values obtained from the ARAMIS system with time–strain curves experimentally obtained from the testing machine,