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Mechanical properties of crystalline and amorphous Ti alloys

Tomoki Shigeoka
Graduate School of Natural Science and Technology,
Okayama University
3-1-1 Tsushimanaka, Kita-ku, Okayama, 700-8530, Japan
p1fd4z52@s.okayama-u.ac.jp

Mitsuhiro Okayasu
Graduate School of Natural Science and Technology
Okayama University
Kita-ku, Okayama, Japan
okayasu@okayama-u.ac.jp

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Abstract- Tensile and fatigue properties of titanium based bulk metal glass (Ti-BMG) were studied experimentally on the basis of one of the authors task [Okayasu et al., Fatigue and tensile properties of titanium based bulk glassy alloys, Int. J. Marter. Eng. Tech., 5(2011)77]. To understand clearly the mechanical properties of Ti-BMG, commercial crystalline titanium alloy was employed. The ultimate tensile strength of Ti-BMG was about 20% higher than that for the Ti alloy, and that was more than twice high compared to the carbon steel and Al alloy ones. In contrast, different mechanical properties were obtained in the result of fatigue test, where the rapid reduction of the fatigue strength occurred especially in the later fatigue stage, namely the low endurance limit, which was lower than that for the crystalline Ti alloy.

1. Introduction

It is generally considered that bulk metallic glasses (BMG) have excellent material properties because of high corrosion resistance, good electromagnetic properties and high mechanical properties and low elastic constant. BMG is used for various industrial applications. Since Klement Jun et al. [1] found metal glasses in 1960, a great number of researchers have developed different types of BMGs, and studies their mechanical properties. Scopus searching system reveals that more than 4000 searchable “amorphous and metal glass” academic papers have been published. In general, BMG could be created via,-rapid solidification of more than 10^3K/s, in which the atoms distribution in the liquid condition is reflected even in the solid status. To make this, liquid metal is solidified by shooting a fine stream of it on to a copper drum. Until now, various bulk metal glasses have been proposed, e.g., such as Zr-, Fe-, Ni-, Al, Pb- and Ti-based alloys [2-4].

The mechanical properties of BMGs are different depending on the material, i.e., chemical composition. In this instance several investigators have examined the tensile properties of Pb-based and Zr-based BMG, and those have high strength of 1700MPa [5] and 1650MPa [6], respectively. The tensile strength of Zr-BMGs is higher than that of usual crystalline materials. It is reported that the fatigue properties of Zr-BMGs are lower than that of the crystalline materials. It is also reported that the fatigue properties of Zr-BMG is particularly low significantly as cyclic loading is conducted at low cyclic frequency [7]. On the other hand, the high fatigue properties could be obtained at high cyclic frequency. Furthermore, fatigue damage characteristics have been investigated. Even though there are fatigue properties of BMGs, no clear information regarding the fatigue properties and fatigue failure mechanism. One of the authors has examined material properties of Ti-BMG [8]; however, their properties have not been compared to the crystalline Ti alloy. The aim of this study is therefore to investigate the fatigue properties in detail using commercial 64Ti alloy with crystalline structure to make comparison of the obtained our experimental data of Ti-BMG [8].

2. Materials and Experimental Procedure

2.1 Material preparation

The material selected in this investigation is the titanium based bulk metal glass (Ti-BMG, $Ti_{31.7}Zr_{3.6}Cu_{43}$-X) with a tubular shape (ϕ2.0mm (OD), ϕ1.8mm (ID) and 200mm (length)). This BMG sample was created by rapid solidification method using copper mold. In order to investigate the mechanical properties of Ti-BMG, dumbbell shaped test specimen was made through electro-discharge machining (EDM) with ϕ0.2mm wire.

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Figure 1 shows the specimen configuration and the testing fixture for the mechanical tests. As the specimen is special shape with small size. The specimen was fixed with four thin pins made of hardened carbon steel. To understand clearly the mechanical properties of Ti-BMG more clearly, three commercial crystalline materials (titanium alloy (64Ti), medium carbon steel (S45C) and aluminum alloy (A5056)) were used. Table 1 indicates the chemical compositions of samples. Figure 2 shows the XRD patterns of Ti-BMG and 64Ti alloy. As seen the Ti-BMG is identified with a hello peak because of amorphous structure. On the other hand, 64Ti alloy is formed with a sharp peak, related to the crystalline structure, where two different features, e.g., α and β phase, are appeared.

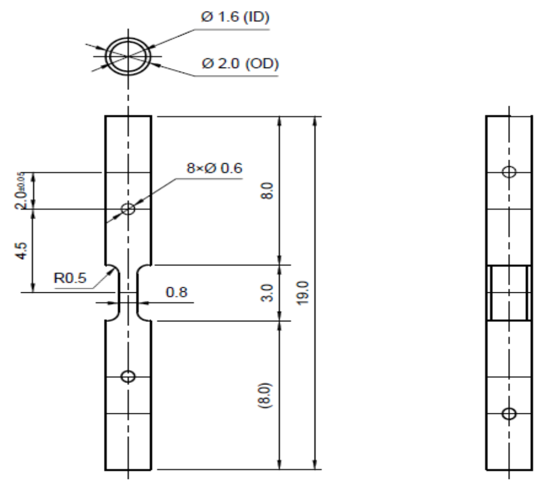

Figure 1(a). Dimensions of specimen for the tensile and fatigue test.

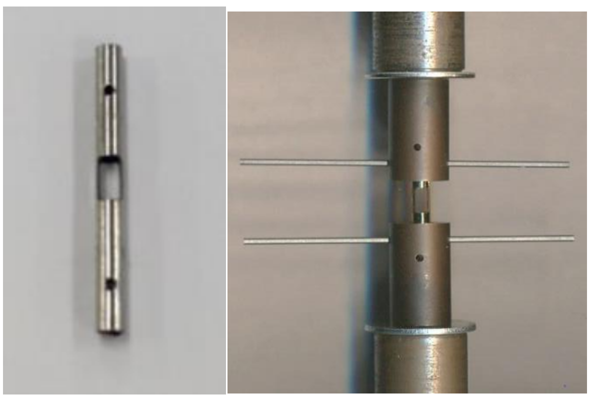

Figure 1(b). Specimen and testing fixture for the tensile and fatigue tests.

2.2 Mechanical properties

The material strength was examined by the tensile and fatigue test. The tensile test was conducted at 1mm/min to final fracture. The tensile stress data was monitored by using a standard load cell. For the fatigue test, tensile-tensile cyclic loading was carried out at 1Hz to final failure or to endurance limit at 10^5 cycles. The maximum cyclic stress, σ_{max}, was determined on the basis of the tensile strength (σ_{UTS}) of the material, where the σ_{max} is determined to be less than 90% of σ_{UTS}. In addition, the fatigue crack growth properties were investigated. The crack growth length was measured created from the machined notch (ρ=1mm), and it its crack growth rate was examined during the tensile-tensile stress at 1Hz. The crack length was measured using a traveler-typed microscope. After fatigue test, the fracture surface observation was executed using a scanning electron microscope (SEM)

Table 1. Chemical compositions of 64Ti, S45C and A5056.

64Ti	Ti	Al	V	Fe	N	O	H	
	Re.	6.1	4.3	0.2	0.04	0.1	0.05	
S45C	Fe	C	Si	Mn				
	Re.	0.45	0.2	0.75				
A5056	Al	Si	Cu	Fe	Mn	Mg	Cr	Zn
	Re.	0.3	0.1	0.4	0.1	5	0.1	0.1

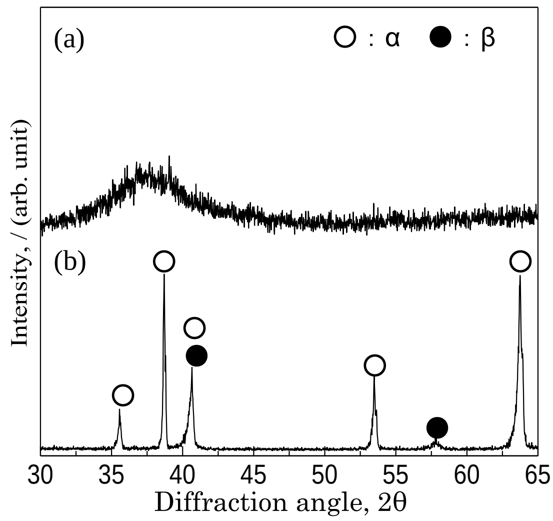

Figure 2. XRD profiles of (a) BMG and (b) 64Ti.

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3. Results and Discussion

Figure 3 presents stress-strain curves for Ti-BMG, 64Ti, S45C and A5056. Note that data for Ti-BMG, S45C and A5056 are referred from Ref.[8]. As can be seen, the stress vs. strain relationship for Ti-BMG is located at a high level compared to the crystalline materials; the ultimate tensile stress (σ_{UTS}) for Ti-BMG is about 1414MPa, which is about 30% higher than that for the crystalline 64Ti, and more than twice high compared to the other conventional metals [8]. It is interest mention that the elastic constant for the 64Ti is similar level compared to the Ti-BMG one. Although the plastic deformation can be seen for 64Ti, that cannot be seen for Ti-BMG [8].

Figure 4 displays the *S-N* relationships for the Ti-BMG, 64Ti, S45C and A5056 samples. Again the fatigue data for Ti-BMG, S45C and A5056 are referred from Ref. [8]. The *S-N* relations of 64Ti and S45C showed the similar trend, and both fatigue limits were almost the same values. On the other hand, in the early fatigue stage, the high level *S-N* relationship is appeared for the BMG. However, the fatigue strength dropped sharply in between 10^3 to 10^5 cycles. The fatigue limit for Ti-BMG is the lowest level, while the high tensile strength is obtained for Ti-BMG. To understand further the fatigue behavior of Ti-BMG in detail, the *S-N* relationships were analyzed a power law dependence of cyclic stresses and cycles to failure [9].

$$\sigma_a = \sigma_f N_f^{-b} \quad \text{, MPa} \tag{1}$$

where σ_a is the stress amplitude, N_f represents the cycle number to the final fracture, σ_f is the fatigue strength coefficient and b is the fatigue exponent. The values of σ_f and b, obtained by least square analysis, are σ_f=25.9GPa, b=0.49 for the BMG and σ_f=1.5GPa, b=0.13 for the 64Ti alloy. In increasing the cycle number, it is expected for a decreasing fatigue strength exponent b and increasing fatigue strength coefficient σ_f. Such low fatigue strength for the Ti-BMG may be attributed to less (or no) permanent deformation. This is because the permanent deformation could provide absorption energy preventing crack growth [8]. In previous works, it has been reported that the low fatigue of Ti-BMG is caused by low slip resistance [10], which is related to low work hardening behavior. Fujita et al. [11] also reported that the strength of the Zr-BMG sample shows the low value of σ_w/σ_{UTS}=0.04, which is attributed to the low slip resistance.

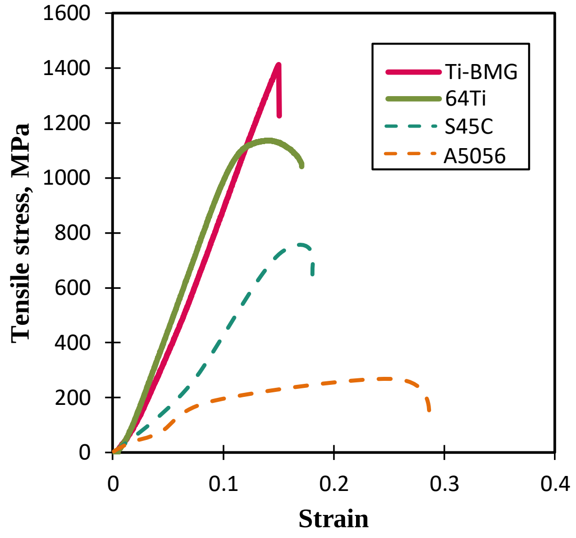

Figure 3. Tensile stress-strain curves for BMG [8], 64Ti, S45C [8] and A5056 [8].

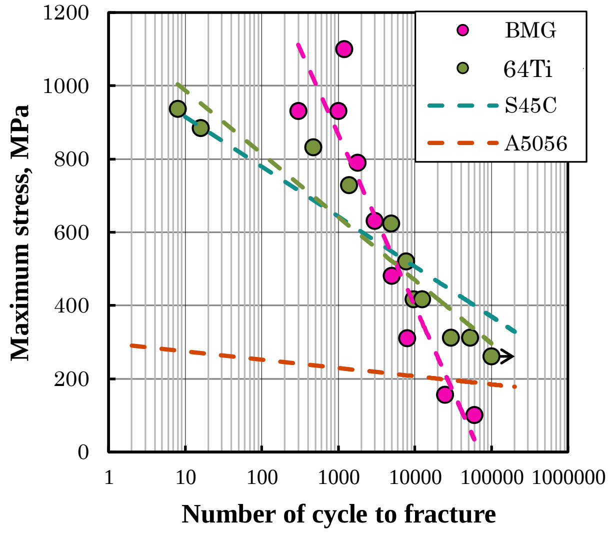

Figure 4. Maximum stress vs. number of cycles to fracture for BMG [8], 64Ti, S45C [8] and A5056 [8].

Figure 5 displays SEM images of the fracture surface; (a)(b) Ti-BMG and (c)(d) 64Ti. Note that the fracture surface in the fatigue crack growth region is shown in Figure 5(a)(c) and the final crack growth stage is represented in Figure 5(b)(d). As can be seen, in the fatigue crack growth area of the Ti-BMG (Figure 5(a)), a striation-like fracture mode is obtained. On the other hand, for the 64Ti sample, Figure 5(c), unlike Ti-BMG, the striation fracture mode is not observed clearly. In the final fracture stage of Ti-BMG, the vein pattern is seen, Figure 5(b)[8]. On the other hand, dimple based fracture is dominated feature for 64Ti, see Figure 5(d).

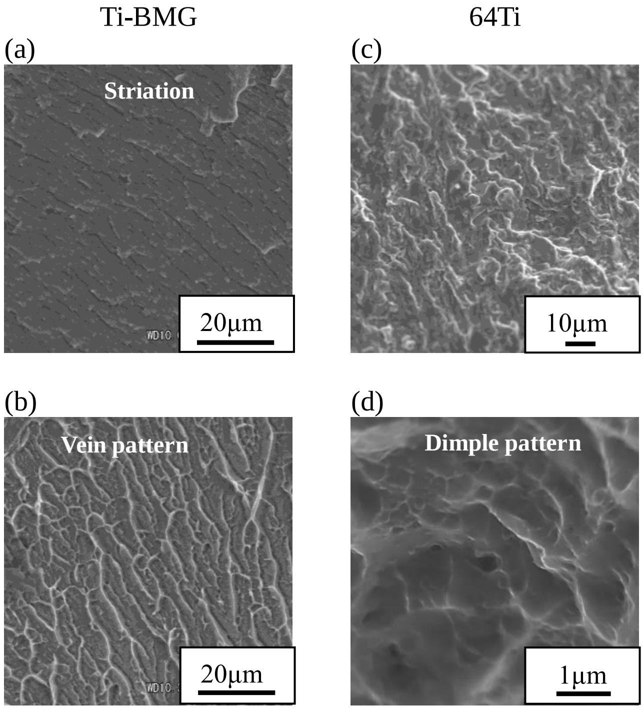

Figure 5. SEM images of the fatigue fracture surfaces: (a)(c) crack growth region of BMG [8] and 64Ti, and (b)(d) final fracture area of BMG [8] and 64Ti.

4. Conclusions

By comparing the mechanical properties of Ti-BMG with the other conventional engineering materials, e.g., 64Ti, different trends of the material properties could be clarified. The results obtained in this study can be summarized as follows:

(1) The tensile strength of Ti-BMG was high compared to the crystalline 64Ti, while the low permanent deformation value is obvious for Ti-BMG.

(2) The fatigue strength of Ti-BMG was the low level especially in the longer fatigue stage, compared to the crystalline 64Ti.

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References

[1] W. Klement Jun, R. H. Willens, P. Duwez, Non-crystalline structure in solidified gold-silicon alloys, Nature 187(1960)869-870.
[2] S. Takayama, R. Maddin, Mechanical behavior of partially crystallized amorphous alloys, J. Mater. Sci. 11(1976)22-26.
[3] G.Y. Wang, P.K. Liaw, Y. Yokoyama, A. Inoue, C.T. Liu, Fatigue behavior of Zr-based bulk-metallic glasses, mater. Sci. Engng. A 494(2008)314-323.
[4] A. Inoue, Stabilization of metallic supercooled liquid and bulk amorphous alloys, Acta. Mater. 48(2000) 279-306.
[5] Y. Yokoyama, N. Nishiyama, K. Fukaura, H. Sunada, A. Inoue, Rotating-beam fatigue strength of Pb40Cu30 Ni10P20 bulk amorphous alloy, Mtater. Trans. JIM 40(1999)696-699.
[6] T. Mukai, T. G. Nieh, Y. Kawamura, A. Inoue, K. Higashi, Dynamic response of a Pb40Ni40P20 bulk metallic glass in tension, Scripta Mater. 41(2002)675-680.
[7] Y. Yokoyama, K.Fukaure, H. Sunada, Fatigue properties and microstructures of Zr55C30P20 bulk metallic glassy alloys, Mater. Trans. JIM 41(2000)675-680.
[8] M. Okayasu, S. Takasu, T. Bitoh, D.H. Shin, M. Makabe, Fatigue and tensile properties of titanium based bulk glassy alloys, Int. J. Mater. Eng. Tech. 5(2011)77-90.
[9] E.S. Puchi-Cabrera, M.H. Staia, D.T. Quuinto, C. Villalobos-Gutierres, E. Ochoa-Perez, Fatigue properties of a SAE4340 steel coated with TiCN by PAPVD, Int. J. Fatigue 29(2007)471-480.
[10] G.Y. Wang, D.C. Qiao, Y. Yokoyama, M. Freels, A. Inoue, P.K. Liaw, Effects of loading modes on the fatigue behavior of Zr-metallic, J. Alloy Comp. 483(2009)143-145.
[11] K. Fujita, T. Takayama, A. inoue, T. Zhang, H. Kimura, Effect of nanocrystalline dispersion on fatigue in a Zr-based bulk metallic glass, J. Jpn. Inst. Metals. 67(2003)79-84.