ULTRAHIGH FATIGUE STRENGTH IN Ti-BASED BULK METALLIC GLASS

K. Fujita¹, T. Hashimoto², W. Zhang³, N. Nishiyama⁴, C. Ma⁵, H. Kimura³ and A. Inoue³

¹Department of Mechanical Engineering, Ube National College of Technology, Ube 755-8555, Japan
²Advanced Production System Engineering Course Student, Ube National College of Technology, Ube 755-8555, Japan
³Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
⁴RIMCOF, Tohoku University Laboratory, Sendai 980-8577, Japan
⁵School of Materials Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100083, P.R.China

Received: March 29, 2008

Abstract. Fatigue tests were carried out on nanocrystal dispersed Ti₄₁₅Zr₂₅Hf₅Cu₄₂₅Ni₇₅Si₁ at.% (Ti-based), Cu₆₀Zr₃₀Ti₁₀ at.% (CuZrTi, Cu-based), and Cu₆₀Hf₂₅Ti₁₅ at.% (CuHfTi, Cu-based) bulk metallic glasses (BMGs) under axial loading at a stress ratio of 0.1 and a frequency of 5-10 Hz. The fatigue limit (σw = σmax - σmin) and fatigue ratio (σw/σB, σB; tensile strength) in the Ti-based, CuZrTi and CuHfTi BMGs were 1610 MPa and 0.79, 980 MPa and 0.49, and 860 MPa and 0.40, respectively. In particular, the Ti-based BMG showed superhigh fatigue strength in comparison to the high strength crystalline alloys with high fatigue strength [e.g. Cr-Mo steel (JIS SCM435), σw about 1000 MPa]. Specimen and fracture surfaces in the Ti-based BMG were observed by using FE-SEM and fatigue crack initiation mechanism was studied.

1. INTRODUCTION

It was reported by authors of [1] that fatigue ratio, fatigue limit(σw)/tensile strength (σB), in the nano-scale crystal dispersed (NC) Zr-based bulk metallic glass (BMG) was three times larger than that in the monolithic Zr-based BMG with no defects [2]. The NC Ti- and Cu-based BMGs are stronger than the NC Zr-based BMGs, but there are still no reports on fatigue strength. Therefore, the fatigue tests on the Ti- and Cu-based BMGs were carried out under pulsating tension and the results were compared with that in the Zr-based BMG under the same stress condition previously reported [1]. Furthermore, in the Ti-based BMG, both the specimen and fracture surfaces in the vicinity of the fatigue crack initiation region and the specimen surfaces after about 6·10⁶ cycles of stressing just under the fatigue limit were observed in detail by using FE-SEM, and fatigue crack initiation mechanism was examined.

2. EXPERIMENTAL

The test alloy rods with a diameter of 2 mm were prepared in Ti₄₁₅Zr₂₅Hf₅Cu₄₂₅Ni₇₅Si₁ at.% (Ti-based), Cu₆₀Zr₃₀Ti₁₀ at.% (CuZrTi, Cu-based), and Cu₆₀Hf₂₅Ti₁₅ at.% (CuHfTi, Cu-based) systems by copper mold casting method. In the observation result of TEM, the nanocrystals were dispersed in the metallic glassy phase in all these BMGs [3,4]. The σB in the Ti-, CuZrTi, and CuHfTi BMGs were 2.04, 2.00, and 2.13 GPa, and Young’ modulus were 95, 114, and 124 GPa, respectively. The test specimens were machined to hourglass shape type (the radius in axial direction; 4.45 mm, the mini-
Fig. 1. Comparison between the fatigue strength of the BMGs and crystalline alloys.

Fig. 2. Specimen surface morphology in the Ti-based BMG after $N=6\times10^6$ cycles of $2\sigma_a/\sigma_w=0.98$. (a) Macroscopic morphology of shear bands, and (b)-(d) examples of the kink, branch, intersection, and rotate in shear bands.

Fig. 3. Fracture and specimen surface morphology near the fatigue crack initiation region in the Ti-based BMG.

3. RESULTS AND DISCUSSION

Fig. 1 shows the S-N curves of the BMGs together with those of the crystalline alloys [5-8]. The fatigue limit ($\sigma_w = \sigma_{min} - \sigma_{max}$) in the Ti-based, CuZrTi, and CuHfTi BMGs show 1610 MPa, 980 MPa, and 860 MPa, respectively. The $\sigma_w/\sigma_B$ are 0.79, 0.49, and 0.40, respectively. In particular, the $\sigma_w$ in the

minimum diameter: 0.9 mm), and after machining the specimen surfaces were electro-polished by 50-100 mm. The specimens were tested by a servo-hydraulic fatigue machine at a stress ratio ($R = \sigma_{min}/\sigma_{max}$) of 0.1 and a frequency of 5-10 Hz.
Ti-based BMG shows superhigh value in comparison to the high $\sigma_{\text{w}}$ in the high strength crystalline alloys (e.g., Cr-Mo steel (JIS SCM435), $\sigma_{\text{w}} = 1000$ MPa [5]).

On the specimen surfaces after about $6 \cdot 10^6$ cycles of stressing just above the $\sigma_{\text{w}} (2\sigma_{\text{w}}/\sigma_{\text{w}} = 0.98$, $\sigma_{\text{w}}$; stress amplitude = $(\sigma_{\max} - \sigma_{\min})/2$), many long shear bands are observed in the Ti-based BMG as shown in Fig. 2. The shear band tips kink and branch, and rotate. In the Zr-based BMG, even small shear bands (less than $10\mu$m) were observed under the same test conditions. It is necessary after time to conform that in the Ti-based BMG they are shear bands or cracks. However, we assume in the present stage that they are the shear bands because in the Zr-based BMG the small crack (about $10\mu$m) continuously grew from the 5% of fatigue life under the repetition of the stress just above $\sigma_{\text{w}}$ (fatigue life; $4.5 \cdot 10^4$ cycles), and the relation between the growth rate and $\Delta K$ agreed well with that in large cracks [1] but in the Ti-based BMG they (more than $300 \mu$m, Fig. 2a) did not grow and did not fracture yet even in $6 \cdot 10^6$ cycles (knee point cycles in S-N curve in Fig. 1; about $1 \cdot 10^6$ cycles).

Fig. 3 shows fracture surface morphologies in the vicinity of the fatigue crack initiation region in the Ti-based BMG. Micro-defects (micro voids and crystals) at the initiation site are not observed. Clear ridge and valley, and also stripes formed by cyclic stressing are observed. The result indicates that fatigue cracks occurred by mode III and I cyclic deformations. In the Cu- and Zr-based BMGs, there were always micro void (1-15 $\mu$m) and dendrite crystal (several tens $\mu$m) at the initiation site, respectively. The $\sigma_{\text{w}}$ and $\sigma_{\text{w}}/\sigma_{\text{w}}$ of the Zr-based BMG were about $220$ MPa and 0.13, respectively [1]. In these NC BMGs, the $\sigma_{\text{w}}$ and $\sigma_{\text{w}}/\sigma_{\text{w}}$ are larger as the size of defects are smaller, and they are much larger than the monolithic Zr-based BMG with no defect [2].

The cause of the ultrahigh $\sigma_{\text{w}}$ in the Ti-based BMG is presumed as follows. There were no micro-defects (micro voids and crystals) at the initiation site. Nanocrystals prevented the initiation and the following slight growth of the shear bands [1]. After growing, long shear bands were stopped due to the difficulty of sliding by the shear band’s cutting to each other and the reduce of shear stress value near the tips by the branching, kinking, and rotating.

4. CONCLUSIONS

Nanocrystal dispersed Ti$_{41.5}$Zr$_{2.5}$Hf$_{5.5}$Cu$_{42.5}$Ni$_{7.5}$Si$_{1}$ at.% BMG with no micro-defects had ultrahigh fatigue limit. This experimental result indicated a possibility that the nanocrystal dispersed BMGs with no micro-defects have higher fatigue strength than the high strength crystalline alloys with high fatigue strength.

REFERENCES