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ULTRAHIGH FATIGUE STRENGTH IN Ti-BASED BULK METALLIC GLASS

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Abstract. Fatigue tests were carried out on nanocrystal dispersed $Ti_{41.5}Zr_{2.5}Hf_5Cu_{42.5}Ni_{7.5}Si_1$ at.% (Ti-based), $Cu_{60}Zr_{30}Ti_{10}$ at.% (CuZrTi, Cu-based), and $Cu_{60}Hf_{25}Ti_{15}$ 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 ($\sigma_w = \sigma_{max} - \sigma_{min.}$) and fatigue ratio ($\sigma_w/\sigma_B$, σ_i; 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), σ_w = 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(σ_w)/tensile strength (σ_B), 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 $6{\cdot}10^6$ 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 $Ti_{41.5}Zr_{2.5}Hf_5Cu_{42.5}Ni_{7.5}Si_1$ at.% (Ti-based), $Cu_{60}Zr_{30}Ti_{10}$ at.% (CuZrTi, Cu-based), and $Cu_{60}Hf_{25}Ti_{15}$ 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 σ_B in the Ti- , CuZrTi, and CuHfTi BMGs were 2.04, 2.00, and 2.13 GPa, and Young' s 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-

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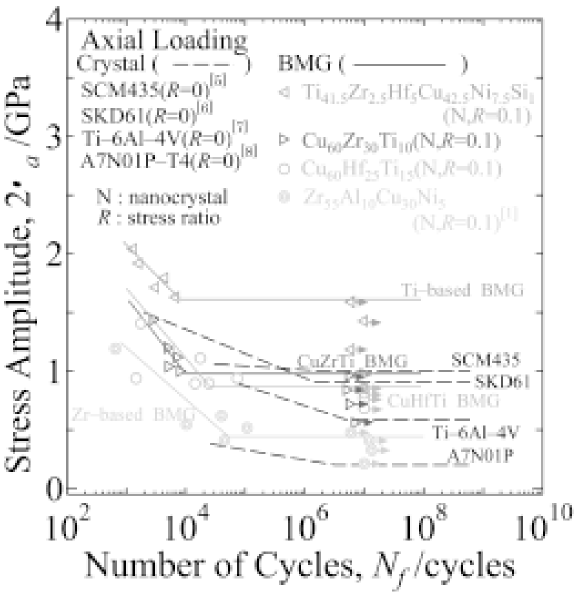

Fig. 1. Comparison between the fatigue strength of the BMGs and crystalline alloys.

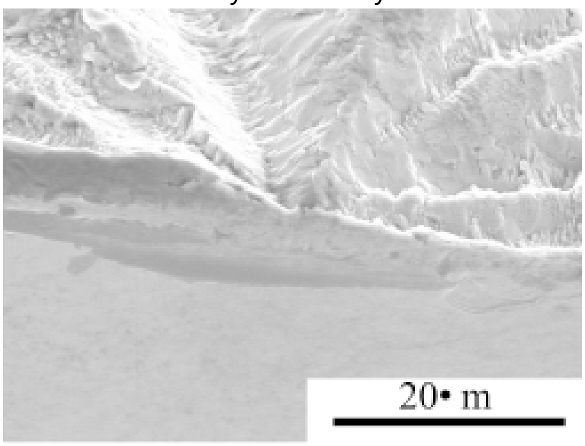

Fig. 3. Fracture and specimen surface morphology near the fatigue crack initiation region in the Ti-based BMG.

mum 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.

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 ($\sigma_w = \sigma_{max.} - \sigma_{min.}$) in the Ti-based, CuZrTi, and CuHfTi BMGs show 1610 MPa, 980 Mpa, and 860 MPa, respectively. The σ_w/σ_B are 0.79, 0.49, and 0.40, respectively. In particular, the σ_w in the

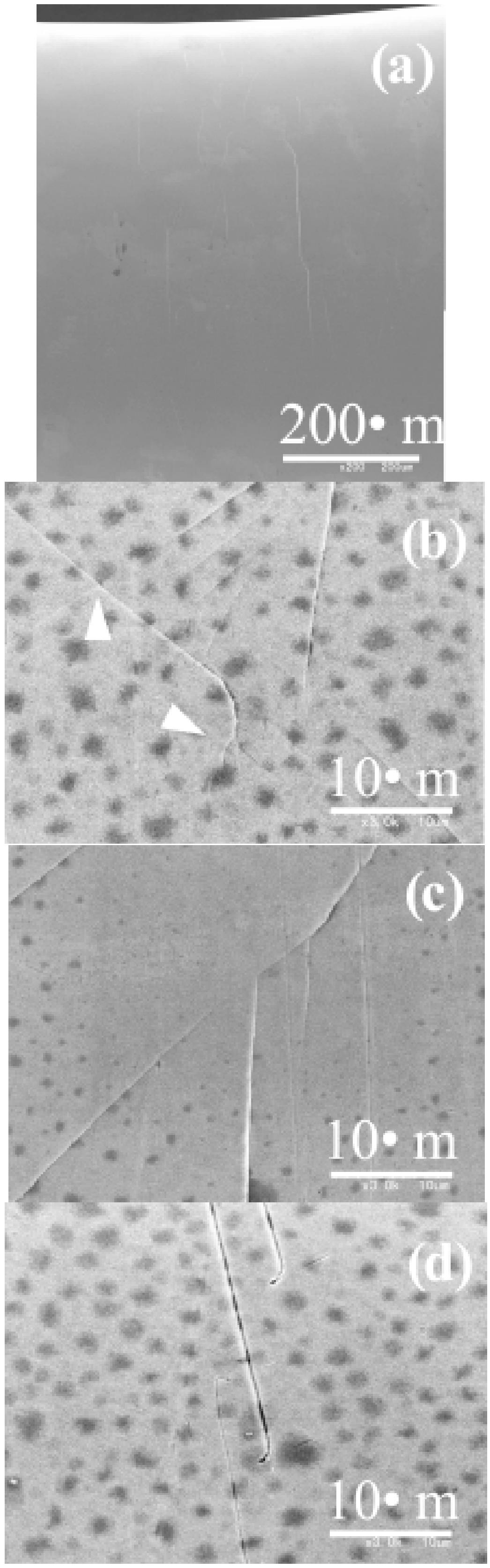

Fig. 2. Specimen surface morphology in the Ti-based BMG after N=6·10^6 cycles of $2\sigma_a/\sigma_w$=0.98. (a)Macroscopic morphology of shear bands, and (b)-(d)examples of the kink, branch, intersection, and rotate in shear bands.

Ti-based BMG shows superhigh value in comparioson to the high σ_w in the high strength crystalline alloys (e.g. Cr-Mo steel (JIS SCM435), σ_w = about 1000 MPa [5]).

On the specimen surfaces after about $6\cdot10^6$ cycles of stressing just under the σ_w ($2\sigma_a/\sigma_w = 0.98$, σ_a ; stress amplitude = $(\sigma_{max.} - \sigma_{min.})/2$), many long shear bands are observerved in the Ti-based BMG as shown in Fig. 2. The shear band tips kink and branch(b), stop at the interception by another shear band (c), and rotate (d). In the Cu-based BMG like as the Zr-based BMG[1]. Even small shear bands (less than 10μm) were observed under the same test conditions. It is necessary aftertime 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 μm) continuously grew from the 5% of fatigue life under the repetition of the stress just above σ_w (fatigue life; $4.5\cdot10^4$ cycles), and the relation between the growth rate and ΔK agreed well with that in large cracks [1] but in the Ti-based BMG they (more than 300 μm, Fig. 2a) did not grow and did not fracture yet even in $6\cdot10^6$ cycles (knee point cycles in S-N curve in Fig. 1; about $1\cdot10^4$ 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 μm) and dendrite crystal (several tens μm) at the initiation site, respectively. The σ_w and σ_w/σ_B of the Zr-based BMG were about 220 MPa and 0.13, respectively [1]. In these NC BMGs, the σ_w and σ_w/σ_B 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 σ_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 $Ti_{41.5}Zr_{2.5}Hf_5Cu_{42.5}Ni_{7.5}Si_1$ 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.

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