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Effects of aspect ratio and loading rate on room-temperature mechanical properties of Cu-based bulk metallic glasses

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Abstract: Room-temperature mechanical properties of $Cu_{50}Zr_{40}Ti_{10-x}Ni_x$ ($0 \le x \le 4$, mole fraction, %) bulk metallic glasses (BMG) with aspect ratios in the range of 1:1−2.5:1 and loading rates in the range of $1\times10^{-5}-1\times10^{-2}$ s^{-1} were systematically investigated by room-temperature uniaxial compression test. In the condition of an aspect ratio of 1:1, the superplasticity can be clearly observed for $Cu_{50}Zr_{40}Ti_{10}$ BMG when the loading rate is 1×10^{-4} s^{-1}, while for $Cu_{50}Zr_{40}Ti_{10-x}Ni_x$ (x=1−3, mole fraction, %) BMGs when the loading rate is 1×10^{-2} s^{-1}. The plastic strain (ε_p), yielding strength (σ_y) and fracture strength (σ_f) of the studied Cu-based BMGs significantly depend on the aspect ratio and the loading rate. In addition, the σ_y of the studied Cu-based BMGs with an aspect ratio of 1:1 is close to the σ_f of those with the other aspect ratios when the loading rate is 1×10^{-2} s^{-1}. The mechanism for the mechanical response to the loading rate and the aspect ratio was also discussed.

Key words: Cu-based bulk metallic glasses; aspect ratio; loading rate; plasticity; strength

1 Introduction

Cu−Zr−Ti ternary alloys are one of Cu−Zr-based glass forming alloys. Critical diameter (d_c) and plastic strain (ε_p) of Cu−Zr−Ti BMGs can reach up to 5 mm [1] and 7.4% [2], respectively. Recently, CAI et al [3−8] have found that structural, thermal and corrosive performances of $Cu_{60-x}Zr_{30+x}Ti_{10}$ (x=0, 5, 10, mole fraction, %) metallic glasses can be significantly changed after the tension/compression. $Cu_{50}Zr_{40}Ti_{10}$ metallic glass characterizes in good deformability [6,7] and low hardness [8] among $Cu_{60-x}Zr_{30+x}Ti_{10}$ (x=0, 5, 10, mole fraction, %) metallic glasses, but its critical dimension and plastic strain are only 2 mm and 1.5% [9], respectively. Interestingly, the glass forming ability, mechanical, electrical and thermal properties can be simultaneously improved for Cu−Zr−Ti glass forming alloys by Ni addition [10−12]. For example, WU et al [11] fabricated a monolithic $Cu_{54.5}Zr_{37}Ti_8Ni_{0.5}$ BMG whose plastic strain and fracture strength can reach up to 26% and 2471 MPa, respectively.

It is well-known that the mechanical properties of the BMG are related with two kinds of factors. One is intrinsic factors such as the composition and/or microstructure of the BMG [10−17]. For example, WU et al [12] designed a $Cu_{51}Zr_{37}Ti_8Ni_4$ BMG which displays remarkable plasticity of 10.5% together with the fracture strength of 2145 MPa through the compositional regulation. LIU et al [15] designed three Zr-based BMGs with room-temperature compressive superplasticity due to the structural heterogeneity. The other is external factors, including the size [18−20], aspect ratio H/D (H and D are the height and the diameter of samples, respectively) [21−23], loading/strain rate [24−33], geometry [34,35], stress/strain state [36,37], and other factors [38−40]. The aspect ratio and the loading/strain rate are two important factors significantly influencing the mechanical properties of the BMG. ZHANG et al [21] and JIANG et al [22] found that the plastic strain

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increased with decreasing aspect ratio and the yield strength almost maintained a constant value. However, BRUCK et al [23] investigated the effect of two aspect ratios (1:2 and 2:1) on the compressive properties and found a slight increase in the yield strength with decreasing aspect ratio. In addition, it was found that the compressive strength decreased with increasing strain rate for $Zr_{38}Ti_{17}Cu_{10.5}Co_{12}Be_{22.5}$ BMG [28], $Zr_{57}Ti_5Cu_{20}Ni_8Al_{10}$ BMG [29], and $Pd_{40}Ni_{40}P_{20}$ BMG [31], respectively. The fracture strength was independent of the strain rate for $Zr_{41.25}Ti_{13.75}Cu_{12.75}Ni_{10}Be_{22.5}$ BMG in compression [32] and $Pd_{40}Ni_{40}P_{20}$ BMG in tension [30], respectively. However, the compressive strength was found to increase with increasing strain rate for $Ti_{40}Zr_{25}Ni_8Cu_9Be_{18}$ BMG [20] and $Nd_{60}Fe_{20}Co_{10}Al_{10}$ BMG [27], respectively. In addition, the dependence of the plastic and/or fracture strain of the BMG on the loading rate and the aspect ratio is similar to that of the mechanical properties. For example, the plastic and fracture strain were found to decrease with increasing strain rate for $Zr_{38}Ti_{17}Cu_{10.5}Co_{12}Be_{22.5}$ BMG [28], $Ti_{40}Zr_{25}Ni_8Cu_9Be_{18}$ BMG [20], $Ti_{45}Zr_{16}Ni_9Cu_{10}Be_{20}$ BMG [26], and $Nd_{60}Fe_{20}Co_{10}Al_{10}$ BMG [27] in compression, and increase with increasing strain rate for $Zr_{41.25}Ti_{13.75}Cu_{12.75}Ni_{10}Be_{22.5}$ BMG in tension [33], while they were independent of the strain rate for $Pd_{40}Ni_{40}P_{20}$ BMG in tension [31] and $Zr_{41.25}Ti_{13.75}Cu_{12.75}Ni_{10}Be_{22.5}$ BMG in compression [32], respectively. Interestingly, ZHANG et al [26] found little effect of the mechanical properties on the strain rate when the strain rate was below 1×10^{-3} s^{-1} and a positive strain rate dependence of yield strength when the strain rate was up to 1×10^{-1} s^{-1} for $Ti_{45}Zr_{16}Ni_9Cu_{10}Be_{20}$ BMG. In addition, both the strength and plasticity increased with increasing the strain rate up to a critical value, above which the strength and plasticity started to decrease for $Zr_{56}Al_{10.9}Ni_{4.6}Cu_{27.8}Nb_{0.7}$ BMG [24] and SrCaYbMg(Li)Zn(Cu) BMGs [25], respectively. Nevertheless, no reports for these problems can be found for Cu-based BMGs.

In the present work, the effects of the aspect ratio and the loading rate on the mechanical properties of $Cu_{50}Zr_{40}Ti_{10-x}Ni_x$ ($0\le x\le4$, mole fraction, %) BMGs were investigated by room-temperature compressive tests. It is found that the yield strength, fracture strength and plasticity significantly depend on the aspect ratio and the loading rate for the studied Cu-based BMGs.

2 Experimental

Master ingots of Cu−Zr−Ti−(Ni) alloys with normal compositions (in mole fraction, %), as shown in Table 1, were prepared by arc melting the mixture of ultrasonically cleaned high purity Cu (99.99%), Zr (99.99%), Ti (99.99%) and Ni (99.99%) in a Ti-gettered argon atmosphere. Then, d2 mm samples were prepared by suction casting into a water-cooled Cu mold.

The glassy natures of the as-cast samples were characterized by X-ray diffraction (XRD) using an

Table 1 Yielding strength σ_y, fracture strength σ_f, plastic strain ε_p, fracture strain ε_f, and $\varepsilon_p/\varepsilon_f$ under different aspect ratios and loading rates for $Cu_{50}Zr_{40}Ti_{10-x}Ni_x$ ($0\le x\le4$) bulk metallic glasses

x(Ni)/%	Aspect ratio	Loading rate/s^{-1}	σ_y/MPa	σ_f/MPa	ε_p/%	ε_f/%	$(\varepsilon_p/\varepsilon_f)$/%
0	1:1	1×10^{-2}	1860.3	1915.7	1.9	15.9	11.9
		1×10^{-3}	1720.5	1922.8	3.0	15.5	19.4
		1×10^{-4}	1877.1	Superhigh	Superhigh	Superhigh	100.0
		1×10^{-5}	1905.6	2449.2	14.5	29.5	49.2
	1.5:1	1×10^{-2}	1102.9	1259.6	2.3	9.6	24.0
		1×10^{-3}	1736.2	1917.6	1.4	9.4	14.9
		5×10^{-4}	1986.4	2049.6	1.6	10.7	15.0
		1×10^{-4}	1723.5	1911.2	2.5	12.9	19.4
		1×10^{-5}	1573.1	1755.1	2.6	10.7	24.3
	2:1	1×10^{-2}	1609.6	1978.2	3.3	10.4	31.7
		1×10^{-3}	1710.9	1923.9	2.1	10.7	19.6
		1×10^{-4}	1553.4	1880.6	2.4	9.4	25.5
		1×10^{-5}	1553.0	1860.3	2.5	8.5	29.4
	2.5:1	1×10^{-2}	−	1264.6	−	6.0	0
		1×10^{-3}	1615.7	1827.0	1.0	9.7	10.3
		1×10^{-4}	1671.3	1927.5	1.7	7.1	23.9
		1×10^{-5}	1632.0	1877.5	1.4	7.8	17.9

to be continued