The Effect of Al on the Mechanical Properties and Microstructure of Copper-based Metallic Glass

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ABSTRACT

An investigation was carried out into the effect of different amounts of Al on the mechanical properties, and glass-forming ability, of a three component alloy (Cu–Zr–Al). The mechanical properties were studied using a universal materials tester and a Split-Hopkinson bar tester. A series of amorphous alloys with different Al content were subjected to static compression and dynamic high-speed impact tests at 10^{-1} s^{-1}, 10^{-2} s^{-1}, and 10^{-3} s^{-1} for the static condition and 2000 s^{-1}, 3000 s^{-1}, and 4000 s^{-1} for the dynamic condition. Experiment showed that the flow stress value and the strain rate sensitivity coefficient of the copper-based amorphous alloys varied with changes of strain and strain rate. An increase in the rate of strain caused the flow stress value and the sensitivity coefficient of the strain rate to rise. When the Al content in an amorphous alloy Cu_{47.5}Zr_{45.5}Al_{7} was 7%, both the flow stress value and the strain were improved and effectively upgraded the mechanical properties of the material.

Relationship of the static stress–strain curves at different strain rates for (a) Cu_{51.5}Zr_{45.5}Al_{3} and (b) Cu_{47.5}Zr_{45.5}Al_{7}.

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Conventional metals have many excellent properties, such as high mechanical strength, hardness, low modulus of elasticity, wear resistance, corrosion resistance and excellent magnetic properties [6–8]. However, an amorphous alloy has been made using copper, titanium, nickel, aluminum, magnesium, iron, cobalt, chromium, and zirconium and palladium. It is a bulk metallic glass (BMG) [9,10] that currently has a strength which can be up to 1700 MPa, higher than many metal alloys, and has therefore drawn much attention. In the earlier development of copper-based metallic glass, Johnson et al. [11] first synthesized a piece of bulk Cu_{47}Zr_{11}Ti_{34}Ni_{8} metallic glass in 1995, with a critical size of up to 4 mm.

While amorphous alloys have many excellent properties, they are brittle and exhibit no significant plastic deformation under tensile or compressive force. They are not ductile-like crystalline material and are very limited in real applications. An amorphous alloy exhibits uneven plastic deformation and becomes brittle under compressive stress at the glass–transition temperature [12]. Deformation in BMG arises from the generation of highly localized shear bands, causing plastic deformation [13]. However, plastic deformation only occurs at a few of the shear bands and low strain can cause the shear bands to quickly spread to areas, where plastic deformation has not occurred. This causes localized softening, and fracture occurs at the softened area. This uneven plastic deformation is referred to as work softening [13]. Recent work has shown that the ductility of BMG can be improved by the phase strengthening method. This involves precipitation from the base phase of the BMG alloy, to inhibit the spread of a single shear band to form...
multiple bands. This improves the mechanical properties and ductility. Tungsten, niobium, and tantalum and molybdenum can be evenly scattered or precipitated in the base to not only improve the mechanical properties, but also to promote the formation of amorphous alloy glass by the addition of such types of material. This new type of alloy is referred to as metallic glass composite (BMGC).

2. Experimental Principle and Methods

2.1. Rules for the Formation of an Amorphous Alloy

Much attention is being paid to the formation of amorphous alloys and the mechanism by which they are formed. A systematic theory that can be used to analyze and estimate the amorphous-forming ability of a material is needed for use as a credible and practical reference. So far no sound and predictable theory has been developed. Some rules are being integrated for reference based on actual experimental results and the Japanese Inoue team has made a great contribution to this. They hold the leading position in metallic glass development. They have compiled research data for several alloys and have established three empirical rules based on comparisons between amorphous alloy series [14–17].

2.2. Characteristics of Plastic Deformation

Plastic deformation, as a response to stress, occurs in some materials when they are subjected to an external force. In a material that has a slip system this is referred to as plastic stress. In general, plastic stress will increase with an increase in the rate of strain. At the same time, the yield stress of the material will also rise and cause it to become harder and more brittle [18]. The characteristics of each deforming mechanism in the material will be revealed in the mechanical properties. Generally speaking, the plastic stress of a material is related to its own structure, temperature, strain, and strain rate. This means plastic stress can be expressed by a functional relationship, as \( \sigma = f(\varepsilon, \varepsilon, T, \text{structure}) \). There are four types of plastic deformation [19], diffusion, athermal, thermal, and dislocation-drag controlled.

2.3. Experimental Method

A copper-based metallic glass alloy was formulated by weight from three pure metals: copper, zirconium, and aluminum (all 99.9% pure) at a ratio of \( \text{Cu}_{54.5-x}\text{Zr}_{45.5}\text{Al}_x \) \((X = 3, 7)\). The amorphous alloys were smelted under vacuum in an electric arc furnace and cast into the form of rods on which and a series of macro-analyses of the mechanical properties were carried out. A static compression test was done using the universal material tester (MTS 810), after which a dynamic high-speed impact...
alloy. It can also be seen that the peak for Cu$_{10}$Zr$_7$ became stronger with an increase of Al content. From this we can deduce that the addition of 7% aluminum effectively supports the precipitation of Cu$_{10}$Zr$_7$ (see Figure 2).

The experiment was carried out using the Hopkinson dynamic impact tester (Figure 1). The wave patterns and data from the signal processing system were used to compute the stress and strain curves. The microscopic structure of the fracture surfaces of the test specimens was examined using SEM and micro-analysis was done by EDS.

3. Results and Discussion

3.1. X-ray Diffraction of Ti-based BMG

To verify the BMG structure of the Cu$_{51.5}$Zr$_{45.5}$Al$_3$ and Cu$_{47.5}$Zr$_{45.5}$Al$_7$ alloy test pieces, X-ray diffraction analysis of the BMG specimens was conducted. Figure 2 shows an X-ray diffraction diagram of Cu$_{51.5}$Zr$_{45.5}$Al$_3$. It can be seen that a peak is present at 37° and 39° of the 2θ angles. After phase appraisal and comparison, this was verified as a characteristic peak of the precipitate phase of Cu$_{10}$Zr$_7$. There were no other characteristic component peaks. However, there was a wide diffraction peak from 33 to 47°, characteristic of the amorphous alloy. It can also be seen that the peak for Cu$_{10}$Zr$_7$ became stronger with an increase of Al content. From this we can deduce that the addition of 7% aluminum effectively supports the precipitation of Cu$_{10}$Zr$_7$ (see Figure 2).
on the test pieces was associated with a lower strain rate, and the dimples and veins were smaller and denser. The lower strain rates also produced a smoother fracture surface. The dimple distribution across the fracture surface of the 7% Al test piece was wider and denser than that of the 3% Al alloy. The fracture surface was also smoother and more even than that of the amorphous alloy test piece without aluminum. The fracture strain was also greater. Aluminum clearly makes the alloy more ductile and the fracture surface morphology of the test pieces corresponds well with the stress–strain curves.

4. Conclusion

The XRD analysis of the experimental amorphous alloys and the control specimens all showed slight brittle phase diffraction peaks. However, the wide diffraction peak in the base phase confirms that the base phase is amorphous. The precipitate phase can be effectively induced by the addition of 7% Al and this clearly improved the mechanical properties. The plastic stress value and the strain of

3.2. Stress–Strain Curves

Figures 3 and 4, show static and dynamic strain curves at three different rates in the Al alloys. It can be clearly seen that the alloy with 7% aluminum had the best strain value and was the more ductile. This extra ductility will add to its overall strength. Furthermore, the flow stresses are increased with increased strain rate in static and dynamic condition. It can be present the mechanical properties of two Cu-based BMG with different Al elements are influenced by strain rate [20,21].

3.3. SEM Fracture Morphology Analysis

Scanning electron microscopy of the fracture surfaces of the alloy test pieces showed a range of significant morphological features in both alloy test pieces compared to the control specimen (shown in Figures 5–7), which had no aluminum. Notable features were differences in dimple shape, size, and distribution as well as fracture direction. An obvious feature was that a wide distribution of dimples

Figure 6. Fracture surface of Cu$_{51.5}$Zr$_{45.5}$Al$_{3}$ at strain rate of (a) 2000 s$^{-1}$; (b) 4000 s$^{-1}$.

Figure 7. Fracture surface of Cu$_{51.5}$Zr$_{45.5}$Al$_{7}$ at strain rate of (a) 2000 s$^{-1}$; (b) 4000 s$^{-1}$.
the amorphous Cu_{47.5}Zr_{45.5}Al_{7} alloy were greater than in the amorphous Cu_{51.5}Zr_{45.5}Al_{3} alloy. This clearly shows that the ductility and overall strength of the material can be increased by the addition of 7% Al. Scanning electron microscope examination of the specimen fracture surface morphology showed that the dimple organization on the fracture surface changes with different strain rate and fracture strain rate. The lower strain rate is associated with a wider and denser dimple distribution. The dimple veins are also smaller and denser and the fracture surface is smoother. The dimple arrangement associated with greater strain is looser and more widely distributed and the veins are also larger.

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**Disclosure Statement**

No potential conflict of interest was reported by the authors.

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**References**

[1] Wang WH, Dong C, Shek CH. Bulk metallic glasses. Mater Sci Eng R. 2004;44:45–89.

[2] Klement W, Willens RH, Duwez P. Non-crystalline structure in solidified gold–silicon alloys. Nature. 1960;187:869–870.

[3] Lin XH, Johnson WL. Formation of Ti–Zr–Cu–Ni bulk metallic glasses. J Appl Phys. 1995;78:6514–6519.

[4] Inoue A, Zhang T and T. Masumoto, 1989, Mater Trans, JIM. 30:965.

[5] Chen TH, Tsai C-K. The microstructural evolution and mechanical properties of Zr-based metallic glass under different strain rate compressions. Materials. 2015;8(4):1831–1840.

[6] Qin CL, Zhang W, Asami K, Kimura H, Wang XM, Inoue A. A novel Cu-based BMG composite with high corrosion resistance and excellent mechanical properties. Acta Materialia. 2006;54:3713–3719.

[7] Inoue A. Bulk amorphous alloys. Zurich: 2thTrans.Tech. Publications; 1998.

[8] Miller M, Liaw P. Bulk metallic glasses: an overview. New York (NY): Springer Science Business Media; 2008.

[9] Suryanarayana C, Inoue A. Bulk metallic glass. Boca Raton: CRC Press, Taylor & Francis Group; 2011.

[10] Jang JSC, Jian SR, Pan DJ, Wu YH, Huang JC, Nieh TG. Thermal and mechanical characterizations of a Zr-based bulk metallic glass composite toughened by in-situ precipitated Ta-rich particles. J Intermetallics. 2010. 18:560–564.

[11] Glade SC, Löfler JE, Bossuyts, S, Johnson, WL. Crystallization of amorphous Cu_{47.5}Ti_{34}Zr_{11}Ni_{8}. J Appl Phys. 2001;89:1573–1579.

[12] Davidson DL. Metall Trans A. 1991;22A:97.

[13] He G, Loser J, Eckert J and Schultz L. J. Mater. Res. 2002;17:3015.

[14] Inoue A. Stabilization and high strain-rate superplasticity of metallic supercooled liquid. Mater Sci Eng A. 1999;267:171–183.

[15] Inoue A. Stabilization of metallic supercooled liquid and bulk amorphous alloys. Acta Materialia. 2000;48:279–306.

[16] Inoue A. High strength bulk amorphous alloys with low critical cooling rates (overview). Mater Trans, JIM. 1995;36:866–875.

[17] Chen TH, Hsu YK. Mechanical properties and microstructural of biomedical Ti-based bulk metallic glass with Sn addition. Comput Mater Sci. 2016;117:584–589.

[18] Campbell JD. Dynamic plasticity: macroscopic and microscopic aspects. Mater Sci Eng. 1973;12:3–21.

[19] Klahn D, Mukherjee AK, Dorn JE. 1970. Proceedings of the 2nd International Conference on the Strength of Metals and Alloys, vol. III, ASM. p. 951.

[20] Chen T-H, Chen T-Y. Microstructural evolution and high strain rate mechanical property of cobalt superalloy contain titanium. Sains Malays. 2015;44(12):1751–1756.

[21] Chen T-H, Wu J-H. Mechanical behaviour and fracture properties of NiAl intermetallic alloy with different copper contents. Appl Sci. 2016(3);6:1–9. Article 70.