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# Properties of Zr-based bulk metallic glass under shock compression

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**Abstract**

Many kinds of bulk metallic glasses have been discovered since the 1990s. However, there have been very few investigations of the dynamic compression properties of bulk metallic glasses with amorphous structured single-phase. In this study, Hugoniot-measurement experiments have been performed on $Zr_{55}Al_{10}Ni_5Cu_{30}$ (at.%) bulk metallic glass by the inclined-mirror method combined with a powder gun in the pressure range up to 45 GPa in order to investigate the elasto-plastic transition and phase transition of the bulk metallic glass. The Hugoniot-elastic limit stress of $Zr_{55}Al_{10}Ni_5Cu_{30}$ bulk metallic glass was >5 GPa which is much larger than that of the other metals. A kink was observed on the shock velocity versus particle velocity relationship of bulk metallic glass, which may be caused by phase transition. Ductile dimple fracture with a vein pattern was observed on the fracture surfaces of the recovered bulk metallic glass under low pressures.


*Keywords:* Shock compression; $Zr_{55}Al_{10}Ni_5Cu_{30}$; Hugoniot-elastic limit stress

## 1. Introduction

Recently, new breeds of bulk metallic glasses with high glass-forming ability have been discovered. Their high glass-forming ability lets us fabricate large-sized single-phase amorphous alloy by rapid casting method. It was known that the bulk metallic glasses have superior mechanical properties, such as high strength under ambient static pressure, high corrosion resistance, soft magnetism, etc. [1]. However, there has been very few investigations of the dynamic compression properties of bulk metallic glasses with amorphous structured single-phase [2,3]. The yielding behavior of bulk metallic glass under shock compression is a fascinating and up-to-date problem, because the fracture mechanism of bulk metallic glass which differs to one crystalline metal has no dislocation. It is thought that these properties of bulk metallic glass differ from that of a crystalline alloy due to the absence of long-range order. Investigating these properties in bulk metallic glass is important for understanding yield mechanism and fracture behavior at high strain rates from $10^3$ to$10^6$.

The purpose of this study is to clarify the shock compression properties of Zr-base bulk metallic glasses. Hugoniot-measurement experiments have been performed on $Zr_{55}Al_{10}Ni_5Cu_{30}$ bulk metallic glass in the pressure range up to 45 GPa in order to investigate the elasto-plastic transition and phase transition pressures (PT). Recovery experiment was performed in order to investigate the structure of shock-compressed specimens.

## 2. Experimental procedure

Hugoniot-measurement experiments have been performed on $Zr_{55}Al_{10}Ni_5Cu_{30}$ (numbers indicate at.%) bulk metallic glass of about 2 mm in thickness and about 15 mm × 10 mm in width. The bulk metallic glass was produced by arc melting the pure elements together under a purified Ar atmosphere. The density of bulk metallic glass was measured to be 6.75 g/cm$^3$ by Archimedean method.

Plane shock wave was generated by the high-velocity impact method using the keyed-powder gun of 27 mm bore diameter [4]. The Hugoniot parameters (shock velocity, particle velocity)

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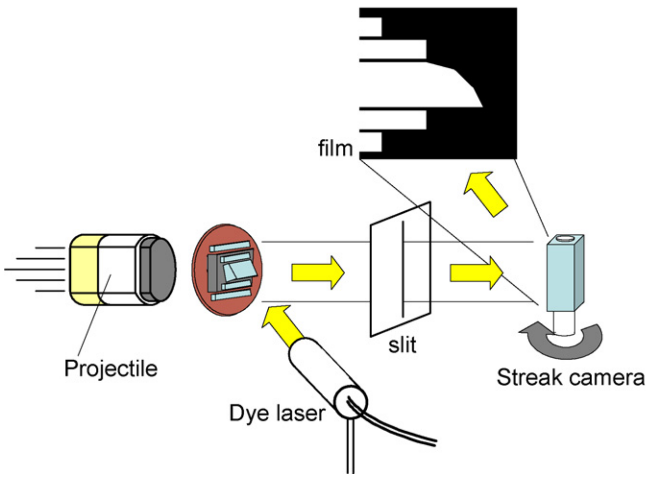


Fig. 1. Schematic illustration of inclined-mirror method.

were measured by means of the inclined-mirror method using the rotating-mirror-type streak camera which provided a maximum writing rate on film greater than 10 mm/μs [5]. Schematic illustration of inclined-mirror method is shown in Fig. 1. In particular, we used a long-pulsed dye laser [6] as light source in the measurements in low pressure region to increase the accuracy. Time resolution was higher than 1 ns. The setting angles of the inclined-mirror were 2–6° in this study. Tungsten, copper, or, aluminum alloy (A2024) plates was used as the impact and driver plates. These specimens and plates were finished parallel to an accuracy of 2–3 μm. Impact velocities were measured by the electromagnetic method with an accuracy of 0.2%. The particle velocities of elastic wave and plastic wave were analyzed by free-surface approximation and impedance-matching method, respectively. The Hugoniot parameter of tungsten, copper, or, aluminum alloy (A2024) used for the impedance-matching method was obtained from [7]. Density, pressure, and temperature under shock compression are given by using the measured shock velocity and particle velocity through the conservation relations. The conservation equations of mass, momentum, and energy, in which the material in front of the shock wave is at rest are given by:

Mass equation :

$$\rho_{(i-1)}(U_{S(i)} - U_{P(i-1)}) = \rho_{(i)}(U_{S(i)} - U_{P(i)}) \tag{1}$$

Momentum equation :

$$P_{(i)} - P_{(i-1)} = \rho_{(i-1)}(U_{S(i)} - U_{P(i-1)})(U_{P(i)} - U_{P(i-1)}) \tag{2}$$

Energy equation :

$$E_{(i)} - E_{(i-1)} = \frac{1}{2}(P_{(i)} + P_{(i-1)})\left(\frac{1}{\rho_{(i-1)}} - \frac{1}{\rho_{(i)}}\right) \tag{3}$$

where $P$, $\rho$, $E$, $U_S$, and $U_P$ are pressure, density, internal energy, shock velocity and particle velocity, respectively. The subscript $i$ denotes the $i$th state of multistructure shock wave. The $i$th shock compression state is determined on the basis of $(i-1)$ prestate. The Hugoniot-elastic limit and phase transition are discussed from the relationship between density and pressure. Hugoniot-elastic limit (HEL) is the stress of elastic shock wave which related to the strength at high strain rate.

The recovery experiments were performed on bulk metallic glass sample. The recovery experiments were conducted using a propellant gun [6,8]. The samples were enclosed in a brass (Cu:Zn = 70:30 in wt.%) capsule or a iron with an inside diameter of 12 mm and with an inside height of 4–5.6 mm. The porosities of pellets were 45–54%. Shock loading was carried out by impacting the capsule with an aluminum alloy (A2024) or tungsten flat flyer plate whose thickness was about 3 mm. Their fracture surface of shock-compressed specimens was investigated with the SEM and micro-focused X-ray diffractometry using Cu Kα radiation.

## 3. Results and discussion

Fig. 2(a) shows the streak photograph of bulk metallic glass by inclined-mirror method for the test with an impact veloc-

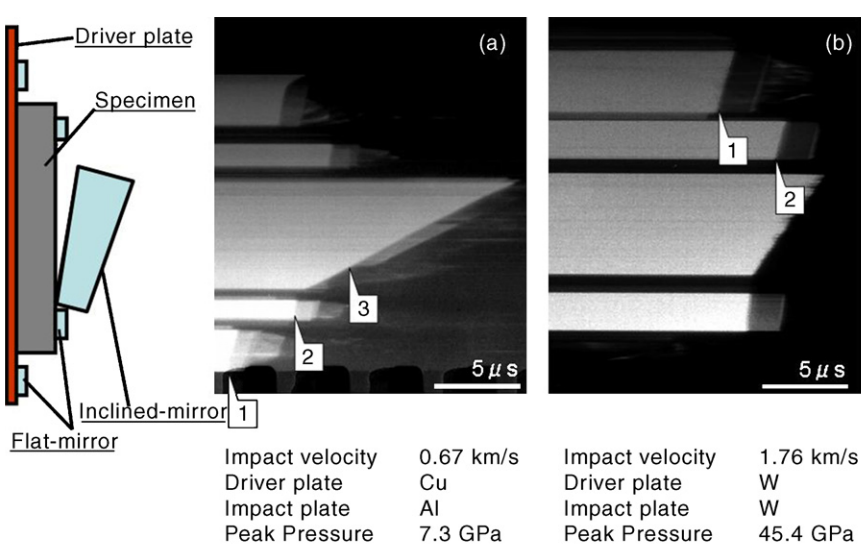


Fig. 2. Streak photograph of $Zr_{55}Al_{10}Ni_5Cu_{30}$ bulk metallic glass by the inclined-mirror method for the test with an impact velocity of (a) 0.67 and (b) 1.76 km/s.