Materials Science and Engineering A 498 (2008) 475–481

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Mechanical properties of a $Ni_{60}Pd_{20}P_{17}B_3$ bulk glassy alloy at cryogenic temperatures

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ARTICLE INFO

Article history:
Received 24 June 2008
Received in revised form 20 August 2008
Accepted 25 August 2008

Keywords:
$Ni_{60}Pd_{20}P_{17}B_3$ bulk glassy alloy
Cryogenic temperature
Compressive stress
Plastic strain
Elastic parameter

ABSTRACT

Little is known about mechanical properties of bulk glassy alloys (BGAs) at cryogenic temperatures. In this study, we investigated the effects of temperature and strain rate on the mechanical properties of a $Ni_{60}Pd_{20}P_{17}B_3$ BGA. Compression tests were performed at temperatures of 295, 223, 173 and 77 K and at strain rates from 5×10^{-5} to $5 \times 10^{-3}\ s^{-1}$. Measurements of the elastic parameters were also made at temperatures from 91 to 371 K. It is found that both the maximum compressive stress and plastic strain to failure increase with decreasing testing temperature. The Young and shear moduli, and Debye temperature monotonically increase with decreasing temperature, while Poisson's ratio decreases, indicating that the BGA becomes rigid and the effective atomic distance decreases at cryogenic temperatures. The mechanism reflecting the changes in the maximum compressive stress and plastic strain with temperature is discussed.

1. Introduction

Bulk glassy alloys (BGAs), which exhibit no long-range structural periodicity, possess many unique properties, such as extremely high fracture strength and large elastic strain [1–3], relatively high fracture toughness [4–6], good magnetic properties [7,8], high corrosion resistance [9,10] and high strain rate formability and workability at elevated temperatures [11,12]. These unique properties are applicable to industrial materials [13,14].

Although many current studies are now directed toward improving the ductility of BGAs or bulk glassy alloy matrix composites (BGACs) at room temperature [15–19], little is known about mechanical properties of BGAs and BGACs at cryogenic temperatures. It is important to study the mechanical properties of BGAs at cryogenic temperatures from viewpoints of wider ranges of applications, such as space exploration and liquefied gas storage [20]. However, the literature associated with the mechanical behavior of the BGAs at low temperatures is available only for Zr-based BGAs and the number of literature is few [20–22]. Therefore, we [23,24] performed compression tests at cryogenic temperatures and at various strain rates for $Cu_{45}Zr_{45}Al_5Ag_5$ BGA [25] rods. It was found that the compressive maximum strength and plastic strain to fracture of the samples are higher at cryogenic temperatures than at ambient temperature. However, they displayed low overall plastic strain (<1%), limiting the potential of BGAs as structural materials at cryogenic temperatures.

Our interest lies in not only high strength but also large plastic strain at cryogenic temperatures. Therefore, we studied a newly developed $Ni_{60}Pd_{20}P_{17}B_3$ BGA [26], which has a large super-cooled liquid region of 90 K and high glass forming ability with a diameter over 10 mm. The alloy also exhibited good mechanical properties, such as high compressive strength of 2060 MPa and maximum plastic strain of 8% at ambient temperature. However, there have been no data on the mechanical properties of Ni-based BGAs at cryogenic temperatures. Recently, there have been several reports of significantly large plastic deformation in Zr- and CuZr-based BGAs containing nanocrystals and nanoquasicrystals [27,28]. TEM observation for the Ni-based alloy revealed the homogeneously dispersed medium-range ordered (MRO) regions in the glassy matrix. It is thus expected that the alloy possesses high strength and large plastic strain at cryogenic temperatures. The objective of the present work is to clarify the effects of temperature and strain rate

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doi:10.1016/j.msea.2008.08.033

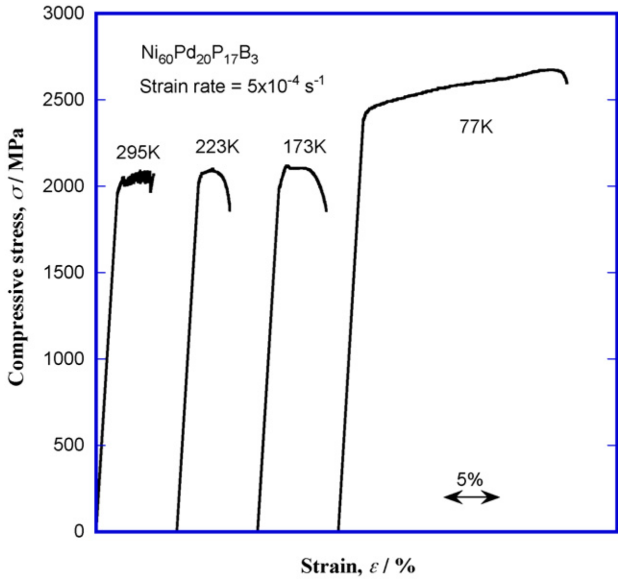

Fig. 1. Compressive nominal stress–strain curves of $Ni_{60}Pd_{20}P_{17}B_3$ BGA rods measured at room (295 K) and cryogenic temperatures (223, 173 and 77 K), at an initial strain rate of 5×10^{-4} s^{-1}.

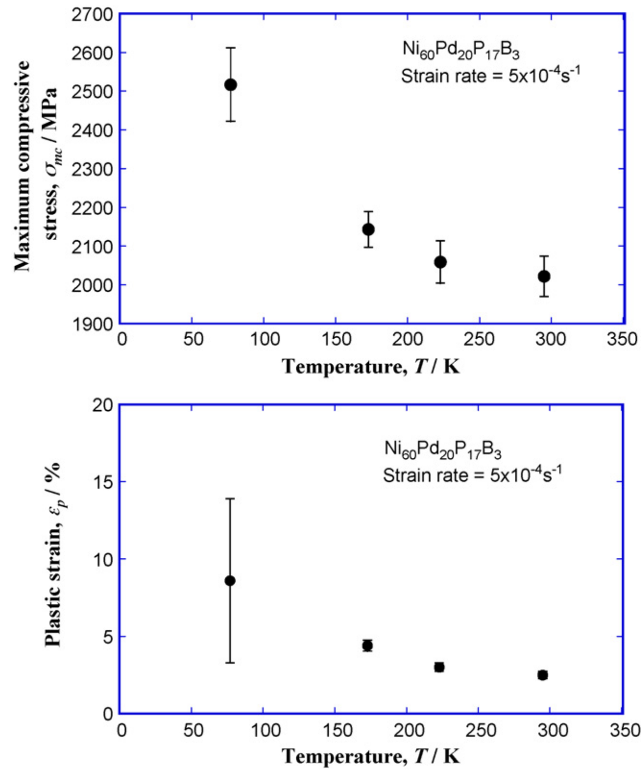

Fig. 2. Temperature dependence of the maximum compressive stress and plastic strain of the $Ni_{60}Pd_{20}P_{17}B_3$ BGA rods at an initial strain rate of 5×10^{-4} s^{-1}.

on the mechanical behavior of a $Ni_{60}Pd_{20}P_{17}B_3$ BGA at cryogenic temperatures under compressive load. In order to further investigate the mechanical behavior for the BGA, the measurements of the elastic parameters were attempted at various temperatures.

2. Experimental procedures

The alloy composition of the sample was $Ni_{60}Pd_{20}P_{17}B_3$ (at%). Mother alloys were prepared by melting a mixture of pure Ni, Pd metals, B crystal and a pre-alloyed Pd–Ni–P ingot in vacuumed fused silica tubes, followed by a B_2O_3 flux treatment. Cylindrical rods of the BGA with diameters ranging from 2 to 7 mm were prepared by copper mold casting and water quenching methods in a purified argon atmosphere. The glassy structure of the as-cast materials was confirmed by X-ray diffraction (XRD) using Cu Kα radiation and differential scanning calorimetry (DSC) at a heating rate of 0.67 K/s.

In order to investigate the temperature dependence of mechanical properties, compression tests were conducted at 295, 223, 173 and 77 K using a servo-hydraulic testing machine (Shimadzu Servopulser with a 50-kN shear type load cell) at an initial strain rate of 5×10^{-4} s^{-1}. The samples were cooled to the test temperature between 77 K (liquid nitrogen) and room temperature by immersing them in a cooling mixture with ethanol during testing. To examine strain rate dependence, compression tests were conducted at 295 and 77 K at various strain rates of 5×10^{-3}, 5×10^{-4} and 5×10^{-5} s^{-1}. The sample size for compression tests was 2 mm in diameter and 4 mm in height. The deformation and fracture behavior was examined by scanning electron microscopy (SEM).

For a better understanding of the mechanical behavior at cryogenic temperatures, we measured the elastic parameters, such as Young's, shear, and bulk moduli and the Lamé parameter, Poisson's ratio and elastic Debye temperature by an ultrasonic pulse method [29]. The $Ni_{60}Pd_{20}P_{17}B_3$ specimen (density of 8.773 Mg/m^3) was in the form of a long rod (7 mm in length and 5.5 mm in diameter) and fastened to a stainless steel waveguide with threads of 1.5 mm pitch, using a domed cap nut of copper. We used a longitudinal wave generating piezoelectric transducer with 7 MHz frequency as the optimum frequency. The elastic parameters were measured at temperatures from 91 to 371 K at a heating rate of 0.03 K/s in vacuum. The experimental procedure is described elsewhere [30]. The value of the Young's modulus at 77 K was estimated by extrapolation of the modulus-temperature curve. For the calculation of the Debye temperature [31], we used 2 as the number of degrees of freedom and 3.516×10^{-28} m^3 as the average atomic volume.

3. Results and discussion

Fig. 1 shows compressive nominal stress–strain curves of the cylindrical BGA rods tested at various temperatures and at an initial strain rate of 5×10^{-4} s^{-1}. The slopes of the stress–strain curves were calibrated by the Young's modulus obtained by an ultrasonic pulse method. At all testing temperatures, the specimens show initial elastic strain, and then yield, followed by a certain amount of plastic strain. The mechanical properties of the BGA are summarized in Table 1.

Fig. 2 shows the temperature dependence of the maximum compressive stress ($\sigma_{m.c.}$) and plastic strain (ε_p) of the $Ni_{60}Pd_{20}P_{17}B_3$

Table 1
Summary of mechanical properties of the $Ni_{60}Pd_{20}P_{17}B_3$ BGA at room and cryogenic temperatures, at an initial strain rate of 5×10^{-4} s^{-1}

$Ni_{60}Pd_{20}P_{17}B_3$	295 K	223 K	173 K	77 K
Maximum stress, $\sigma_{m.c.}$ (MPa)	2022 ± 52	2059 ± 55	2143 ± 46	2517 ± 95
Plastic strain, ε_p (%)	2.5 ± 0.22	3.0 ± 0.28	4.4 ± 0.35	8.6 ± 5.3
Young's modulus, *E* (GPa)	106	108	109	111