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Anomalous decrease of propagation rate of the macroscopic shear band in the Zr-based bulk metallic glasses at temperatures 170 and 77 K

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ABSTRACT

The plastic deformation and fracture of cylindrical samples of the bulk metallic glasses $Zr_{62}Cu_{15.5}Ni_{12.5}Al_{10}$ and $Zr_{64.13}Cu_{15.75}Ni_{10.12}Al_{10}$ have been studied in uniaxial compression in the temperature range 300–4.2 K. At the temperature 300 K the deformation curve has serrated (jump-like) type, caused by the propagation of narrow shear bands. At the deformation level of approximately 3–4% the catastrophic, uncontrolled failure of the specimens occurs resulting from propagation of the macroscopic shear band with a rate $\sim 10^3$ m/s, which is comparable with the sound velocity. A decrease of the temperature from 300 K down to 170 and 77 K changes the type of deformation curves from a jump-like to a smooth one. An interesting low temperature anomaly of deformation process was found: "slow" (with a rate of approximately 10^{-6} m/s) propagation of a single macroscopic shear band is observed at 170 and 77 K. When the samples are cooled to 4.2 K their macroscopic plasticity vanishes, and they undergo fracture, just as at 300 K, as a result of the propagation of the catastrophic shear band with nearly sound speed.

1. Introduction

Presently, the mechanisms of plastic deformation in bulk amorphous metallic alloys (BAMAs) are rather uncertain and provoke much disputation [1–4]. Visual observations of the surfaces on specimens deformed at room and lower temperatures show that plastic flow in BAMAs is not homogeneous: it has the stages of nucleation and propagation of shear bands [1–3,5].

We have detected a new experimental fact: the propagation velocity of the macroscopic plastic shear in the bulk metallic glasses $Zr_{64.13}Cu_{15.75}Ni_{10.12}Al_{10}$ and $Zr_{62}Cu_{15.5}Ni_{12.5}Al_{10}$ decreases by many orders of magnitude as the specimen is cooled from 300 to 170 and 77 K. This phenomenon is the subject of this paper.

2. Experimental technique

The bulk amorphous metallic alloys $Zr_{62}Cu_{15.5}Ni_{12.5}Al_{10}$ and $Zr_{64.13}Cu_{15.75}Ni_{10.12}Al_{10}$ were produced at the Institut National Polytechnique de Grenoble (France) and at the Institute for Materials Research (Tohoku University, Japan), correspondently, according to procedures described in [6,7]. The X-ray diffractograms of specimens show their fully amorphous state. The stress (σ)–strain (ε) curves are recorded under uniaxial compression of the specimens (cylinders 4 mm long and 2 mm in diameter) in a stiff deformation machine at the 3.5×10^{-4} s^{-1} initial strain-rate and T = 300, 220, 170, 77 and 4.2 K. The stress (σ) was determined as the ratio of the load to the initial cross-sectional area of a sample, and the value of strain (ε) was calculated as the ratio of the change of the length of a sample due to plastic strain to its initial length. The measurement accuracy was ±1 MPa (σ) and ±0.1% (ε). Values of the activation volume were calculated from the strain-rate sensitivity according to the relation suggested in [8] with the assumption that amorphous alloys plastic deformation has the thermally activated character.

The activation volume of the plastic deformation process was estimated at the stage of easy glide (T = 300, 170 and 77 K) by cycling the deformation rate [8]. Some specimens were unloaded before their failure so that we could investigate the changes in their shape. The lateral and fracture surfaces of the deformed specimens were investigated using a metallurgical MIM-7 microscope and a Hitachi S4800 scanning electron microscope at an accelerating voltage of 15 kV.

3. Results and discussion

Both studied bulk amorphous metallic alloys have shown the same mechanical behavior and all information in this section concerns each of them.

The typical stress–strain curves of the studied alloys taken at different temperatures are shown in Fig. 1. It is seen that at T = 300 K the σ–ε curves have practically one stage—the stage of easy glide. At this stage the plastic deformation is serrated and the lateral surfaces of the specimens have narrow shear bands. At $\varepsilon \sim 3$–4% the specimen suffers uncontrollable catastrophic failure caused by the propagation of a macroscopic shear band whose velocity ($\sim 10^3$ m/s) is comparable to the sound velocity. The failure is accompanied by an intense acoustic pulse.

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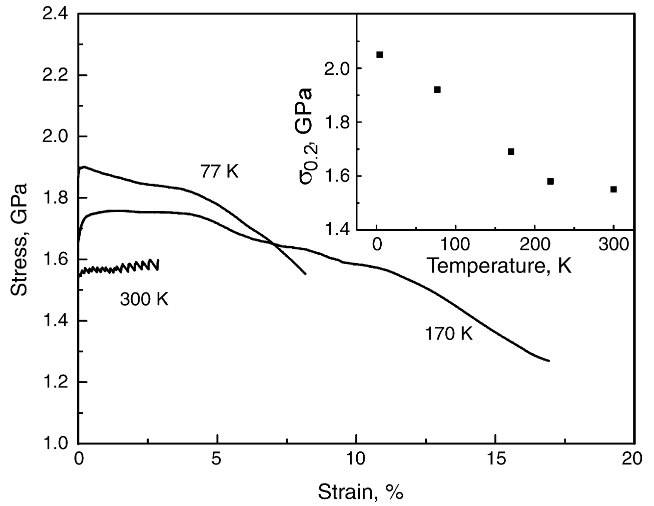

Fig. 1. Typical stress–strain curves taken at T = 300, 170, and 77 K of the $Zr_{64.13}Cu_{15.75}Ni_{10.12}Al_{10}$ bulk amorphous metallic alloy (inset: the temperature dependence of the yield strength).

The process of deformation is greatly influenced by the decrease in the temperature first to 170 K and then to 77 K (Fig. 1). The stress–strain curve becomes phased. The initial short stage with a high hardening coefficient is followed by a short plateau with a zero hardening coefficient. Then the σ–ε curve becomes smooth with no jumps in the stress. The lateral surfaces exhibit narrow glide bands making a ∼45° angle with the compression axis. On a further loading a “softening” stage appears after the easy glide region (Fig. 1). At this stage the deforming stress decreases smoothly and the strain amounts to ∼15%. The softening stage observed for the specimen under deformation corresponds to the macroscopic shear strain that is localized within one narrow band and shifts one part of the specimen relative to the other (Fig. 2). Note that the propagation of the macroscopic shear deformation is not an avalanche-type process: the shear rate within a band is not more than 2×10^{-6} m/s (see Fig. 2). It is possible to stop loading at the softening stage and unload the specimen avoiding its complete failure. By doing so, we can observe a macroscopic shear through the whole section of the specimen (Fig. 2). The view of the surface in the region of the “slow”

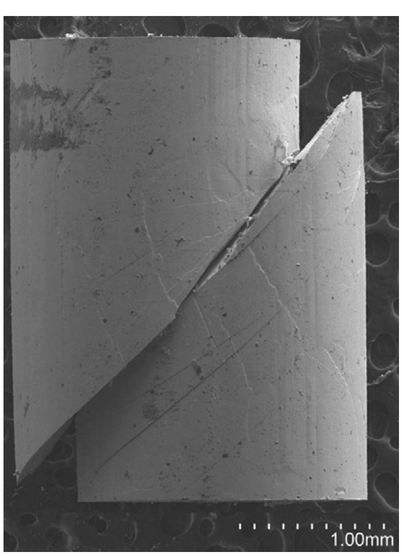

Fig. 2. The sample shape of $Zr_{64.13}Cu_{15.75}Ni_{10.12}Al_{10}$ bulk amorphous metallic alloy after deformation at T = 170 K (note: the specimen is not destroyed, the loading was stopped at $\varepsilon \sim 17\%$).

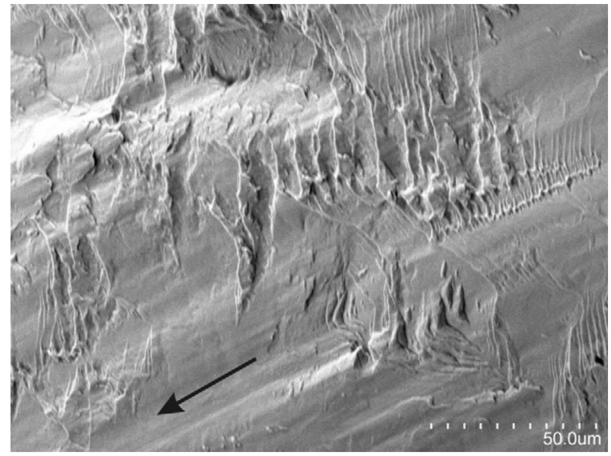

Fig. 3. Typical pattern of the specimen fracture surface after a “slow” shear, $Zr_{64.13}Cu_{15.75}Ni_{10.12}Al_{10}$, T = 170 K, (the macroscopic picture of an incomplete shear is shown in Fig. 2).

macroscopic shear (see Fig. 2) is shown in Fig. 3. The shear surface has no “vein” pattern [9] typically observable in the fracture surface of BAMA at T = 300 and 4.2 K and pointing to intensive local heating of the catastrophic shear surface in the process of the specimen failure. It is therefore reasonable to assume that no intensive heating occurs at the fracture surface of the specimens deformed at T = 170 and 77 K.

As the temperature of the experiment decreases to 4.2 K, the stage of macroscopic plastic deformation disappears from the σ–ε curve. The lateral surfaces have no narrow shear bands either. The specimens fail before reaching their yield point. The failure proceeds in an uncontrollable catastrophic way (like at T = 300 K) and the fracture surface exhibits the characteristic “vein” pattern. Note that at the temperatures used in the experiment the fracture is always along the plane making a ∼45° angle with the compression axis.

The inset in Fig. 1 shows the temperature dependence of the conventional yield strength $\sigma_{0.2}$ (the highest achievable stress is shown for T = 4.2 K). The growth of $\sigma_{0.2}$ at lowering temperature suggests that the plastic deformation in the interval 300–77 K is a thermally activated process.

The activation volume V of plastic deformation estimated at the starting stage of easy glide is about $20\,a^3$ (a is the interatomic spacing) and is practically independent of temperature within the temperature region of the experiment. The models [10,11] analyzing heterogeneous plastic deformation in BAMAs consider different physical mechanisms of the formation and propagation of shear bands but they all use practically the same value of activation volume ($\sim 10\,a^3$). For example, $V \approx (r/a)^{1/2}\, a^3 \sim 10\,a^3$ (r is the nanocluster size) in the model [10] which describes the atomic structure of BAMAs on the basis of a set of experimentally detected polyclusters and assumes that glide bands are produced by the thermally activated motion of the edge of the internal boundary between the clusters. Another model [11] assumes that plastic deformation in BAMAs is caused by the glide bands generated by thermally activated cooperative shear in the regions with excessive concentrations of free volume. In this case $V \sim 10\,a^3$. Thus, our V value is very close to theoretical estimates [10,11] and we are unable to identify the physical mechanism mainly responsible for the formation and propagation of shear bands in the process of plastic deformation in the alloy investigated.

The disappearance of the intermittent flow in the stress–strain curve observed in this study at lowering temperature was reported previously for other BAMAs [5,12,13] and discussed on the basis of the hypothesis of thermally activated structural relaxation in the region of shear deformation provoked by diffusion processes.

The new low temperature feature detected in this study, namely, the anomalous behavior of plasticity showing up as localization of deformation within one band and a drastic decrease (as against the $T = 300$ K case) in the propagation velocity of macroscopic shear may indicate that the heat dissipated at the band front has enough time to escape outwards. This allows no intensive local heating and impedes a catastrophic propagation of shear.

To explain the detected low temperature anomaly of plasticity more adequately, further experimental and theoretical investigations are necessary, in particular more detailed measurements of the rate and temperature dependences of this phenomenon would be helpful.

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