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Temperature dependence of pressure sensitivity in a metallic glass

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The constraint factor, C, given by the hardness to the yield strength ratio and an indirect measure of the pressure sensitivity of plastic flow in amorphous alloys, of a Zr-based bulk metallic glass was measured as a function of temperature. Results show that, contrary to expectations, C increases linearly from ~3.2 to 3.5 within the 300–525 K range. Gradual transition in the shear band-dominated deformation mechanism was suggested as a possible reason for the observed increase in C.

Keywords: Metallic glasses; Hardness; High temperature deformation; Shear bands; Pressure sensitivity

The pressure sensitivity of plastic deformation in amorphous alloys has been a topic of active research. After an initial uncertainty, it is now widely accepted that room temperature yielding of metallic glasses is sensitive to pressure [1]. Patnaik et al. [2] have shown – on the basis of the modified expanding cavity model developed by Narasimhan [3] – that the pressure-sensitive plastic flow in metallic glasses leads to high constraint factors during indentation. This is because the yielding of the material underneath the indenter is affected by hydrostatic stress due to the resistance offered by the surrounding elastic cavity. The constraint factor, C, is given by the ratio of the hardness, H, to uniaxial compressive yield strength, σ_y. The value of C depends on the geometry of the indenter as well as the mechanical properties of the material being indented. For amorphous alloys it ranges between 3 and 4.5, whereas it is always below 3 for crystalline metals [4]. In this paper, we examine the influence of temperature, T, on the pressure sensitivity in a bulk metallic glass (BMG) by measuring the variation of C with temperature within the inhomogeneous deformation regime.

A Zr-based BMG with a composition of $Zr_{41.2}Ti_{13.75}Cu_{12.5}Ni_{10}Be_{22.5}$ (referred to as Vit-1 here afterwards) is used in the present study. This BMG has a glass transition temperature, T_g, of 625 K [5]. Other relevant properties can be found in Ref. [5]. Three-millimeter-thick plates of 50 mm × 80 mm dimensions were procured from Liquid Metal Technologies (Lake View, CA). From these, 5 mm × 10 mm discs were cut and polished to a 1 μm finish and then glued to a copper disc that was placed on a resistive heating plate. Samples were heated to the desired temperature at a heating rate of 0.833 K s^{-1} and soaked for 300 s for thermal equilibration of the sample 500 microns below the Zircon indenter tip. A series up to 10 of Vickers indentations were performed with a loading and unloading rates of 0.0333 N s^{-1} with a 15 s hold time at the maximum load of 2 N. The indentations were separated by a distance of 0.1 mm and a time of about 120 s. In all, the specimen will be at the test temperature for up to a maximum of 1 h. After this, the imprint diagonals were measured to calculate the Vickers hardness, H. To prevent structural relaxation effects from accumulating, a fresh sample was used for each of the temperatures tested.

Variation of H within the temperature range of 300–573 K is shown in Figure 1. It is seen that H decreases approximately linearly with temperature up to ~500 K. At higher temperatures H appears to drop much faster. Lu et al. [7] measured the σ_y for Vit-1 (same alloy as that used in the present study) as a function of temperature and strain rate. They report that, within the 300–573 K range, the BMG does not show any significant strain rate sensitivity. Figure 2 shows the σ_y vs. temperature data taken from Lu et al.'s work. Like H, σ_y also decreases linearly with temperature within the 300–550 K range. Computed values of C are plotted in Figure 3 as a function of temperature. It is seen that C increases almost linearly within the temperature range of 350–550 K and then a slight decrease is noted, albeit within the scatter. The latter may be due to the fact that the temperature of testing is close to the T_g (0.9 × T_g).

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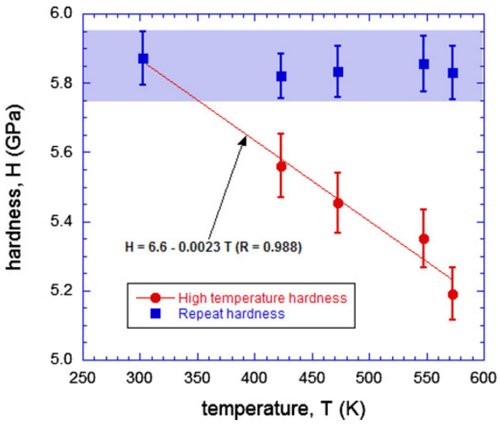

Figure 1. Plot showing the variation of Vickers hardness, *H*, with temperature. Also plotted are the room hardness values, measured after the high temperature exposure, as a function of the temperature of exposure.

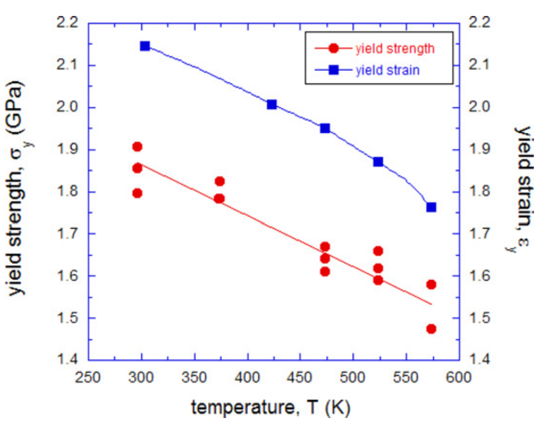

Figure 2. Variation of yield strength, σ_y, and yield strain, ε_y, as a function of temperature. The σ_y data are taken from Lu et al. [7] and the strain rate effects are neglected.

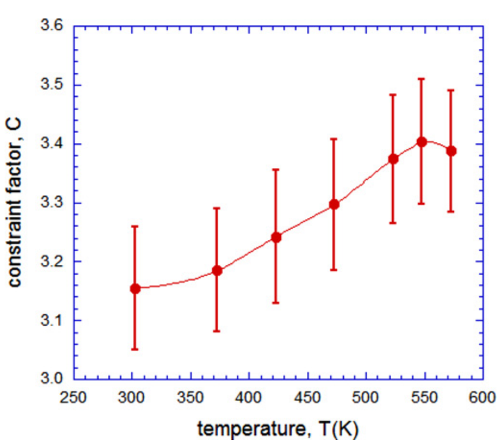

Figure 3. Variation of the constraint factor, *C*, given by the H/σ_y ratio, as a function of temperature.

However, the former, i.e. the increase in the value of *C* with temperature, which implies that pressure sensitivity to plastic flow in amorphous alloys does not decrease with temperature, is contrary to our expectations. In the following, we explore the possible reasons for this.

First, we examine the possibility that the observed increase in *C* with *T* is an experimental artifact by virtue of BMG undergoing structural relaxation at higher temperature. In order to examine this possibility, we examined the hardness values obtained at each temperature in sequence. Figure 4 shows the sequential variation of the *H* at several high temperatures. If there is significant structural relaxation, due to the exposure at high temperatures, a clear trend from indentation measurement nos. 1–10 should be apparent. However, no particular trend was observed. In addition, room temperature hardness measurements were performed on samples that were subject to high temperature hardness measurements, i.e. exposed to high temperatures. Figure 1 shows these values as a function of the temperature they have experienced prior to room temperature hardness measurements. The *H* values are similar to those measured on a sample that was not exposed to high temperatures at all. Both these observations imply that the isothermal structural relaxation that occurs while the high temperature indentation tests are being performed is not significant enough to influence the hardness values and hence the inferred conclusions of this study. This is also in accord with the observations of Murali and Ramamurty [5], who report that the room temperature hardness values of the Vitraloy-1 are invariant even after annealing for prolonged time at temperatures close to T_g. As an aside, it is worth noting that the toughness values are affected markedly due to structural relaxation although the hardness values are not [5,6].

A second possibility is related to the yield strain, ε_y. Amorphous metals exhibit pressure sensitivity because the shear transformation zones (STZs) – unit deformation processes in amorphous materials – require relatively large local dilations (vis-à-vis those required for dislocation motion in crystalline solids) and hence are influenced by both deviatoric and hydrostatic components of the stress tensor for operation [1]. This requirement of significant microscopic dilatation is also the reason for the high ε_y values (typically ~2% or more) observed in metallic glasses. It naturally follows that, with increasing temperature, STZs should be easier to

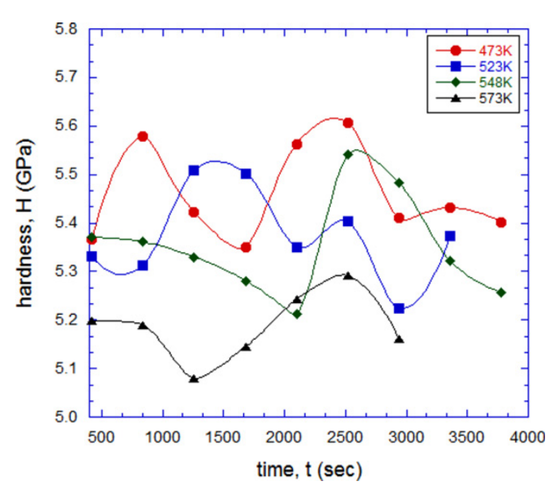

Figure 4. Sequential variation of hardness values as a function of time at temperature during high temperature indentation tests.

activate and hence ε_y should decrease. This logic leads us to the expectation that pressure sensitivity should decrease with increasing temperature. At temperatures close to the T_g, the experimental results of the current work agree with this expectation. However, the results between 300 and 550 K are contrary to this expected behavior.

In order to examine if there is a correlation between ε_y and C, the Young's modulus, E, of Vit-1 was measured as a function of temperature with the aid of a dynamic mechanical analyzer. A rectangular beam ($42 \times 5 \times 3$ mm^3) loaded in flexure was employed for this purpose and a frequency of 10 Hz was employed. The E values thus obtained combined with the σ_y data of Figure 2 were used for computing the ε_y variation with T, which is also shown in Figure 2. It is seen that there is only a slight decrease in ε_y within the 300–550 K range, whereas above 550 K, ε_y begins to drop precipitously, indicating the onset of homogeneous plastic flow. Thus, C increasing with T assumes more significance as it happens despite a reduction in ε_y. In this context, it is instructive to examine the response of crystalline metals. Kumaraswamy and Venkataraman [8] have examined the variation of C with T in Ti–6Al–4V alloy. (To the best of our knowledge, this is the only paper available in the open literature that deals with the variation of C with T.) They observe a significant reduction in C with T in the elastoplastic regime, whereas C remains invariant in the fully plastic regime. Since the Vickers hardness measurement in BMGs corresponds to the elastoplastic regime [2,4], the contrast in the C vs. T behavior of the Vit-1 vis-à-vis the Ti alloy becomes obvious.

Plastic deformation in metallic glasses at relatively low temperatures occurs inhomogeneously, through localization of flow into shear bands [1]. Examination of the indenter impression indicates a gradual reduction in the propensity for shear banding with increasing temperature. SEM micrographs of two such indentations taken at two different temperatures (423 and 573 K) are shown in Figure 5a and b, respectively. To quantify this, the total number of slip steps associated with each Vickers indent is counted and the average value of their number density, Ψ, is plotted as a function temperature in Figure 6. It is seen that there is a monotonic decrease in Ψ, reaching to less than one slip step per edge of the indent at above 550 K. We note here that our ability to image – and hence count – slip steps is a function of the slip offset on each band. There may be some shear bands with too small an offset to be effectively seen, which influences the results presented in Figure 6.

In this context, it is worth noting that the strength of a metallic glass depends only weakly on temperature (as reflected by the σ_y variation with T seen in Fig. 2) and virtually strain rate-independent within the temperature range of interest [1]. However, the character of the shear banding was reported to change in terms of the nucleation rate and the amount of strain each band carries [9]. Schuh et al. [9] demonstrate, through nanoindentation experiments as well as analytical modeling, that with increasing temperature higher strains are required to induce shear banding, all within the inhomogeneous deformation regime. This is because, at higher temperatures, STZs get triggered at relatively lower strains and

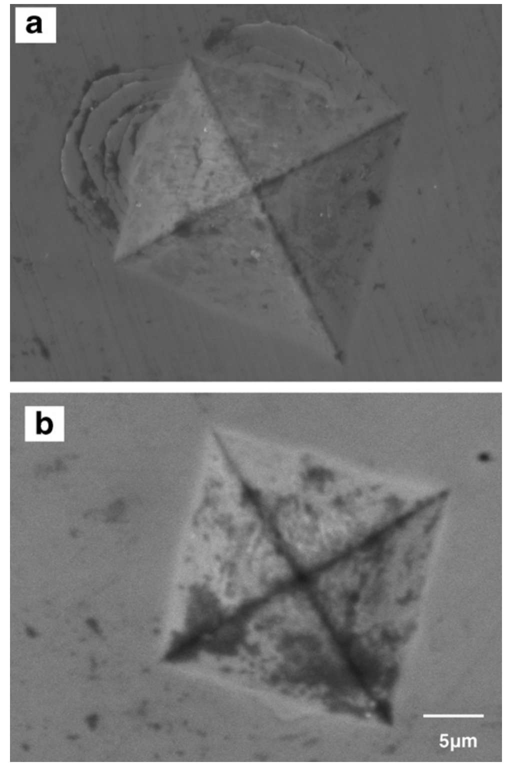

Figure 5. Typical Vickers indentation impressions obtained at (a) 423 K and (b) 573 K.

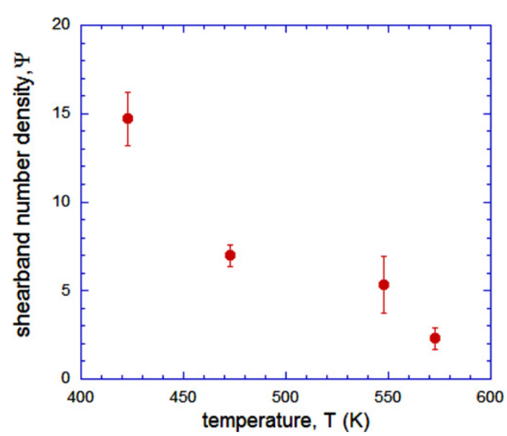

Figure 6. Variation of shear band number density (calculated on per indent basis) as a function of temperature.

hence occur in a diffusive manner, which does not facilitate shear localization. For accommodating the same amount of strain, Schuh et al. [9] predict that, at lower temperatures, there will be a higher number of shear bands but with closer spacing, which is consistent with the observations in Figure 6.

Encouraged by the above observation, we extend the predictions of Schuh et al. [9] to offer a possible explanation for the observed increase in C as follows. Plastic deformation associated with the inhomogeneous flow in metallic glasses can be divided into two distinct events: shear band initiation and shear band propagation. With increasing temperature, shear band initiation becomes relatively easier. Nonetheless, this process becomes increasingly dominant with increasing temperature, i.e. shear band propagation occurs readily. It is reasonable to assume that shear band initiation is more sensitive to the applied pressure – recall the STZ operation requires local dilation and hence is pressure sensitive. It is thus possible that the relative pressure sensitive component is likely to increase with increasing temperature. However, this possibility needs critical experimental and theoretical evaluation.

In summary, a linear increase in the constraint factor was observed in a Zr-based BMG, implying that the sensitivity of plastic flow in amorphous alloys to pressure continues – and in fact increases slightly – at high temperatures. This is despite a small drop in yield strain. We hypothesize that the retention – if not the enhancement – of the pressure sensitivity with temperature is due to a gradual transition in the dominant deformation mechanism.

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