

# A methodology to assess the energy absorption during homogeneous deformation of amorphous alloys

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Compression tests at a constant stress below the global yield were conducted on amorphous alloys at room temperature to evaluate their energy-absorbing capability during homogeneous deformation. It was found that compressive stress below the global yield imposed on amorphous alloys causes permanent deformation, which at room temperature induces irreversible structural disordering. During the disordering process, free volume was created, dissipating the externally applied mechanical energy. This paper reports a methodology for evaluating the energy-absorbing capability of amorphous alloys during homogeneous deformation. © 2008 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.

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Permanent deformation of amorphous alloys is normally achieved by the formation of shear bands when the alloy subjected to a stress higher than the global yield strength. Such a flow characteristic is known as inhomogeneous deformation. During inhomogeneous flow, shear bands form by coalescence of the locally dilated regions which occur preferentially at regions with loose atomic packing [1–5]. As shear bands correspond to those regions with comparatively open structure, they are in high energy state and thus can act as a dissipation site for the mechanical energy during inhomogeneous deformation [6].

Another type of permanent deformation exhibited by amorphous alloys at room temperature is that occurring at stresses below the global yield strength. This type of deformation is achieved in the absence of shear bands and is known as homogeneous deformation [7–9]. However, unlike inhomogeneous deformation, which is typified by the formation of shear bands, the plasticity caused by homogeneous deformation arises from structural disordering. During the disordering process, the

externally applied mechanical energy is consumed by the creation of free volume. Considering that free volume is generated as a result of atomic dilatation driven by shear stress, a dominant parameter that determines the degree of the energy absorption by the creation of free volume is thought to be the atomic binding force, i.e. the strength of amorphous alloys [10]. Therefore, alloys with higher strength can absorb more energy during homogeneous flow, since they can sustain higher stress levels before yielding.

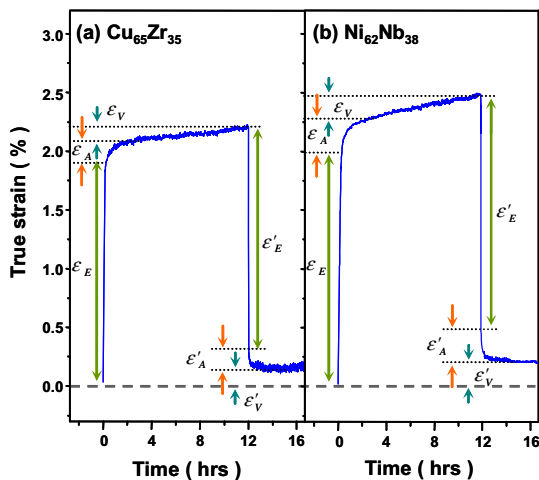
This study demonstrated that compressive stress below the global yield strength imposed on amorphous alloys at room temperature can cause homogeneous deformation. The energy-absorbing capability of alloys with different strengths were evaluated by assessing the stored energy associated with the disordering process during homogeneous deformation.

In this study, we selected two model alloys, Cu<sub>65</sub>Zr<sub>35</sub> and Ni<sub>62</sub>Nb<sub>38</sub>, with strengths of 2.3 and 3.2 GPa, respectively. Both alloys are considered to possess the highest atomic packing density [8,11,12] in the Cu–Zr and Ni–Nb binary systems, and thus to be suitable for monitoring the shear-induced dilatation caused by compression at a constant stress below the global yield strength. Ingots of Cu<sub>65</sub>Zr<sub>35</sub> and Ni<sub>62</sub>Nb<sub>38</sub> were prepared by arc

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melting under a purified Ar atmosphere and then cast into a copper molds to produce 50 mm long cylindrical rods with a diameter of 1 mm. In order to promote structural disordering, the model alloys with an aspect ratio of 2 were machined and preloaded via compression at a constant stress and room temperature for 2–30 h at the preloading level of 90% of their global yield strength. Hereinafter, this loading method imposed on the samples is referred to as “elastostatic compression”. The energy stored within the samples as a result of structural disordering was evaluated by measuring the exothermic energy released during heating below the glass transition temperature using differential scanning calorimetry (DSC, Perkin-Elmer DSC7, USA) at a heating rate of  $40 \text{ K min}^{-1}$ .

The conventional wisdom on “homogeneous” permanent deformation of amorphous alloys is that it occurs at low stresses and high temperatures (usually  $\sim 70\%$  of  $T_g$ ) [13], where diffusional processes play a key role. On the other hand, we recently demonstrated that permanent deformation of bulk amorphous alloys is also feasible even under a high stress comparable to the global yield strength and at room temperature [14,15]. Figure 1 shows the typical strain–time response measured from the two as-cast model alloys during a loading–unloading cycle of  $0\% \rightarrow 90\% \sigma_y \rightarrow 0$  at room temperature. The results clearly show that the total strain caused by the elastostatic compression consists of three strain components corresponding to elastic response ( $\epsilon_E$ ), anelastic response ( $\epsilon_A$ ) and viscoelastic response ( $\epsilon_V$ ). Of these strain components, the elastic and anelastic strains are fully recoverable upon the removal of the applied load, although their strain response differs in terms of their instant recoverability. However, the viscoelastic strain remains unrecoverable, even if the load is removed, and thus produces a permanent deformation as can be seen from Figure 1. In addition, the surfaces of the preloaded samples did not show any evi-

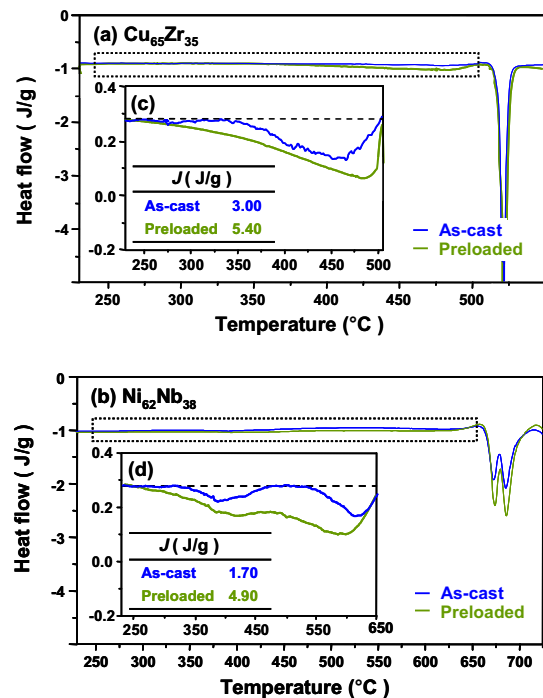


**Figure 1.** Strain responses recorded during a loading–unloading cycle at 90% of the yield strength of (a)  $\text{Cu}_{65}\text{Zr}_{35}$  and (b)  $\text{Ni}_{62}\text{Nb}_{38}$ .  $\epsilon_E$ ,  $\epsilon_A$  and  $\epsilon_V$  denote the strain components corresponding to the elastic, anelastic and viscoelastic responses measured during the loading stage, whereas  $\epsilon'_E$ ,  $\epsilon'_A$  and  $\epsilon'_V$  are the same components measured during the unloading stage.

dence of the formation of noticeable shear bands. Therefore, this permanent deformation observed during the elastostatic compression at room temperature can be regarded as being “homogeneous”. This deformation is probably caused by atomic-scale local deformation occurring uniformly throughout the whole volume of the samples [13], or by the formation of embryonic shear bands that are not observed visually at the surface of the samples [16].

Permanent deformation resulted from homogeneous flow causes atomic dilatation, resulting in the creation of free volume. The resultant dilated structure with large free volume sites corresponds to that with high energy [6], suggesting that the applied mechanical energy is stored by means of free volume within amorphous alloys. The stored energy will then be released during heating due to structural relaxation, which can be used as a basis for evaluating the energy absorbed by amorphous alloys during homogeneous deformation. Of various currently applied techniques, DSC is a practical method for evaluating the relative energy state because the exothermic heat is proportional to the energy release associated with the changes in the structural state, in particular the annihilation of free volume during heating below the glass transition temperature [17–19].

Figure 2a and b show the DSC thermograms recorded from the as-cast samples of  $\text{Cu}_{65}\text{Zr}_{35}$  and  $\text{Ni}_{62}\text{Nb}_{38}$ , which are superposed with those of samples subjected to preloading for 12 h. Figure 2c and d show the magnified views of the thermograms below the glass transition temperatures, demonstrating that the externally applied energy was stored in the preloaded samples



**Figure 2.** DSC thermograms recorded from the as-cast and preloaded samples of (a)  $\text{Cu}_{65}\text{Zr}_{35}$  and (b)  $\text{Ni}_{62}\text{Nb}_{38}$ . The insets denoted as (c) and (d) are the magnified view of the rectangular regions of (a) and (b), respectively, and correspond to the stored energy within the alloys.

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