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Towards more uniform deformation in metallic glasses: The role of Poisson's ratio

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ABSTRACT

We develop a quantitative analysis of how the plastic deformation in a metallic glass is more uniform if its Poisson ratio ν is higher. The plasticity of metallic glasses under ambient conditions is mediated by shear localized in thin bands, and can be characterized by experiments on the bending of thin plates. We extend the analysis by Conner et al. (Conner et al., *J. Appl. Phys.* 94 (2003), 904–911) of bands in bent plates to include the micromechanics of individual shear bands. Expressions are derived for the shear-band spacing and the offset on each band. Both these quantities are predicted to decrease as ν is increased. The predictions are tested against measurements on metallic glasses with a wide range of ν. Good agreement is found, supporting the new model for the shear-band spacing, and pointing the way towards more diffuse deformation, and consequently improved plasticity and toughness, of metallic glasses as ν increases toward the limiting value of 0.5.

1. Introduction

In metallic glasses (MGs), many atomic-level shear transformation zones are activated under stress, and the initial deformation is uniform. Soon, however, the deformation localizes into rather few macroscopic shear bands (SBs) that lead to catastrophic failure [1–4]. This shear localization is a key factor limiting the wider application of MGs, which otherwise can have attractive mechanical properties. There is much active research on making the plastic deformation more uniform by increasing the population density of SBs. The bending of thin plates is particularly useful for studies of SBs and their spacing, since the propagation of SBs stops as they approach the neutral plane and early catastrophic failure is avoided, permitting substantial deformability when the samples are sufficiently thin [5–8]. Bending experiments are also directly relevant for such applications as MG foams [9,10] and coatings [11].

Noting that resistance to plastic shear is proportional to the shear modulus μ, and that resistance to dilatation and cracking is proportional to the bulk modulus B, Pugh [12] in surveying polycrystalline metals suggested that the ratio μ/B should correlate with the degree of plasticity or brittleness. A low value of μ/B, equally expressed as a high value of Poisson's ratio ν, favours plasticity. The link between ν and plasticity was noted for metallic glasses by Chen et al. [13], and was explored quantitatively by Lewandowski et al. [14], who found a sharp transition: Metallic glasses show significant toughness only when ν exceeds a critical value of 0.31–0.32. This has excited interest in tuning compositions to increase ν, and in this way many tough bulk MGs have been realized [15–17].

While the critical value of ν separating plastic and brittle behaviour is important, it is equally of interest to consider the extent of plasticity. Indeed, in Pugh's survey [12], none of the polycrystalline metals failed by truly brittle fracture, and the point of interest was the correlation of ν with the extent of the plastic range. In the present work we extend considerations of this type to metallic glasses. We explore their plasticity when ν exceeds the critical value noted above. The study by Lewandowski et al. [14] suggests that away from the plastic-brittle transition, the toughness continues to rise as ν rises. Demetriou et al. [17] have shown that a metallic glass with a particularly high ν is tougher than any other. But quantification of the rôle of ν has so far been lacking.

For polycrystalline metals, quantitative analyses [18,19] following Pugh [12] consider the stress state at a crack tip and the local conditions for spontaneous emission of dislocations. In metallic glasses, in contrast, plasticity is mediated by the shear bands. Their spacing is of particular interest and, as seen in the work of Demetriou et al. [17], is very fine (i.e. the deformation is more uniform) when ν is high. The degree of plasticity of metallic

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glasses is dependent on sample size [20–22], and many aspects of this were analysed in the important study by Conner et al. [5], who derived expressions for shear-band spacing λ and shear offset Δu in bent plates. They found that both λ and Δu depend, among other factors, on ν. While adopting the essential elements of the analysis by Conner et al. [5], we now refine the derivation of λ, explore further how λ and Δu depend on ν, and test these predictions against observations on bent plates.

2. Theoretical analysis of shear-band spacing

While following the analysis by Conner et al. [5], we abandon the assumption of isotropic yielding that is usual in such analyses [5–7]. We derive the stress and strain induced by individual SBs and apply a fully self-consistent approach to derive the most probable SB spacing. We focus on the deformation typical of small MG plates under bending (Fig. 1a), showing an array of SBs that have a characteristic angle θ with respect to the neutral plane of the bent plate. Such an array of SBs, with spacing λ, is geometrically necessary to accommodate the applied strain. The SBs are analogous to mode II cracks (and indeed their evolution into cracks may be important in analysing the onset of brittle fracture) [5–7].

We define reference axes (x, y, z) as in Fig. 1b. Taking the shear offset on a SB to be Δu, the net axial extension or contraction from a symmetric pair of SBs is $2\Delta u\cos\theta$ (Fig. 1b). For most MGs under simple tension, θ is slightly greater than 45°. For small deformations, the axial strain ε_x can be decomposed into elastic and plastic components, $\varepsilon_x^{\mathrm{e}}$ and $\varepsilon_x^{\mathrm{p}}$:

$$\varepsilon_x = \varepsilon_x^{\mathrm{e}} + \varepsilon_x^{\mathrm{p}} \tag{1}$$

The distribution of axial stress σ_x through the thickness of the bent plate has the same form as $\varepsilon_x^{\mathrm{e}}$ (Fig. 1c).

Assuming that the strain field around a SB is the same as for a mode II crack, the offset at a SB in a bent plate of half-thickness h is given by:

$$\Delta u = \begin{cases} \frac{(1-2\nu)}{(1-\nu)\sin\theta}\frac{a}{R}\sqrt{a^2-(y-h)^2} & \text{if } (h-a) < y \le h \\ 0 \quad \text{if} \quad 0 \le y < (h-a)\,, \end{cases} \tag{2}$$

where R is the bending radius, and a is the projected length of the SB on the y-axis (Fig. 1c). Please see the Appendix for the derivation of Eq. (2), which starts from the analysis by Conner et al. [5]. Taking the geometry in Fig. 1b, we can express the plastic strain associated with each shear band as

$$\varepsilon_x^{\mathrm{p}} = \frac{\Delta u\cos\theta}{(\lambda/\cos\theta)} = \frac{\Delta u\cos^2\theta}{\lambda} \tag{3}$$

We limit our consideration to the case where the plate has a large width (i.e. parallel to the z axis); in that case, the bending is in plane strain with $\varepsilon_z = 0$ (and $\sigma_y = 0$). The axial stress is then given by

$$\sigma_x = \frac{E\varepsilon_x^{\mathrm{e}}}{1-\nu^2}, \tag{4}$$

where E is Young's modulus. The local strain-energy density (energy per unit volume) w in the bent plate is

$$w = \frac{(1-\nu^2)}{2E}\sigma_x^2 = \frac{E}{2(1-\nu^2)}\left(\varepsilon_x^{\mathrm{e}}\right)^2 \tag{5}$$

The total elastic strain energy W of the plate is then given by

$$W = LB\int_0^h w\,dy = \frac{LBE}{(1-\nu^2)}\left[\int_0^{h-a}\left(\frac{y}{R}\right)^2 dy + \int_{h-a}^{h}\left(\frac{y}{R} - \frac{\Delta u\cos^2\theta}{\lambda}\right)^2 dy\right], \tag{6}$$

where L is the length of the plate (parallel to x) and B is its width (parallel to z). The second integral on the right-hand side of

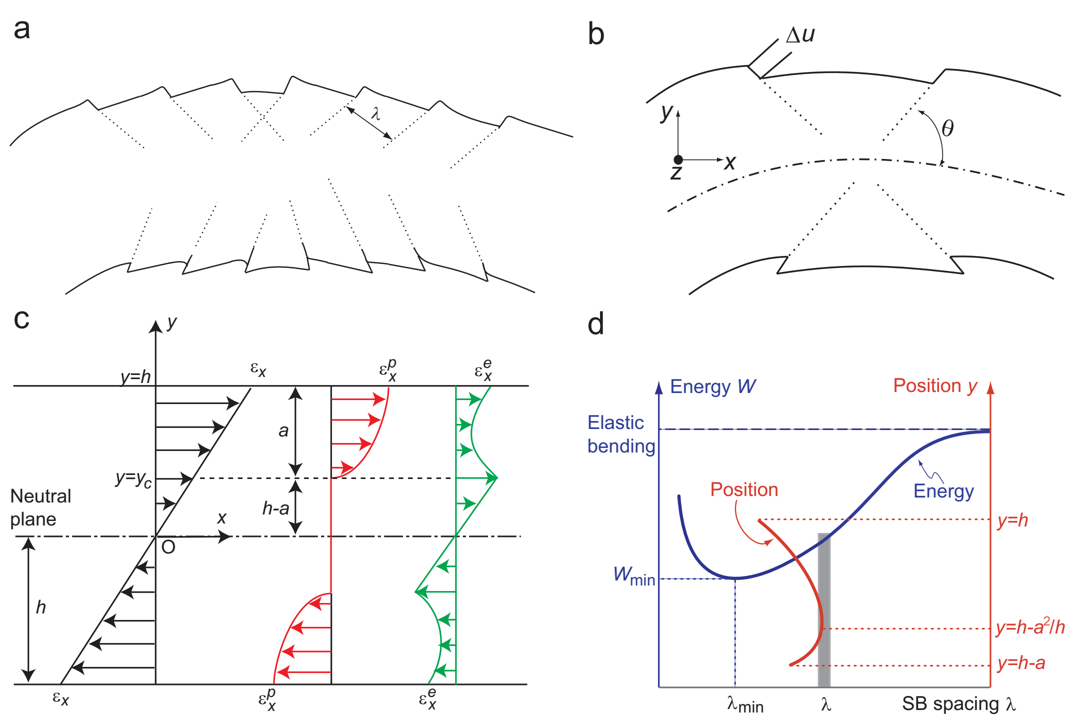

Fig. 1. The bending of a thin metallic-glass plate. a,b, the pattern of primary shear bands, showing the SB spacing λ, the shear offset Δu, and the material-dependent angle θ with the neutral plane. (c) The strain distribution ε_x through a plate of thickness $H = 2h$, decomposed into plastic $\varepsilon_x^{\mathrm{p}}$ and elastic $\varepsilon_x^{\mathrm{e}}$ components. Plastic relaxation by discrete SBs gives a stress distribution differing from that if isotropic yielding is assumed. The axial elastic strain and axial stress share the same profile (in green) because of the linear correspondence between these two. d, The competition between strain energy (favouring small λ, Eq. (8)) and the critical shear stress for SB formation (no less than the maximum critical value of λ, varying with y according to Eq. (12)). These two factors determine that the most probable shear-band spacing is in the shaded region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)