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Multiple shear band formation in metallic glasses in composites

Y. LENG, T. H. COURTNEY
Department of Materials Science, University of Virginia, Charlottesville, Virginia 22901, USA

Multiple shear banding is observed in metallic glasses during tensile deformation of laminated composites containing such glasses. The phenomenon is related to (1) the local stress concentration that develops as a result of the formation of the first shear band, (2) the distribution in stress required to initiate shear banding in tensile loading, and (3) the properties of the surrounding matrix. The tendency for localized and uniform multiple shear banding has been determined. This was done by utilizing a finite element method (FEM) to simulate the local stress state in the vicinity of the shear band first formed, and by determining the distribution in shear band initiation strengths. The experimental data were combined with the FEM analysis to "predict" locations of secondary shear band initiation. Localized secondary banding is predicted for large initial slip displacements, whereas uniform banding is expected when the initial slip displacement is small.

1. Introduction

As is well known, tensile ductilities for metallic glasses are limited by virtue of the instability accompanying shear band formation in them [1]. The highly localized deformation associated with a shear band in concert with the lack of work hardening within a band leads to failure following propagation of the first (and only) shear band formed during tensile loading. Recent work [2, 3] has shown that multiple shear bands are formed during tensile deformation of metal–metallic glass laminates. In these studies, nickel-based metallic glass ribbons were "sandwiched" between copper or brass sheets, and then deformed in tension. Tensile ductility of the glass in the composite was enhanced by this arrangement, and was a consequence of multiple shear bands formed in the glass. Evidently the constraint and reinforcement provided by the matrix prevent catastrophic failure of the glass and/or provide a stress state conducive to formation of secondary bands.

As mentioned, multiple shear banding of glasses in composites has been observed in two studies. However, the spatial distribution of the secondary bands was different in the investigations. In the work of Alpas and Embury [2], the secondary bands were reasonably uniformly distributed along the length of the glass. On the other hand, the multiple banding found by Leng and Courtney [3] generally occurred in regions in close proximity to the primary shear band.

This paper discusses the phenomenon of secondary shear bands in laminated composites, and the locations in which such bands are apt to be formed. It is believed that the phenomenon is controlled by two factors. One, inherent to the glass, is the distribution in stress required to initiate shear bands in it. The other factor is related to the local stress state developed in the vicinity of the initial shear band. This stress state depends directly (and weakly) on the strength of the adjoining matrix, and indirectly (perhaps strongly) on this strength as it may influence the offset (i.e. strain) of the first shear band formed. These points are elaborated on in Section 3. First, a description is given of a finite element analysis applicable to composites of the type previously studied [3]. The analysis is useful for defining the stress concentration, which develops as a result of band formation, in the vicinity of the first shear band.

2. Results

The influence of stress concentration and shear band strength distribution on the tendency for multiple shear band formation are considered separately. As noted, the finite element analysis is directly appropriate to a composite studied previously [3]. The composite consists of a nickel-based metallic glass (MBF-35, composition $Ni_{91}B_2Si_7$, Allied Signal Corporation, thickness = 0.038 mm) sandwiched (via a thin layer of eutectic Pb–Sn solder) between brass sheets (thickness = 0.2 mm). Details relevant to processing of the composite are provided in [3].

2.1. Finite element analysis

A photograph of a metallic glass in which multiple shear bands have been formed during tensile loading of a composite is given in Fig. 1 [3]. A schematic drawing of the situation following the formation and propagation of the first shear band is given in Fig. 2, which indicates slip in the band is constrained by the surrounding matrix. This results in a stress concentration in front of the band which facilitates the formation of a secondary band. The magnitude of the stress concentration and its spatial variation, as well as the

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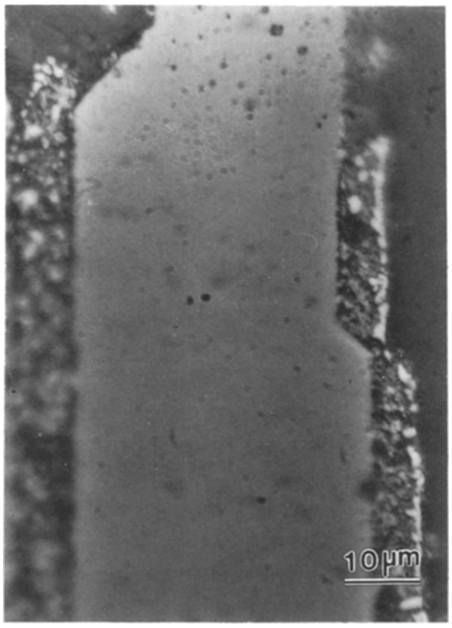

Figure 1 Photomicrograph of a metallic glass ribbon near the tensile fracture surface in a metal–metallic glass composite. In this case fracture is accompanied by the formation of multiple shear bands situated in the vicinity of the fracture surface.

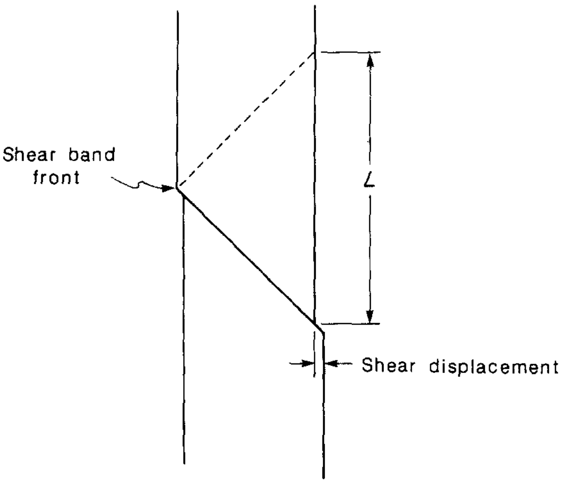

Figure 2 Schematic illustration of initial shear band formation in a laminated composite. The shear band front propagates to the left side of the glass. The resulting displacement causes a stress concentration in the front vicinity.

distribution in the shear band initiation stress of the glass, determines whether the secondary band is formed in the immediate proximity of the first band or is found in a region removed from it.

To evaluate the stress state in the vicinity of the first band, an elastic–plastic finite element analysis was conducted with ANSYS finite element codes. Appropriate meshes (Fig. 3) were stipulated to simulate the composite in a longitudinal section in the vicinity of a shear band. The tensile axis is vertical in Fig. 3, and the first-formed shear band is represented by four parallelogram elements. Because the angle of inclination of observed shear bands is at 35° to 55° to the tensile axis, a 45° inclination was chosen for the simulation. Element sizes of 0.01 mm × 0.01 mm were used in the vicinity of the shear band. For computational efficiency, element sizes were chosen to increase with distance from the shear band. The first shear band was simulated by treating it as a "special" section of the glass which has a lower yield stress than the remaining glass elements; the first band also manifests perfect plasticity (i.e. it does not work harden).

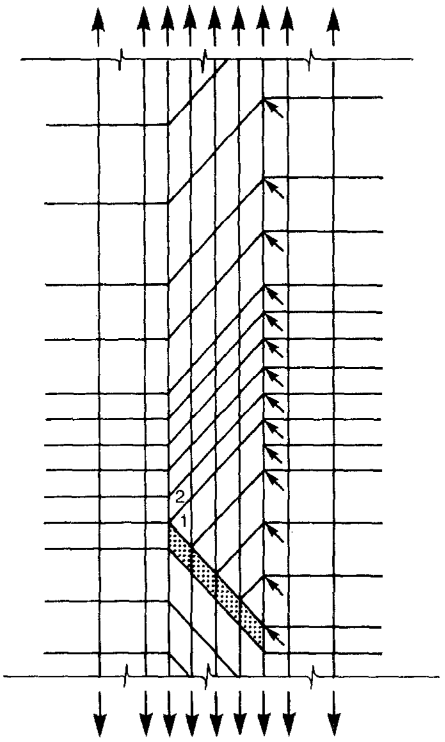

Figure 3 Schematic illustration of displacement input in FEM mesh to simulate shear band slip. The four central column meshes constitute the metallic glass. One adjacent column to each side represents the solder; the remaining column meshes represent the brass.

The meshes were first extended uniaxially along the vertical direction. The first shear band was presumed to initiate at a tensile strain of 1.3% (which corresponds to a tensile stress of 1820 MPa, a value appropriate to the glass studied experimentally (see Section 3 and [3]). To simulate shear band slip, displacements along the slip direction were input to the bonding material (the solder) interface nodes as illustrated in Fig. 3. Such displacements "punch" the glass ribbon to the left, and stress concentrations occur at the opposite side of the ribbon due to the matrix constraints. More details of the finite element modelling are provided in [4].

Results of the FEM analysis show that, as expected intuitively, the shear band front (elements 1 and 2 in Fig. 3) experiences the highest stress. Fig. 4 plots the resulting stress concentration factor (normalized in terms of the yield stress of the first formed band) as a function of the yield strength level of the brass matrix and for several initial slip band displacements. As indicated in this figure, the stress concentration depends weakly on the matrix strength level, but increases rapidly with increases in the initial displacement.

2.2. Shear band strength distribution

Localized shear band deformation is attributed to internal defects, such as dislocations and free volume,

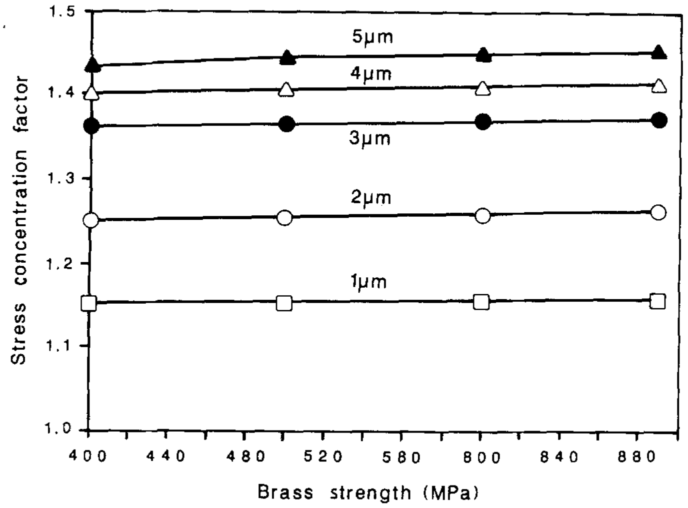

Figure 4 Stress concentration factors (normalized in terms of $\sigma_0 = 1820$ MPa) at the first shear band front as a function of the matrix yield strength and for several shear slip displacements. The stress concentration weakly increases with matrix yield strength, but is a sensitive function of the initial slip displacement.

in metallic glasses [5–7]. Although such defects have not been observed experimentally, considerable indirect evidence supports their existence [8]. The presence of such defects is central to a description of the mechanical characteristics of metallic glasses. A glass can be considered to possess a randomly spatially varying concentration of such defects, the effectiveness of which in catalysing shear band formation can also reasonably be assumed to be variable. As a consequence, a metallic glass ribbon can be considered composed of a large number of potential shear bands that, due to varying defect densities and configurations, manifest different shear band formation strengths. This distribution is important in defining the conditions for secondary shear band initiation.

Using simple bend tests, we determined such a distribution for the metallic glass used in this study. Glass ribbons (about 3 cm long) were bent between the platens of a micrometer. Tensile strains were estimated via the following equation (applicable for uniform macroscopic deformation, see following discussion)

$$\varepsilon = t/(d - t) \tag{1}$$

In Equation 1, d is the platen spacing (which is measured precisely) and t is the ribbon thickness. The bent area of the ribbon was examined via scanning electron microscopy, and the number of shear bands on the ribbon surface counted. Fig. 5 illustrates the appearance of the shear bands for two different strain levels. Fig. 6a is a graph of shear band density (per micrometre of ribbon length) against strain. Knowledge of the modulus allows the shear band density to be plotted against stress for an elastic ribbon (Fig. 6b). The conversion to the stress distribution is valid only in the low strain region where total plastic deformation is limited and in which a constant radius of curvature of the ribbon is maintained along its length while it is being bent. However, the low stress (strain) region is of most consequence for this work in which we are concerned with the initiation of secondary bands as a result of stress concentration effects.

The shear band strength distribution can be described by a modified Weibull distribution expressed as

$$P(\sigma) = 1 - \exp\left[-\left(\frac{\sigma - A}{B}\right)^m\right] \tag{2}$$

In Equation 2, $P(\sigma)$ is the probability of "failure" at the stress σ, A represents a lower stress below which failure does not occur, and B and m are material constants determined by curve fitting. Thus, according

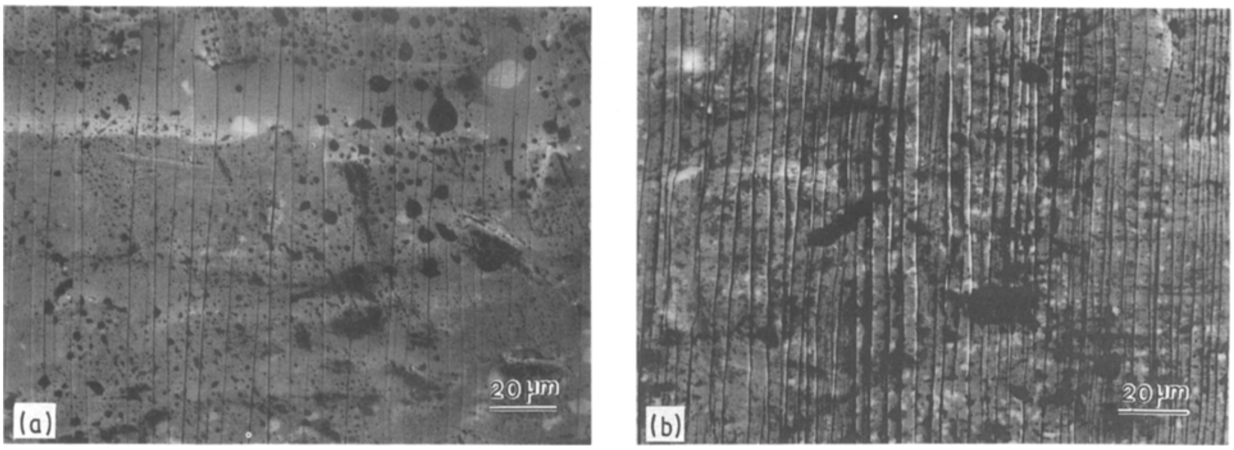

Figure 5 Scanning electron micrographs of surfaces of metallic glass ribbons bent to different radii of curvatures; (a) $d = 2.0$ mm, (b), $d = 1.3$ mm, cf. Equation 1. Increasing strain results in a greater shear band density. Shear band density measurements allow determination of a function describing the shear band stress distribution.

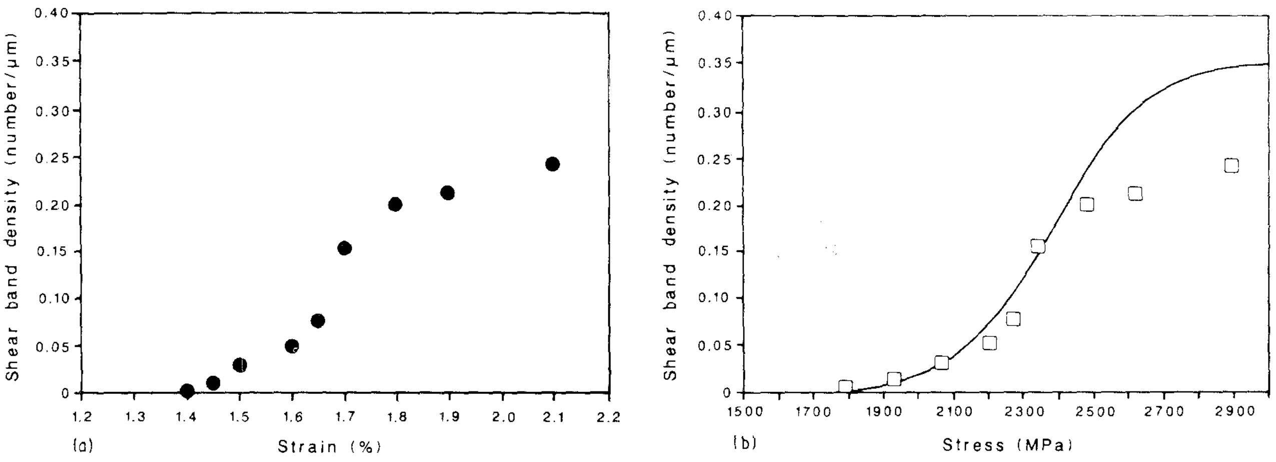

Figure 6 (a) Shear band density (number per micrometre of length) as a function of strain calculated via Equation 1. (b) Knowing the glass modulus, the distribution of (a) can be converted to a distribution in stress. The solid line represents the modified Weibull function, Equation 3. This function describes the data well in the low stress region where the (elastic) conversion from strain to stress is most accurate.

to this scheme, the shear band density distribution can be written as

$$D(\sigma) = K\left\{1 - \exp\left[-\left(\frac{\sigma - A}{B}\right)^m\right]\right\} \quad (3)$$

where D (σ) is the shear band density at the stress σ. Curve fitting of the data of Fig. 6b yields $K = 3.52\ \mu\mathrm{m}^{-1}$, $A = 1600$ MPa, $B = 860$ MPa and $m = 4.5$. The solid line drawn in Fig. 6b represents Equation 3 using these values for the several parameters. As can be seen, the deviation between Equation 3 and the experimental data increases at higher stresses because the conversion of strain to stress which was used overestimates the stress at the higher strains. We note that Equation 3, derived from bending tests, may not be a fully accurate representation of shear band strength distributions appropriate to tensile loading. At worst, Equation 3 might be in error by a factor of two because only one side of a ribbon is subjected to a tensile stress in bending, whereas both sides of a ribbon are so stressed in a tension test. However, we also feel that no modification is called for because, as shown in Fig. 2, the first shear band slip produces a stress concentration on one side of the ribbon only. Thus, in this respect, the situation is similar to a bend test. Therefore we use Equation 3 in the form given above in the following analysis.

3. Analysis

As Fig. 2 indicates, formation and propagation of the first shear band is likely to initiate a secondary shear band in the immediate vicinity. We have used the results of the FEM analysis (i.e. Fig. 4) and Equation 3 to calculate probabilities of secondary shear band formation in the proximity of the first. We have defined "proximate" as being within a distance of 10 μm from the first. This distance corresponds to the length of elements 1 and 2 used in the FEM, which showed these to be the regions experiencing the highest stress concentration. The probability is expressed as the likely number of shear bands in the stated length, and is found by knowing the stress concentration (i.e. Fig. 4) and the distribution in shear band initiation strengths (i.e. Equation 3). The most likely number of shear bands at this first "shear front" is plotted against the yield strength level of the brass for several stipulated shear displacements in Fig. 7. Because the probability depends directly on the stress concentration, the probability is, as is the stress concentration, a weak function of the brass' strength and a fairly strong one of the initial displacement. Large displacements ($\gtrsim 3$ μm) most likely lead to secondary bands forming in the vicinity of the first. This is consistent with previous experimental observations [3]. Uniform shear band distributions are more likely

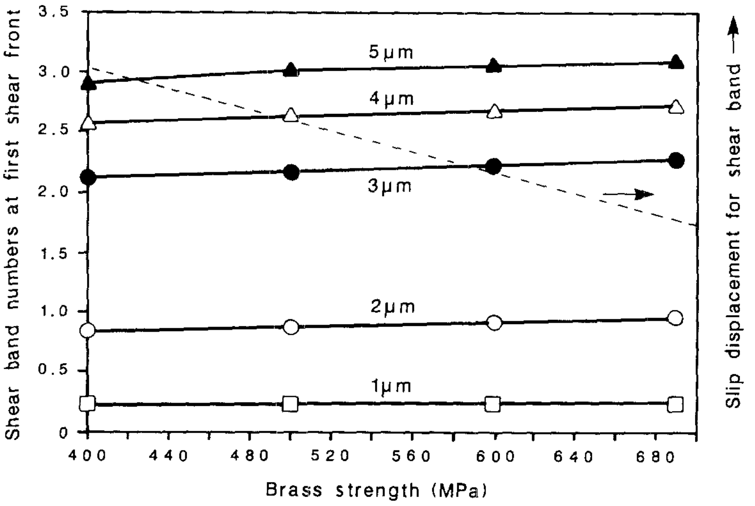

Figure 7 The probability of shear band initiation at the first shear band front as a function of matrix yield strength and for several initial slip displacements. The probability is represented as the most likely number of shear bands within 10 μm of the shear band front. The probability of a shear band initiating at the front increases (slightly) with increasing matrix strength, but is a more sensitive function of initial slip displacement. It is expected that the latter should decrease with increasing matrix strength. The dotted line indicates this possibility.

(as in [2]) when the first displacement is $\gtrsim 2\ \mu m$ (about 5% of the ribbon thickness).

While Fig. 7 indicates that matrix yield strength has a nominal effect on the propensity for secondary shear band formation, we caution it may well influence the slip displacement length which we have taken as an independent parameter. In particular, a higher yield strength matrix may result in lesser initial slip displacements of the glass as a result of the greater constraint provided by a higher strength matrix. We have qualitatively indicated the "sense" of this effect with the dotted line in Fig. 7, which indicates that the slip displacement should decrease with increasing matrix strength. In closing, we note it is reasonable that either localized or uniform secondary shear banding may be observed in composites of the type we are considering, because the probability of secondary yielding is sensitive to relatively small changes in the geometry characterizing flow in the shear band formed initially.

4. Conclusions

The geometry of multiple shear banding in metallic glasses in laminated composites is controlled by the local stress state and the stress distribution describing shear band yielding. In the work presented here we have shown that finite element modelling, combined with knowledge of the aforementioned distribution, provides a useful semiquantitative description of the geometrical characteristics of secondary banding. One deficiency of our work is the inability of the analysis, in its current form, to couple matrix strength levels to the geometry attendant with the initial shear band displacement. A more refined analysis could improve the predictive capabilities of the present treatment.

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