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Development of slip bands in a nickel-based metallic glass

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The initiation and development of slip bands were analysed using scanning electron microscopy (SEM) and by bending resistance tests. The results of the SEM analysis and the bending resistance tests indicate that the generation of slip bands and their subsequent development are responsible for an erratic increase in resistance due to plastic deformation. A physical argument is presented that this increased resistance is the result of restricted electron motion due to the deformation processes. To facilitate slip band development, a generation of free volume is believed to occur at the base of a slip band. Finally, it is considered that slip nucleates due to a decreased shear resistance resulting from a disordered structure at the base of a slip band.

1. Introduction

It has been well established that the first indications of observable plastic deformation of metallic glasses are the initiation and development of slip bands [1, 2]. However, the slip mechanism is not clearly understood. Polk and Turnbull [2] proposed that the slip mechanism was related to a decreased shear resistance that resulted from a destruction of the compositional and/or structural short range order (SRO) by plastic deformation. Pampillo [3] found that slip bands were preferentially attacked by chemical etching, which indicated that a different chemical potential existed within the slip bands. Another explanation by Leamy *et al.* [4] suggested that plastic flow was a result of adiabatic heating due to plastic deformation.

Other suggestions for the slip mechanism are based upon generalized dislocations. Li [5] proposed that slip nucleates heterogeneously at surface irregularities or excess volume concentrations, and that the slipped area is a Somigliana dislocation. More recently, Zielinski and Ast [6] proposed that a slip band can be modelled as a distributed pile-up of Volterra edge dislocations.

Furthermore, other theories have been proposed for plastic deformation and flow involving transition state theory and recovery processes. Argon [7] presented a theory of plastic deformation based upon two modes of thermally activated shear transformations initiated around free volume regions under an applied shear stress. Spaepen [8] proposed a microscopic mechanism for steady state inhomogeneous flow based upon a dynamic equilibrium between stress-driven creation and diffusional annihilation of structural disorder. Finally, Perez [9] presented a theory of plastic deformation that is principally dependent upon the recovery processes (implying atomic diffusion) which occur after the shear microdomains are formed.

This paper presents a study of the initiation and development of slip bands in a nickel-based metallic glass by bending, and includes a scanning electron microscopic (SEM) analysis and bending resistance tests, to gain a better understanding of the slip mechanism.

2. Experimental procedure

2.1. Specimen preparation

A melt spun $Ni_{92.24}Si_{4.5}B_{3.2}C_{0.06}$ metallic glass was supplied by Allied-Signal Corp., and was verified to be amorphous by X-ray diffraction. The cross-sectional area had a width of 13 mm and a thickness of 76 μm. Ribbons were cut into lengths of 25 mm, and these ribbons were then cut to approximately 6 mm widths. The edges of these ribbons were polished by sandwiching the ribbon between two plexiglass plates, resulting in a final width of approximately 5 mm. After removal of the plexiglass plates, the specimens were annealed in a tube furnace at specific temperatures for 30 min. During the annealing process, argon was passed over the specimens to prevent oxidation. After the anneal, each specimen was quenched to room temperature using acetone. These ribbons were then cleaned using soap and water and then sonically cleaned in freon to remove any residues.

2.2. Scanning electron microscopy

A special stage mounted on a Jeol JSM-35CFII scanning electron microscope was used in compression to bend 5 mm wide metallic glass ribbons into hairpin configurations. The tensile ribbon surface was examined for slip band development at an initial bending diameter of 20 mm. The bending diameter was reduced by 1 mm increments to 6 mm, and below this value, the bending diameter was reduced at desired increments which were less than 1 mm. At each reduced bending diameter, the ribbon surface was examined for slip band initiation and development. Once slip band initiation was found, the corresponding bending diameter was labelled as the threshold bending diameter.

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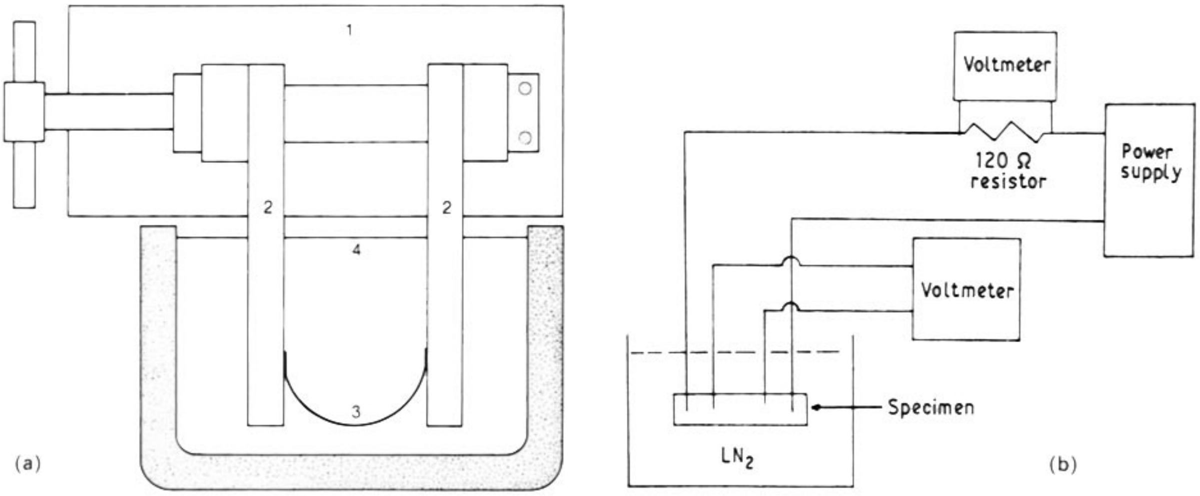


Figure 1 Bending resistance measurements were made using (a) a bending resistance device and (b) a schematic illustration of the resistance measurement apparatus. 1, Fixed vice; 2, aluminium bars; 3, specimen; 4, liquid nitrogen.

2.3. Bending resistance tests

The bending resistance tests are a modification of a four-point resistivity method that allowed the transient changes in resistance to be measured during a bending procedure. The bending resistance device and a schematic illustration of the resistance measurement apparatus are shown in Figs 1a and b. Copper wires were spot welded to as-quenched ribbon specimens with a length of 55 mm and a width of 5 mm. Each specimen was mounted in plexiglass fixtures which constrained the ribbon allowing deformation to occur only in the radius of curvature. The plexiglass fixtures were attached to aluminium bars approximately 260 mm long, so that the bending procedure could be performed in a bath of liquid nitrogen. The aluminium bars were fixed to the faces of a precision vice, which controlled the bending procedure with a precision of ± 1 mm. A constant current of 100 mA flowed through the specimen and the resulting voltage change was measured as the bending diameter was decreased. The bending diameter was initially 20 mm and was decreased in desired increments until fracture occurred or the spacing could not be reduced any further. For all bending experiments, the specimen and the copper wires were completely submerged in a bath of liquid nitrogen.

3. Results

3.1. Scanning electron microscopy

A representative sequence of micrographs shows the initiation and development of slip bands in a nickel-based metallic glass ribbon (Figs 2 to 5). The initiation of slip bands corresponds to a critical bending diameter or a threshold bending diameter that distinguishes a ribbon with localized inhomogeneous slip from a ribbon without slip.

Slip bands were found to initiate in the middle of the tensile surface, near the top of the radius of curvature (Fig. 2). Also, the slip bands were not observed to propagate instantaneously across the ribbon width, but rather in quasi-equilibrium spurts. That is, the slip bands could continue to propagate only after enough energy was supplied by the bending stresses, which resulted in the slip bands reaching the edge of the ribbon at different times.

With a decrease in the bending diameter, the slip band concentration and the slip band height increased (Fig. 3). Upon a further decrease in the bending diameter, an area or region near the top of the radius of curvature deformed into a point or an apex (Fig. 4). It is in this localized region that other forms of slip developed (Fig. 5), such as secondary slip, i.e. the branching of new slip bands from existing primary slip bands, and sub-slip which is the formation of slip bands between the primary slip bands. These additional forms of slip were characteristic of the apex region only, and are believed to develop due to a geometrical constraint.

3.2. Bending resistance tests

The results of the bending resistance tests are shown

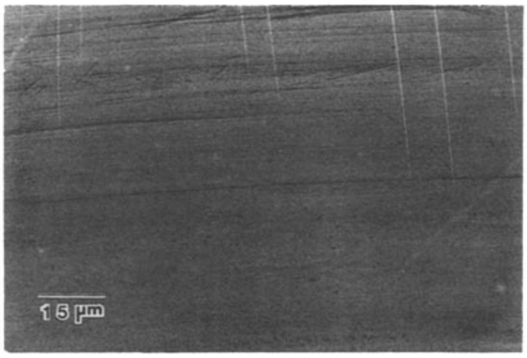


Figure 2 The initiation of slip bands at the threshold bending diameter, that distinguishes a ribbon with localized inhomogeneous slip from a ribbon without slip.

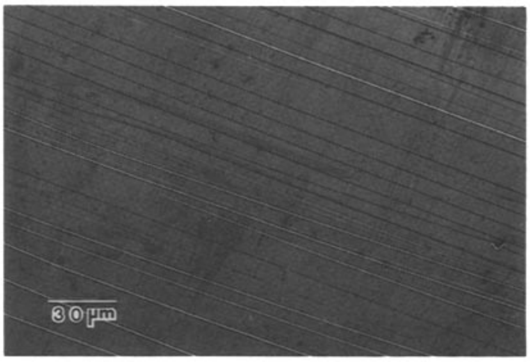


Figure 3 Increased slip band height and concentration as a result of increased deformation.

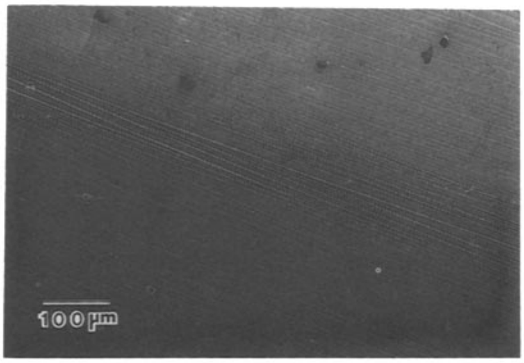


Figure 4 Development of the highly localized region of plastic deformation.

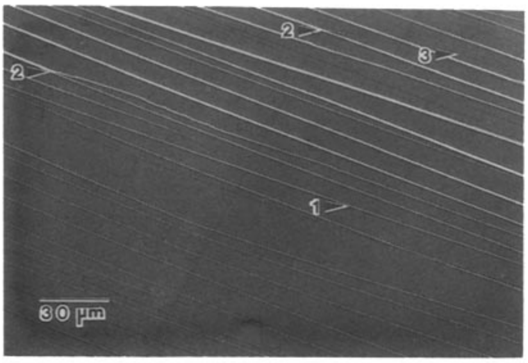


Figure 5 Region of additional forms of slip bands showing (1) primary slip bands, (2) secondary slip bands and (3) sub-slip bands.

for an as-quenched ribbon, and for a ribbon annealed at 200° C, in Figs 6 and 7, respectively. The general response of the change in resistance showed a non-linear increase with a decrease in the bending diameter and, at small bending diameters, the resistance showed an erratic increase. It was observed that these small bending diameters corresponded to the threshold bending diameter which is the critical bending diameter for the initiation of slip bands. This suggests that the erratic increase in resistance was produced by slip-band initiation and subsequent development.

When the bending resistance curves were fitted to a polynomial curve (Fig. 8), it was supposed that a linear increase in resistance was produced by elastic deformation and an erratic non-linear increase in resistance is due to plastic deformation. In addition, it was found that annealing shifted the change in resistance to higher values.

4. Discussion

The results of the SEM analysis and the bending resistance tests indicate that the initiation of slip bands and their development are responsible for the increased erratic resistance.

4.1. Elastic deformation

During elastic deformation, particular regions of the ribbon are not able to conduct electrons efficiently due to a shorter mean free path for electron motion, such that there is restricted electron flow through an essentially reduced cross-sectional area. As the bending stresses are increased, electron motion is further restricted and the resistance increases. This corresponds to the linear increase in resistance due to elastic deformation in Figs 6 and 7 at approximate bending diameters of 6 and 7 mm, respectively.

A calculation of the mean free path of the electron reveals that the mean free path is less than the specimen thickness. Therefore, the electron is able to discern between high and low regions of conductivity, and find the easiest path.

4.2. Plastic deformation

At the threshold bending diameter, when slip bands are initiated, the conductivity should show a further decrease due to a combination of a reduced physical cross-sectional area and a restricted electron motion due to a shorter electron mean free path resulting from the disordered material in the slip bands. Also, when slip bands initiate and develop, the slipped region is assumed to be essentially of infinite resistance. As the slip band concentration and slip band height increase with deformation, the resistance increases and becomes erratic which is shown in Figs 6 and 7 at approximate bending diameters of 6 and 7 mm, respectively. It is believed that the stress concentration produced at the base of a slip band increases the local stress level. This locally higher stress should increase the atomic

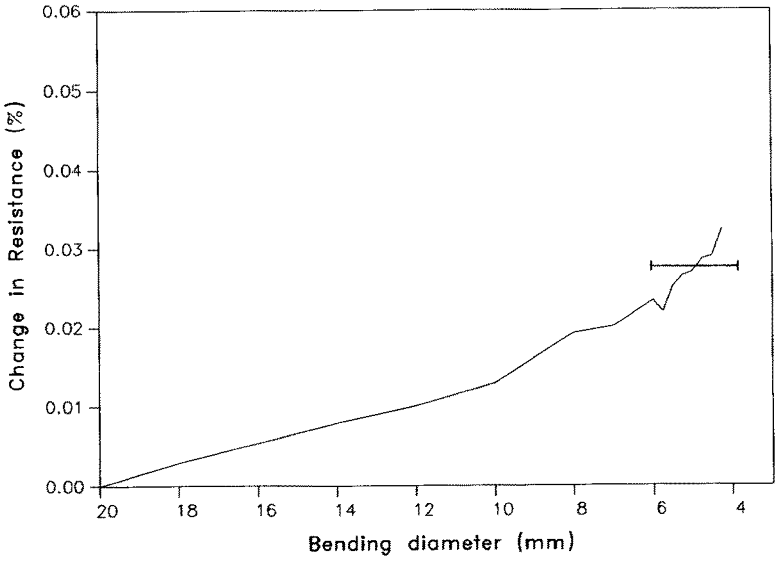


Figure 6 Change in resistance due to bending of a ribbon in the as-quenched state showing an erratic increase (——) in resistance in the range of slip-band development.

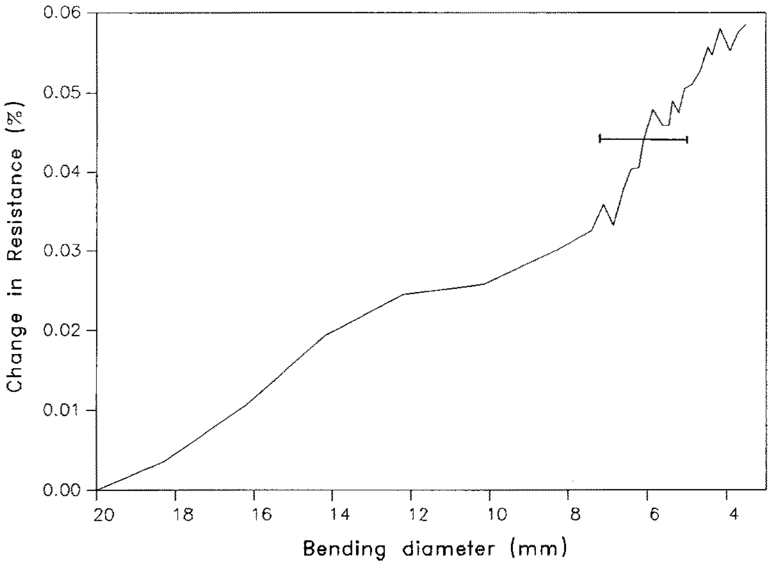


Figure 7 Change in resistance due to bending of a ribbon with a heat treatment of 200° C showing an erratic increase (|——|) in resistance in the range of slip-band development.

spacing and lead to more atomic disorder at the base of the slip band which would further inhibit the electron conduction.

4.3. Slip-band development

The supposition that resistance changes are a result of restricted electron motion due to deformation leads to a possible understanding of the slip mechanism and the subsequent generation of slip. It has been proposed that slip bands are initiated at the ribbon surface due to surface irregularities [10] and/or excess volume concentrations [5]. In the present argument, under an applied bending load, the largest normal and shearing stresses occur at the ribbon surface. When these stresses are increased by stress concentrations resulting from the surface irregularities and/or excess volume concentrations, the material reaches its yield strength in a localized region which initiates slip. Once slip is initiated, the slip band can be defined as either a Volterra dislocation or a Somigliana dislocation (Fig. 9), depending upon the variance of the slip vector [5]. The slip band observations in this study indicate that the slip vector is not constant, suggesting that the slip mechanism in a metallic glass may be modelled as a Somigliana dislocation which was proposed by Li [5]. The observation that slip is capable of developing extensively before fracture, indicates that metallic glasses are capable of plastic deformation, and therefore there is a flow mechanism involved. The flow of atoms involves the movement of atoms from a source (excess volume) to a sink (free volume). In a metallic glass, free volume is already abundant, but the flow of atoms to this existing free volume is restricted due to inhomogeneous deformation. Therefore, free volume other than the existing free volume needs to be produced, or existing free volume needs to be increased, to provide a sink for atomic flow within the locally deformed region. A process by which this may occur is due to a stress concentration at the base of a slip band that locally increases the atomic spacing (Fig. 10).

Li [5] proposed a diffusionless transfer of excess volume involving the driving force of an applied stress. In the case of bending, the developed shear stresses could supply or drive atoms to regions of free volume. Because the stress is greater at the top surface of the ribbon, the free volume creation and/or expansion would occur there first. The transfer of atoms to fill this region would then create new regions of free volume within the bulk material. With continued

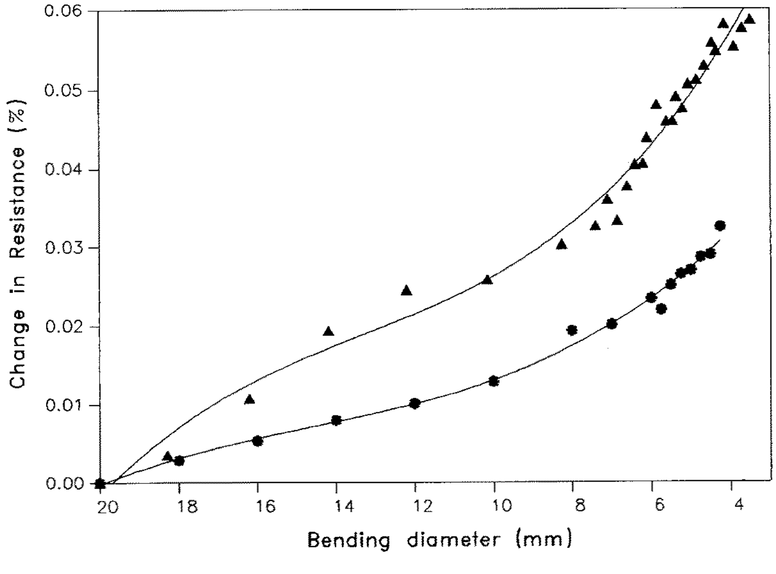
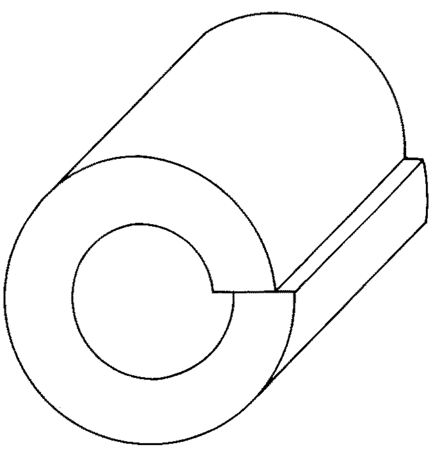
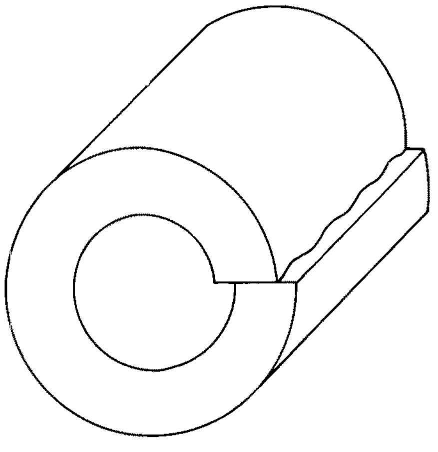


Figure 8 Comparison of resistance changes with a polynomial curve fit, showing a non-linear increase in resistance. Heat treatment: (∗) as-quenched, (▲) 200° C.



Volterra Dislocation



Somigliana Dislocation

Figure 9 Illustrations of generalized dislocations showing a Volterra dislocation with a constant slip vector, and a Somigliana dislocation with a variable slip vector.

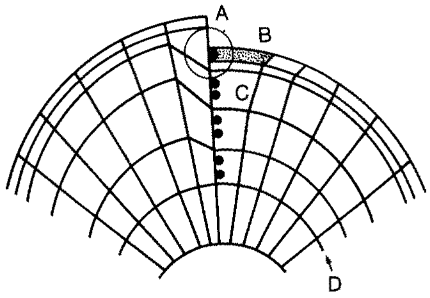


Figure 10 An illustration of the creation of excess volume that results from a stress concentration located at the base of a slip band at A, which increases the stress that locally increases the atomic spacing shown at B. A result of plastic flow is the formation of internal regions of excess volume that may lead to the veined pattern fracture shown at C. The neutral axis corresponds to D.

deformation, the above process would be repeated, which could continue the flow process. This creation of free volume within the bulk material may explain the vein pattern fracture that commonly appears on fracture surfaces, which is believed to result from a decreased viscosity [4, 10] or the initiation and growth of shear discs or cracks that result in internal necking [11, 12]. In the case of a decreased viscosity, the disordered structure at the base of the slip band may be sufficiently disordered to decrease the glass transition temperature locally, such that adiabatic heating occurs which decreases the local viscosity resulting in the viscous fracture. On the other hand, the regions of vacancies distributed through the thickness may develop into shear discs or cracks which could continue to grow together under the applied stresses and lead to internal necking.

In addition this argument suggests that slip is continued essentially within itself. That is, once slip is initiated, it becomes easier to promote slip along that plane. It is noticed that the structure is distorted in a localized region near the base of a slip band (Fig. 10), which also resembles the distorted atomic structure surrounding an edge dislocation in a crystalline solid. This distorted structure suggests that the shear resistance in the localized region is lower than that of the bulk material. Therefore, the distorted structure then promotes slip by transforming the random short-range order of the atomic structure into a disordered structure with a lower shear resistance.

Polk and Turnbull [2] suggested that the lowered shear resistance of a metallic glass results from the destruction of the compositional and/or structural order by plastic deformation. Pampillo [3] verified that slip bands were preferentially attacked by chemical etching, which indicated that a different chemical potential existed within the slip bands. This strongly suggests that a different, disordered, structure exists as a result of slip. Pampillo [13] found that for the continued generation of slip, the slip bands tend to reinitiate after polishing. Furthermore, Davis [12] proposed that in the event of the generation of volume resulting from a disrupted structure [13], or an altered local structure resulting from a compositional change in the SRO [2], the slip bands contain disturbed material that would provide preferential sites for continued plastic flow once the slip bands are initiated. Finally, Li [5] proposed that slip nucleates at and behind the slip front and also within the slipped area. The above experimental observations and proposals provide support for the argument presented in this study. That is, the disrupted structure described above is the disordered structure resulting from a stress concentration at the base of a slip band which allows slip to continue. Furthermore, this same disordered structure is a local increase in atomic spacing which is filled by atoms from the bulk material that are driven to the regions by the applied stress.

5. Conclusions

The initiation and development of slip bands were analysed using SEM and by bending resistance tests. The results of the SEM analysis and the bending resistance tests indicate that the generation of slip bands and their subsequent development are responsible for an erratic increase in resistance due to plastic deformation. A physical argument is presented that this increased resistance is the result of restricted electron motion due to the deformation processes. To facilitate slip-band development, a generation of free volume is believed to occur at the base a slip band. Finally, it is considered that slip nucleates due to a decreased shear resistance resulting from a disordered structure at the base of a slip band.

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