Rate dependence of serrated flow in a metallic glass

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Plastic deformation of amorphous $Al_{90}Fe_5Gd_5$ was investigated using nanoindentation and atomic force microscopy. While serrated flow was detected only at high loading rates, shear bands were observed for all loading rates, ranging from 1 to 100 nm/s. However, the details of shear-band formation depend on the loading rate.

Plastic deformation of metallic glasses at low temperatures is known to be highly localized to narrow shear bands.[1] It is generally believed that shear-band formation is very weakly dependent on the strain rate or temperature.[2] However, some reports suggest that the strain rate affects shear-band formation. Mukai *et al.*[3] reported that the density of shear bands in a Pd-based bulk metallic glass increased with strain rate. Schuh *et al.*[4] recently studied the deformation behavior of $Pd_{40}Ni_{40}P_{20}$ bulk metallic glass by nanoindentation. They observed serrated flow only at strain rates below about 1–10/s. In a Zr-based bulk metallic glass, Wright *et al.*[5] attributed serrated flow behavior to formation of individual shear bands. Consequently, one might conclude that shear bands would form only at low strain rates. However, as Greer *et al.*[6] recently commented, shear-band formation is a high-strain-rate phenomenon. Recently, we also found serrated flow behavior of an Al-based amorphous alloy during nanoindentation at low strain rates. To conclusively determine the formation of shear bands, more direct observations are needed. Here, we present results of nanoindentation and observation of resulting shear bands by atomic force microscopy (AFM). We found shear bands at all strain rates and attribute the observations of Schuh *et al.* to the instrumental resolution of the nanoindenter. We note that the present discussion is restricted to the low-temperature regime, in which metallic glasses deform inhomogeneously.[1]

Amorphous $Al_{90}Fe_5Gd_5$ ribbon, 22 μm thick and 1 mm wide, was obtained by single-wheel melt-spinning in an argon atmosphere using a Cr-coated Cu wheel at a tangential velocity of 40 m/s. Prior to indentation, the ribbon was polished electrolytically using a solution of 25% nitric acid and 75% methanol, at 243 K, and a voltage of 90 V. Indentation experiments were performed using a Nanoinstruments Nanoindenter II (Oak Ridge, TN) with a diamond Berkovich indenter. At least ten indents were made on each of the multiple samples. The distance between adjacent indents was 20 μm. The loading phase of indentation was carried out under displacement control, and the maximum (elastic plus plastic) indentation depth was 1 μm. The thermal drift of the instrument was maintained below 0.2 nm/s. AFM observation on the indents was conducted using a Digital Instruments Nanoscope IIIa (Santa Barbara, CA) in contact mode.

Figure 1 shows the loading portions of typical load-displacement (P-h) curves at loading rates of 100, 50, 10, and 1 nm/s. Serrated flow was observed at 1 nm/s and 10 nm/s only, which is similar to the results of Schuh *et al.*[4] Extensive AFM observation revealed that shear bands are the main morphological characteristics of indents formed at all loading rates. The typical morphologies of indents produced at the highest and lowest loading rates, 100 nm/s and 1 nm/s, are shown in illumination-mode AFM images in Fig. 2. Surface steps due to shear bands are observed around and in the indents. Figure 3 shows the depth profiles of the indents in Fig. 2. Evidently, the number of shear bands is smaller and the step size is larger outside the indent formed at the low-loading rate, indicating that a high deformation rate leads to a greater number of shear bands. For a standard sample of fused silica, relatively smooth load-displacement curves were obtained at all loading rates. This confirms that the serrated flow in the amorphous alloy is due to the material's intrinsic behavior. The present results show that at loading rates ranging from 1 nm/s to 100 nm/s, the characteristics of the load-displacement curves are dependent on the loading rate, and the shear bands formed at high rates are not reflected in load-displacement curves. Since the total strain used is the same for all rates, a smaller number of shear bands corresponds to larger slip steps. Thus, serrated flow is observed only when the step size is sufficiently large. Greer *et al.*[6] report that both the depth increment in a pop-in event and the elastic deformation between pop-ins increase linearly with indentation depth. We observed monotonic, but not linear, relationships.

Discontinuities (i.e., pop-ins or serrated flow of load-displacement curves) are related to discrete processes in a solid. For crystalline materials, they are attributed to several possible mechanisms,[7] while for amorphous alloys, they are related to shear bands, the only characteristic feature of inhomogeneous plastic deformation. We now discuss three possible contributions to the absence of serrated flow at high strain rates: (i) the sampling rate, (ii) the instrumental response time, and (iii) the rate of shear-band formation [(iii) is the only materials-related factor].

(i) The rate of data acquisition is limited to less than 10/s. Therefore, the lower the loading rate, the greater the resolution, as seen in Fig.1. For example, for the same total depth over 3000 data points were obtained at a loading rate of 1 nm/s, as opposed to 90 data points at 100 nm/s.

(ii) Inspection of Fig. 1 suggests that it is not the number of data points alone that affects the resolution. At high loading rates, a rapid response of the load and/or displacement measurements would be required to observe serrations. The instrumental response is apparently not sufficiently fast at these rates.

(iii) The deformation rate affects the number of shear bands, and consequently, serrated flow behavior of amorphous alloys. It has been demonstrated in tensile tests that at low strain rates failure occurred along a single shear band, whereas many intersecting bands were involved in fracture at high strain rates.[3] This is also consistent with our observations outside the indent. Reference 3 indicates that high strain rates result in a larger number of shear bands. If the number of shear bands is sufficiently high, the contribution of an individual shear band to the total strain is indiscernible and consequently, serrated flow disappears. This characteristic is similar to the situation in crystalline solids, where the formation of dislocations causes pop-in or serrated flow only at the very beginning of plastic deformation when few dislocations exist.[8] Upon large proliferation of dislocations, a great number of dislocations contribute to plastic deformation so that individual events become indiscernible, even though deformation is microscopically discontinuous.

Schuh *et al.*[4] quote the work of Kimura and Masumoto[9] on uniaxial compression of metallic glass $Pd_{78}Cu_6Si_{16}$, in which a critical strain rate of approximately $4 \times 10^{-3} - 2 \times 10^{-2}$/s for serrated flow was identified. Schuh *et al.*[4] attributed the large difference, up to two orders of magnitude, between this range and their results to the composition difference. We suggest an interpretation based on the different deformation volumes.

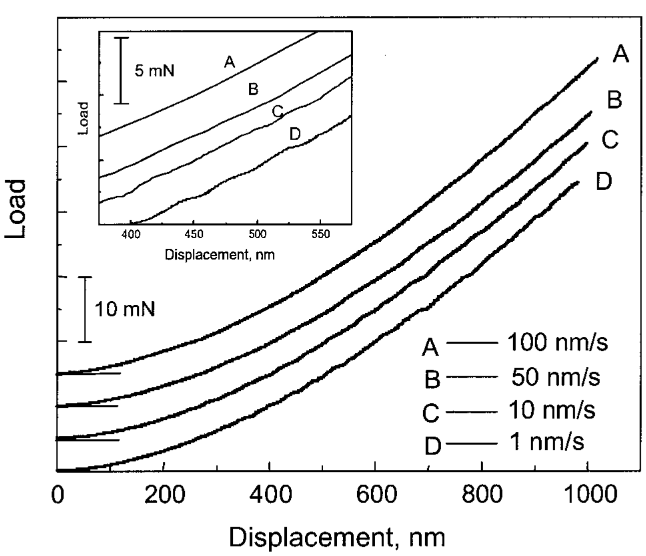

FIG. 1. Load displacement curves for amorphous $Al_{90}Fe_5Gd_5$ during nanoindentation at various loading rates. Inset is an enlarged portion.

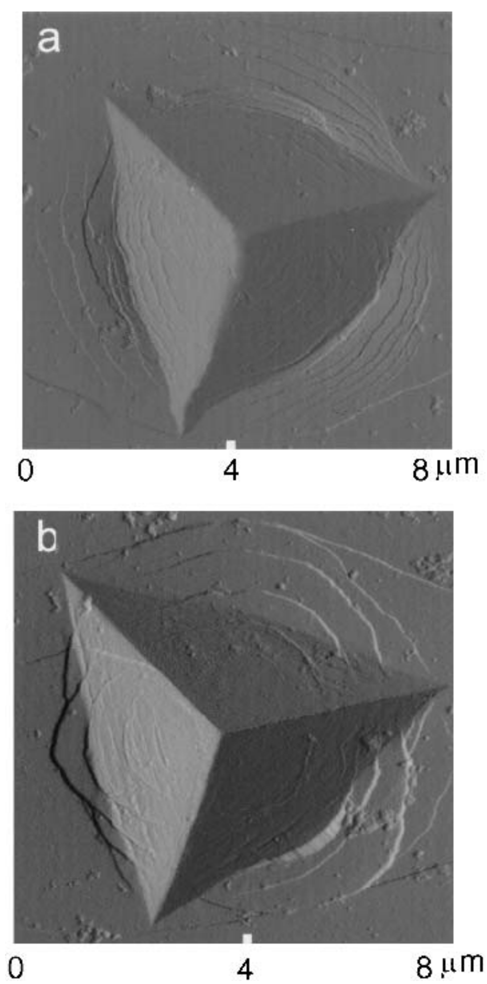

FIG. 2. AFM illumination images of indents produced at loading rates of (a) 100 nm/s and (b) 1 nm/s.

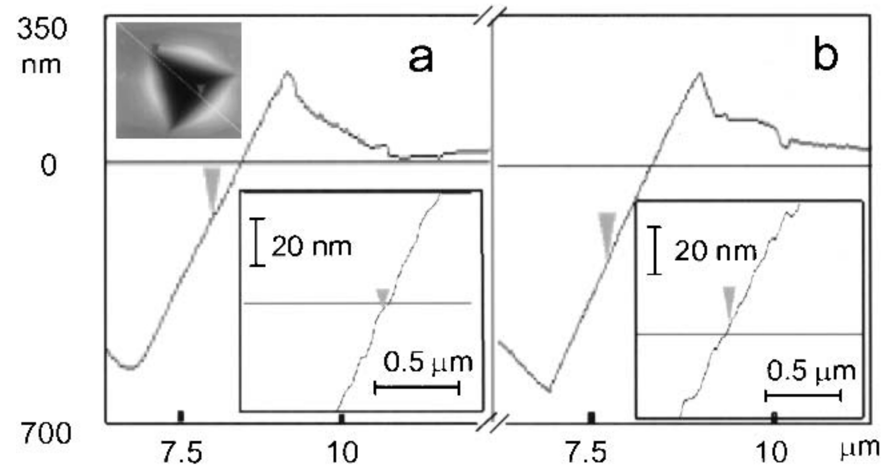

FIG. 3. Parts of depth profiles of indents obtained using AFM at (a) 100 nm/s and (b) 1 nm/s. Insets are enlarged profiles and a height image in which a line indicates the profile position schematically.

In compression testing, the size of the deformed region is at least on the order of millimeters. Therefore, a lower strain rate is required for the contribution from an individual shear band to be resolved. On the other hand, nanoindentation is characterized by a deformed volume with a submicrometer diameter. In this case, the contribution of an individual shear band is easily detected, resulting in observable serrated flow even at higher strain rates.

In summary, the present results confirm that shear-band formation in a metallic glass is affected by the strain rate. Whether shear-band formation manifests itself in serrations in the load-displacement curves for a given strain rate depends on the deformed volume and on the instrumental resolution.

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