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Density changes in shear bands of a metallic glass determined by HAADF-STEM and EELS

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The deformation process in metallic glasses is quite different from that in crystalline materials because there are no defects such as dislocations, twins or grain boundaries available that can act as deformation carriers for an easy flow mechanism. Deformation tests on metallic glasses have shown that when the applied load exceeds the elastic range the plastic flow is confined to narrow regions called shear bands [1]. In conventional TEM, shear bands are usually distinguished from the surrounding amorphous matrix as regions of lower contrast. Such shear bands are locally softer than the surrounding matrix allowing the accommodation of external shear stresses via slip. It is common belief that such shear bands are associated with a structural change like local dilatation, implying a volume change and thus a change in the density, ρ. An important issue is hence the quantification of free volume inside shear bands. It is the purpose of the present contribution to describe and discuss a new method for probing the local density of shear bands using analytical TEM resulting in new insight of shear bands in metallic glasses. In our approach [2] we use the relation of the dark-field intensity I/I_0 (scattered electrons collected by an high-angle annular dark-field detector) and the mass thickness: $\frac{I}{I_0} \propto \rho \cdot t$. The foil thickness, t, is calculated from the low-loss region of the electron-energy loss spectrum [3], which is acquired simultaneously to the HAADF signal. This new experimental approach yielded several new results for shear bands in metallic glasses:

(i) Shear bands can show either an increase or decrease in mass density relative to the surrounding matrix (see Figure 1).
(ii) Compositional changes are observed within the shear bands. The surrounding matrix was not observed to be affected.
(iii) High amounts of free volume (up to 6 % and more) are found for individual shear bands.
(iv) Mixtures of amorphous/crystalline or medium range ordered domains were found within the shear bands.

We associate the decrease in density mainly with an enhanced free volume in the shear bands and the increase in density with concomitant changes of the mass. This interpretation is further supported by changes in the zero loss/Plasmon signal (see Figure 2) originating from such sites. The obtained results indicate clearly that shear bands in one given sample can vary significantly with respect to their specific properties, e.g. their mass density. This fact highlights the importance of local imaging methods for their characterization and it also offers a direct explanation for the wide range of observations that are reported in the literature.

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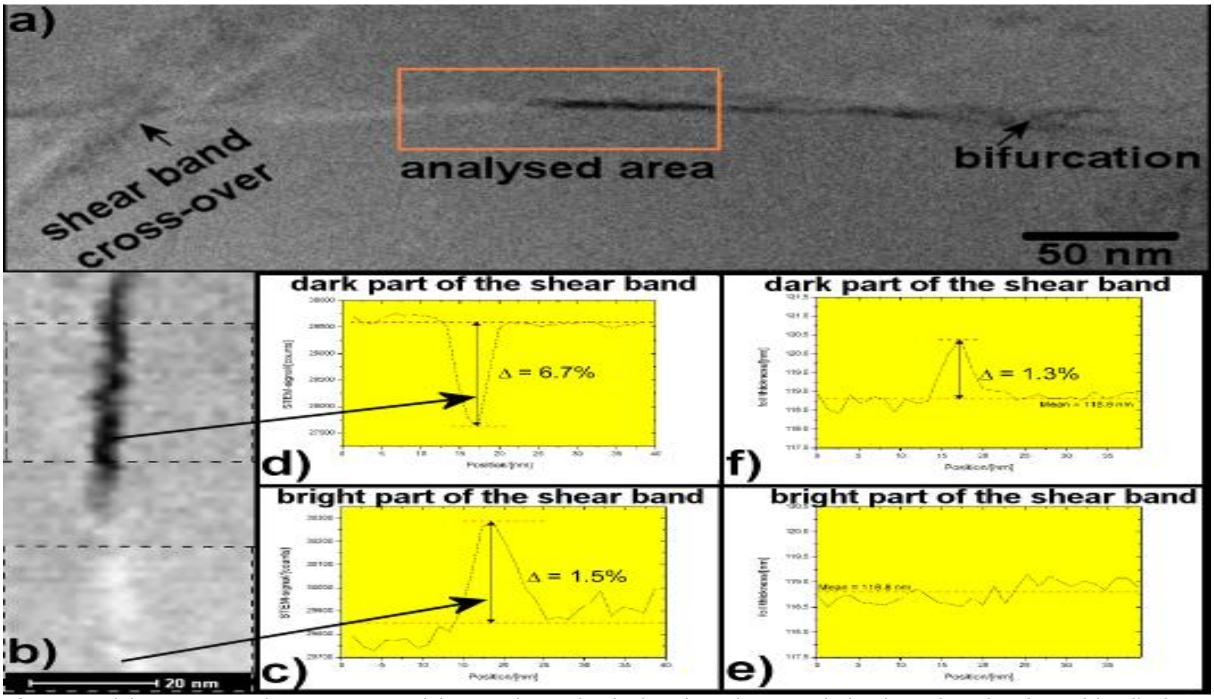

Figure 1. (a) Z-contrast (HAADF-STEM) image (overview) showing characteristic shear bands of a cold-rolled $Al_{88}Y_7Fe_5$ melt-spun ribbon. A cross-over of shear bands is seen on the left side. The horizontal shear band displays a contrast change from bright to dark in the box (analyzed area) and a bifurcation at the end. (b) HAADF detector signal corresponding to the box shown in (a) rotated 90° anti-clockwise. (c, d) Averaged profiles of the HAADF detector signal from the boxed areas indicated in (b). (e, f) Averaged profiles of the foil thickness from the boxed areas indicated in (b).

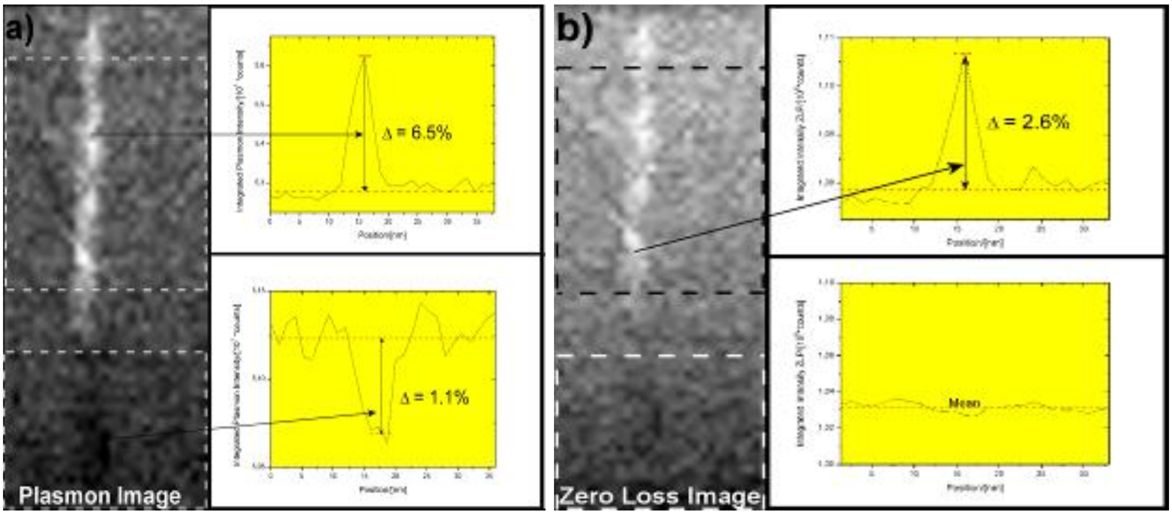

Figure 2. (a) Image of the Plasmon signal (energy window: 12-18 eV) extracted from the individual electron-energy loss spectra and corresponding profiles across boxed regions. Note the contrast inversion compared to the HAADF detector signal in Fig.1. (b) Image of the zero loss peak (ZLP) (energy window: 5 eV) extracted from the individual electron-energy loss spectra and corresponding profiles.