Local density measurements of shear bands in metallic glasses using correlative analytical transmission electron microscopy

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The deformation mechanisms present in metallic glasses are in focus of research since decades. It was shown previously that applying a load exceeding the elastic range of a metallic glass leads to a plastic flow which is confined to narrow regions called shear bands [1]. Shear bands are structures of typically some tens of nanometers in thickness. Therefore, conventional transmission electron microscopy (TEM) was previously used to image shear bands. Such TEM results showed often less scattering of the shear bands, resulting in a dark contrast in dark-field imaging. Thus it was concluded that shear bands are associated with a change in density ρ. Obviously a density change can be directly correlated to the amount of free volume present in the shear bands, however, yet only a few attempts were made to quantify the density change locally. Here a new approach is presented and discussed, probing the local density of shear bands using scanning TEM (STEM) simultaneously gathering different signals. The correlated data from a high-angle annular dark-field (HAADF) detector and the electron energy loss spectrum (EELS) are analyzed in detail. In our approach [2] we use the approximation of the relation of the dark-field intensity I/I_0 (scattered electrons collected by the HAADF detector) and the mass thickness:

$$\frac{I}{I_0} \propto \rho t$$

The foil thickness t is calculated using EELS, which is acquired simultaneously to the HAADF signal. Therefore, preparation artifacts leading to a meniscus at the position of the shear bands can be excluded. Moreover, being in STEM mode nanobeam-diffraction patterns were obtained from the matrix as well as from the shear bands. Such 2-dimensional diffraction data were studied using an analysis of the intensity distributions along rings (constant scattering angles). Based on a detailed analysis of the experimental data we arrived at the following conclusions:

(i) Shear bands can show either an increase or decrease in ρ relative to the surrounding matrix. Abrupt density changes within individual shear bands were frequently observed.
(ii) Compositional changes were observed within the shear bands.
(iii) Free volume up to 10 % and more were found for individual shear bands.
(iv) Mixtures of amorphous and medium range ordered domains were found in the shear bands.

The decrease in density is explained on the basis of enhanced free volume in the shear bands and the increase in density with concomitant changes of the chemistry. This interpretation is further supported by changes in the EELS data 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. The results highlight the importance and opportunity of local imaging methods using different detectors with correlated signals. Moreover, the present results offer a clear hint to explain the wide range of observations on shear bands that are reported in the literature.

1. P.E. Donovan, W.M. Stobbs, Acta Metall. 29 (1981), p. 1419.
2. Submitted to Ultramicroscopy.
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