Study of anelastic behavior of amorphous TiAl by atomic-level elastic strain measurement during in-situ TEM straining

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Metallic glasses exhibit a number of superior mechanical properties such as high strength and high elastic limit that are a consequence of the amorphous nature of the structure [1]. Therefore, high interest exists in the characterisation of the structure of amorphous materials and the correlation to the mechanical properties. Due to the lack of structural order metallic glasses show also a time-dependent elastic behaviour. It is the aim of the present study to investigate this anelastic behaviour of an amorphous TiAl thin film by comparing macroscopic and microscopic strain measurements during tensile deformation in-situ in the transmission electron microscope (TEM).

$Ti_{45}Al_{55}$ films (150 nm thick) were synthesized by co-deposition of Ti and Al on a Silicon waver by DC Magnetron Sputtering. Photolithography and reactive Ion etching techniques were used to co-fabricate MEMS based tensile testing stages with freestanding thin films [2]. The special design of the samples allows macroscopic strain and stress measurements. Figure 1 shows the TiAl thin film next to the stress and strain gauges. Tensile tests were carried out in a Philips CM200 microscope at an accelerating voltage of 200kV. The samples were uniaxially strained in steps of 150 nm and bright-field images and selected area diffraction (SAD) patterns were recorded using Gatan Orius CCD camera. Microscopic strain tensor on atomic level was obtained from electron scattering images by tracing the shift of the maximum of the first broad diffraction halo during tensile loading.

Figure 2 shows a characteristic diffraction pattern of amorphous TiAl from a selected area of 1.2 micrometer in diameter. The position of the first broad ring as a function of the angle χ is obtained by a Digital Micrograph™ plug in. The evaluation procedure is described in detail in the contribution by C. Ebner et al [3]. The strain ε is calculated from the relative change of the maximum position $q_1(\sigma, \chi)$ at a given stress with respect to the unloaded position $q_1(0,\chi)$ by $\varepsilon=(q_1(0, \chi)-q_1(\sigma, \chi))/q_1(\sigma, \chi)$. From a series of SAD patterns recorded from the same area at different stress levels during in-situ deformation the measured strain values and the corresponding fitted curve are plotted in Fig. 3. The maximum and minimum values of the curve increase with increasing stress; these values correspond to the principal strains e_{11} (parallel) and e_{22} (perpendicular to the loading direction), respectively. The macroscopic stresses parallel to the loading direction were calculated from the force gauges (cf. 2-3 in Fig. 1) of the MEMS device. Figure 4 shows the linear dependence of e_{11} and e_{22} on stress as expected from Hooke's law and reach 1% and -0.17% at the maximum stress, respectively. From the linear fit the Young's modulus $E=185\pm2$ GPa and the Poisson's ratio of $\nu=0.23\pm0.02$ are obtained. The macroscopic strain values calculated from the gauges show the same trend but are systematically higher compared to the strain values obtained from reciprocal space measurements. Since the latter correlates with the modulus range of polycrystalline TiAl, the diffraction method traces the atomic-level strain and the difference to the macroscopic strain can be attributed to a non-affine and anelastic deformation resulting from topological rearrangements in metallic glasses.

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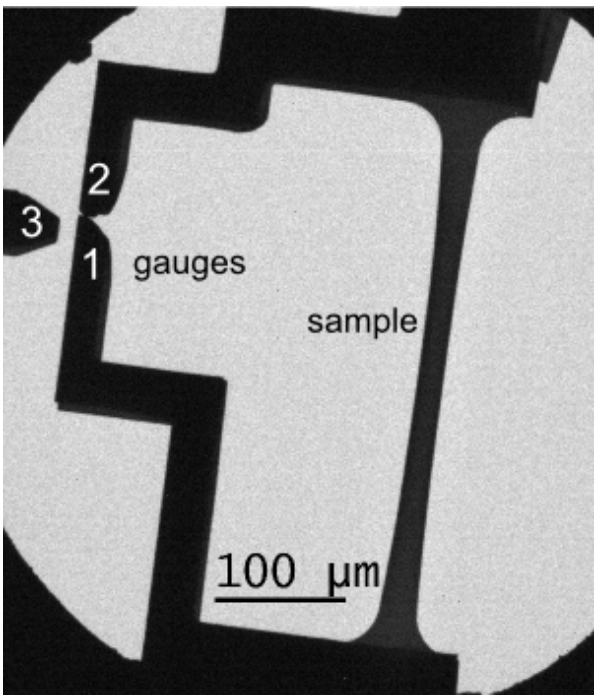

Figure 1: TEM image of the freestanding TiAl thin film and of the strain (1-2) and force-sensing gauges (2-3) facilitating the measurement of the macroscopic strain and stress.

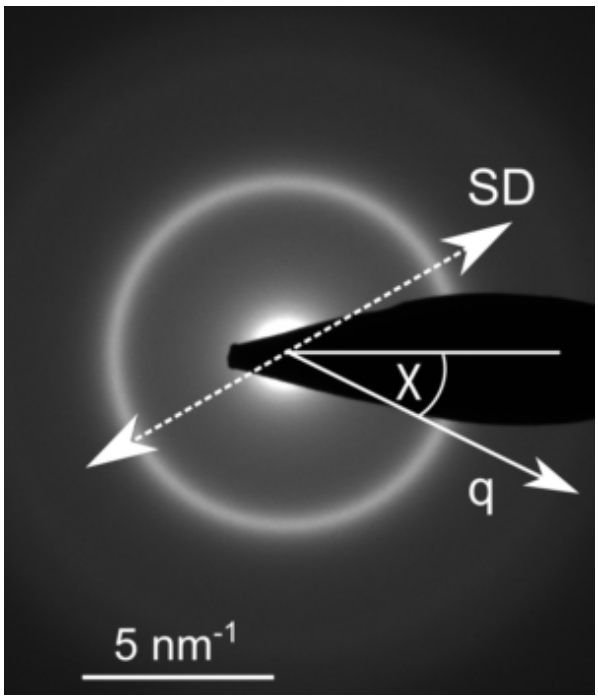

Figure 2: SAD pattern of an amorphous TiAl thin film showing the first intense broad ring and the reciprocal scattering vector q at an angle X. The straining direction (SD) is indicated by the double arrow.

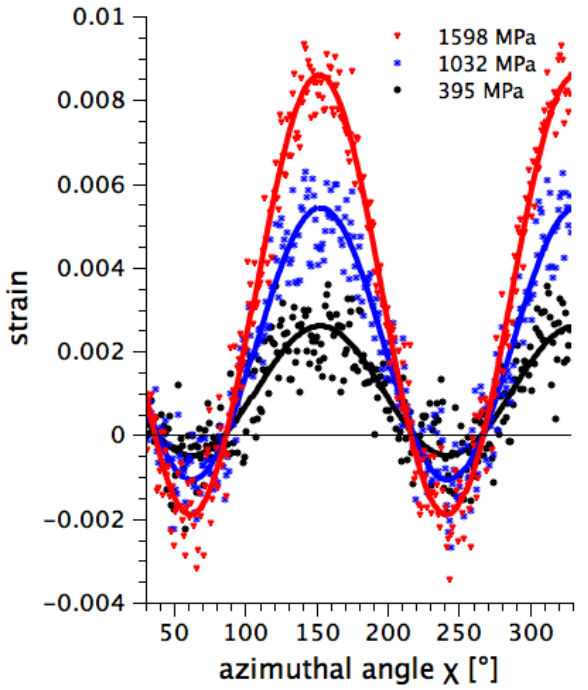

Figure 3: Angular and stress dependence of strain measured from the maxima position of the first broad ring in the SAD pattern. The full lines are the best fits of the experimental data.

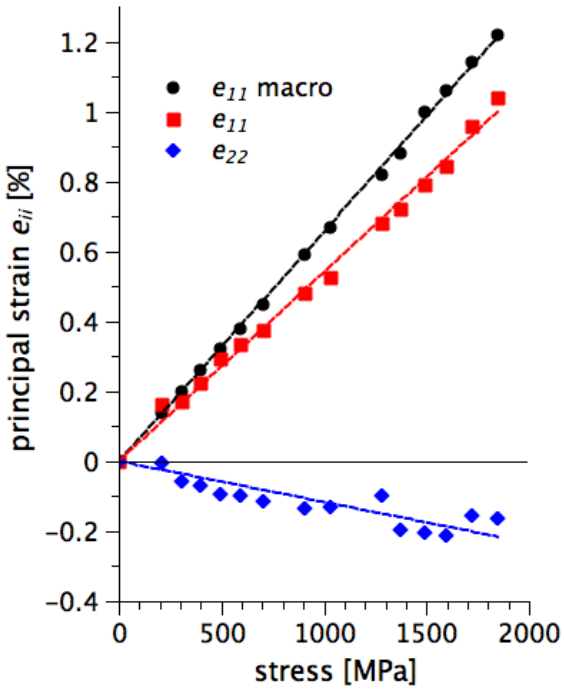

Figure 4: Linear dependence of stress and principal strains (e11, parallel and e22, perpendicular to the loading direction). The macroscopic strain curve shows a line with a different slope.