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Texture evolution during tensile necking of copper processed by equal channel angular extrusion

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Abstract. Polycrystalline copper is severely plastically deformed by equal channel angular extrusion to an equivalent strain of 10. Cylindrical ASTM standard tensile specimens machined from the extruded material are deformed in tension until failure. The forming neck develops an anisotropic cross section with its long axis along the original transversal direction. Microstructure and texture are investigated by electron backscatter diffraction in the as-deformed condition and after additional tensile deformation. The texture is dominated by two components close to $<110>-<112>$ directly related to the shear deformation in the intersection plane of the channels, weakens with tensile deformation and is finally replaced by a restricted $<111>+<100>$ fibre texture characteristic for tensile deformation in the neck region.

1. Introduction
Severe plastic deformation causes refinement of the grain structure and subdivision of original grains by deformation-induced boundaries. Caused by their microstructure, severely plastically deformed metals have higher yield and ultimate tensile strength, but lower ductility (cf. [1,2]). During tensile tests their work-hardening rate is rather low and plastic deformation localizes at an early stage causing necking and finally failure. For an understanding of the mechanical response of severely plastically deformed metals, characterization of the microstructural evolution during homogeneous tensile deformation is insufficient due to the small uniform elongation and the microstructure in the neck must be investigated as well.

2. Experimental details
Polycrystalline OFHC copper is deformed by equal channel angular extrusion (ECAE) [3] to an equivalent strain of 10. Billets are extruded 15 times through a die with an angle of $120^\circ$ between the equivalent cylindrical channels without any rotation of the specimen (route A) (cf. [4]). From the core of the billets cylindrical ASTM standard tensile specimens are spark-eroded with a diameter of 4 mm, a gauge length of 20 mm, and the new tensile direction corresponding to the extrusion direction (ED).

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Using an INSTRON testing machine, the tensile samples are pulled to failure with a cross head speed of 0.5 mm/min (which equals an initial strain rate of $4 \cdot 10^{-4}$ s$^{-1}$). The resulting engineering stress-engineering strain curves are presented in figure 1 (with the engineering strain obtained from fiducial markers on the specimen surface). The maximum force required is reached already at 1% strain (uniform elongation), and the ultimate tensile strength is about 436±5 MPa. The ECAE deformed specimens fail after pronounced necking by a $45^\circ$ shearing of a large section. Cross sections in the homogeneously deformed region remain circular, but the neck develops anisotropically with an elliptical cross section as sketched in figure 2. The long axis of the elliptical neck shape is aligned with the transversal direction (TD) of the extrusion process. An aspect ratio of about 0.7 between shorter and longer axis is determined in a cross section close to the fracture surface. From the area of this cross section, an equivalent strain $\varepsilon = \ln(A_0/A) = 1.2$ is obtained locally in the neck.

The microstructure is investigated by electron backscatter diffraction (ESBD) with a Zeiss Supra 35 FEGSEM using a Nordlys2 detector and data acquisition software HKL Channel5 by Oxford Instruments. EBSD requires a clean planar surface for investigating the microstructure and several preparation techniques for examining the neck region are tested [5]. The microstructural investigations are performed on a midsection through the centre of the tensile deformed specimen comprising the tensile axis and the short axis of the neck (corresponding to normal direction, ND) as sketched in figure 1. Successful preparation is achieved by coating the sample with dissolvable carbon cement prior to embedding it in epoxy. The relevant midsection is then exposed by grinding, extracting the sample manually from the epoxy, mechanical diamond polishing by hand and final electro-polishing.

On the prepared surface large orientation maps are collected on square grids with step size of 0.1 μm between individual measuring points. Two maps are gathered at different positions on the prepared midsection, one in the region of homogeneous deformation, the other in the neck close to the fracture surface. An additional orientation map is collected on a transversal section in the centre of an ECAE deformed billet not subjected to any tensile deformation.

### 3. Results and discussions

Figure 3 presents the spatial arrangement of orientations for the homogeneously deformed region and the neck. The homogeneously deformed region resembles closely the quite heterogeneous microstructure after ECAE [6] with regions of apparently small grains caused by grain refinement and regions with rather large grains which did not fragment severely during ECAE. The elongated grains in the deformation structure of the neck reflect the large tensile deformation to an equivalent strain of more than 1.
(a) homogeneously deformed region ($\varepsilon = 0.01$)

(b) neck ($\varepsilon \approx 1.2$)

**Figure 3.** Orientation maps (80 $\mu$m × 40 $\mu$m with different colours representing different orientations) from tensile deformed ECAE specimen. The tensile direction (and extrusion direction) is vertical. The horizontal direction corresponds to the normal direction and the short axis of the elliptical neck.

From the measured orientations the texture of the deformation structures is inferred. In figure 4 the determined 111, 110 and 100 pole figures are summarized. A 110 pole close to the extrusion and tensile direction is obvious for the ECAE deformed specimen (figure 4a) and for the additionally homogeneously deformed region (figures 4b). Such a preferred [110] direction along the extrusion direction has been observed e.g. by [7] and can be related to the shear deformation along the channel intersection plane during ECAE [4]. The 111 pole figure of the ECAE deformed specimen in figure 4a reveals a 111 pole pointing along the transversal direction. Taking into account the multiplicity of four for 111 poles, the existence and position of six other 111 poles indicate the presence of two distinct preferred orientations. Both preferred orientations have a common 111 pole and are rotated from each other by 180° around the crystallographic [111] axis or TD. Combining the information of ED being parallel to [110] and TD to [111], ND must be along a crystallographic [112] direction and the texture of the ECAE deformed specimen an orthorhombic <110>{112} texture. Taking into account the geometry of the 120° die and the inclination by 60° of the intersection plane of the two channels with respect to ED, the rotated texture in the intersection plane is also a <110>{112} texture with two components. This confirms occurrence of simple shear on the intersection plane as these two texture components are commonly observed after shear deformation and designated B and B orientation [8].

Orientations with a [110] direction along the tensile axis are unstable under the following tensile deformation and replaced by a <111>+<100> fibre texture characteristic for unidirectional tension as obvious from the 111 and 100 pole figures of the neck regions: The orthorhombic texture developed during ECAE has a maximum pole density of 6.1 with respect to a random distribution of orientations. This texture weakens due to the slight tensile deformation to a tensile strain of 0.01 in the homogeneously deformed region to 5.1 and strengthens again to 7.4 in the neck due to formation of a dominant <111> fibre texture – with an additional weak <100> fibre. The fibre textures are not completely isotropic perpendicular to the tensile direction and variations of the pole density along the diffraction rings observed for both specimens are inherited from the orthorhombic ECAE texture.

Further investigations are required for resolving, if the small inclinations of the poles from the ideal directions are an intrinsic effect of the processing conditions as in the case of ECAE (cf. [6,9]) or an artefact of the chosen preparation technique. For a second ECAE processed specimen, an analogous texture development is observed. In both cases, the elliptical neck shape forms with its long axis along the original transversal direction and hence along an initial crystallographic [111] direction.

### 4. Summary

The microstructure of deformed copper after equal channel angular extrusion is analyzed in the as-deformed state and after additional tensile deformation to failure. After ECAE an orthorhombic texture consisting of two components close to <110>{112} is observed. The small plastic deformation in the homogeneously deforming regions causes a slight weakening of the texture. In the neck a (restricted) <111>+<100> double fibre texture characteristic for tensile deformation is formed. The neck develops an anisotropic cross section with its long axis along the transversal direction of the ECAE processing.
Figure 4. Pole figures: (a) as ECAE deformed and after additional tensile deformation: from (b) the homogeneously deformed region and (c) the neck. Extrusion and tensile direction are vertical; the horizontal direction is the normal direction.

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