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MICROSTRUCTURE, SLIP SYSTEMS AND YIELD STRESS ANISOTROPY IN PLASTIC DEFORMATION

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ABSTRACT-The highly anisotropic microstructures in nanotwinned copper produced by electrodeposition provide an excellent opportunity to evaluate models for microstructurally induced mechanical anisotropy. A crystal plasticity model originally developed for the integration of deformation induced dislocation boundaries with texture is applied to account for the effects of texture as well as twin and grain boundaries, providing good qualitative agreement with experimental yield stress and yield stress anisotropy data.

INTRODUCTION: It is well-known that texture is a major cause of yield stress anisotropy and it has also been found that anisotropic microstructures have a pronounced effect. In the present paper a model originally developed to predict the combined effects of texture and deformation induced dislocation boundaries is adapted to predict the effect of the highly anisotropic microstructures found in the electrodeposited copper samples. These samples typically have strong fibre textures, the grain shapes may vary and they contain nanometer spaced twin boundaries with preferred directions. As shown in Fig. 1 two microstructural geometries are considered: i) a <110> fibre texture with equiaxed grains and twins that are roughly parallel to the growth direction, and ii) a <111> fibre texture with columnar grains and twins perpendicular to the growth direction.

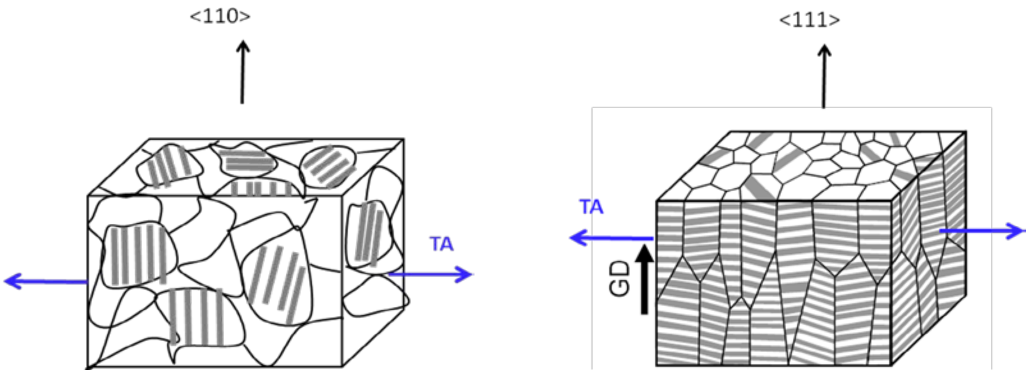

Fig. 1. Schematic microstructures of the two samples. Left: <110> fibre texture, equiaxed

grains and twins parallel to the growth direction (GD). Right: <111> fibre texture, columnar grains and twins perpendicular to GD. TA marks the tensile axis.

At first the yield stress of the two samples for tension along the axes (TA) shown in Fig. 1 is modeled as a function of twin spacing. Subsequently the yield stress anisotropy of the <111> fibre textured sample is modeled for a fixed twin spacing.

PROCEDURES, RESULTS AND DISCUSSION:

Model: The model is based on a previous extension of the Taylor model to include anisotropic critical resolved shear stresses given by a Hall-Petch type equation taking the relative orientation of the slip system and the plane of the boundaries into account (Winther et al. [1997], Winther [2005]. In the present case the boundaries considered are twin and grain boundaries.

Slip systems on the twinning plane are assumed unaffected by the twin, i.e. only the grain boundary spacing D is taken into account. For slip systems on the other slip planes the twin spacing λ is assumed much smaller than the grain boundary spacing D, so that the grain boundary contribution is neglected. The critical resolved shear stress for the slip systems are:

Slip systems parallel to the twinning plane: $\tau_{crss} = \tau_0 + k \cdot D^{-1/2}$

Other slip systems: $\tau_{crss} = \tau_0 + k \cdot \lambda^{-1/2}$

The constants τ_0 and k are assumed common to all slip systems in both samples and are derived from the macroscopic values of the friction stress in copper and the Hall-Petch slope by division with an approximate value of 3 for the Taylor factor, i.e. τ_0=8MPa and k=46MPa μm$^{1/2}$ .The grain boundary spacing D for the <110> fibre case is 400 nm and the width of the columnar grains is 3000 nm for the <111> fibre case.

Predictions:

Fig. 2 shows the measured and calculated yield stress values for the two sample geometries as a function of twin spacing. As expected the yield stress increases with decreasing twin spacing. The agreement for the <110> fibre case is very good while the yield stress is somewhat overpredicted for the <111> case.

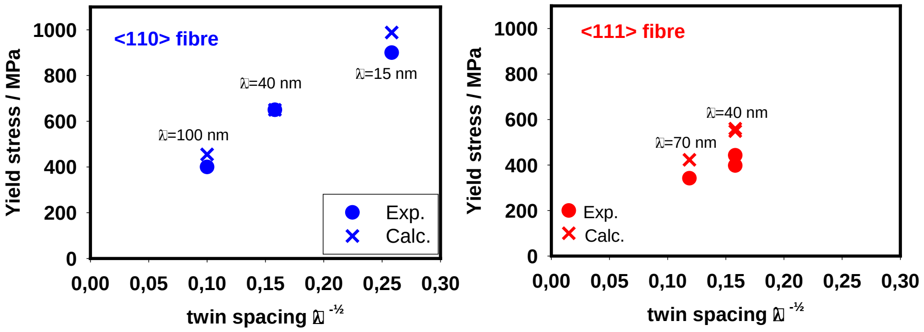

Fig. 2. Experimental and calculated yield stress as a function of twin spacing. Experimental data for the <110> fibre from Shen et al. [2005] ; <111> case from You et al. [2011].

The yield stress anisotropy of the sample with the <111> fibre texture was measured with the tensile axis the tensile axis inclined 0°, 45° and 90° to the twin boundaries. As seen in Fig. 3 the calculated absolute values are somewhat too high like in Fig. 2. The difference between experiment and prediction is furthermore largest for the 45° case. Geometrically this case is set up to very much favor slip on the twinning plane in all grains, i.e. the geometry has some resemblance with a single crystal in easy glide, where pronounced shear strains are known to develop. Relaxing the boundary conditions on all three shear strains for the individual grains gives a predicted yield stress that is lower than the observed one. The standard deviation of the shear strain distribution of the grains is of the order of twice the mean values, and accommodation of at least some of this shear at the grain boundary regions may be a plausible explanation for the low value at 45°. It has also been suggested that the very small twin spacing induces scale effects so that the use of a Hall-Petch expression for all slip systems may not be valid (You et al. [2011]).

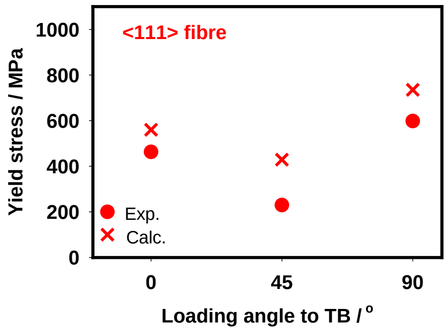

Fig. 3. Yield stress anisotropy for λ=40 nm and D=3µm.

CONCLUSIONS: The complex geometry and the size effects in nanotwinned electrodeposited copper is qualitatively well accounted for by a crystal plasticity incorporating the effects of twin and grain boundaries in the form of a Hall-Petch equation. Quantitative differences may be due to the boundary conditions enforced in the model, the use of the same Hall-Petch equation for twin and grain boundaries as well as for all slip systems, which may not correctly account for size effects in the nanotwinned copper .

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