MODELLING OF NON-UNIFORM DEFORMATION OF METALS WITH DISLOCATION CELL STRUCTURE.

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Summary The hardening behaviour of metals physically originates from a complex microstructure evolution. To describe non-uniform deformation of metals a model of the dislocation cell structure is proposed in this contribution. The material containing cells is modelled to behave like a composite consisting of a periodic array of two types of elements: hard cell walls and soft cell interiors. To ensure compatibility of plastic deformation across the interface between the hard and soft phases, polarised layers of geometrically necessary dislocations are introduced at the interface. The internal stresses created in the material by the geometrically necessary dislocations are taken into account.

The model is capable of describing the material behaviour for monotonic deformation and for deformation with a strain path change. The model predicts the strain path change effect, its dependency on the amount of prestrain and on the amplitude of the strain path change.

INTRODUCTION

The hardening behaviour of metals physically originates from a complex microstructure evolution. This work deals with the contribution of the dislocation cell structure to the mechanical response. The dislocation structure appears at early stages of deformation due to the statistical trapping of dislocations. Cell walls contain dislocation dipoles and multipoles with high dislocation densities and enclose cell-interior regions with a considerable smaller dislocation density. The presence and evolution of such a dislocation arrangement in the material influence the mechanical response of the material and is commonly associated with the transient hardening after strain path changes. The models developed until now to predict the strain path change effects on the basis of the dislocation structure evolution are either too detailed, and thus computationally costly [1], or phemenological [2]. This contribution introduces a continuum model of the dislocation cell structure based on the physics of the dislocation interactions.

CELL STRUCTURE MODEL

As a number of investigators have proposed earlier, e.g. [3], material with a dislocation cell structure is idealised in the present work as a two phase composite of cell walls and cell interiors. The cell wall component represents the phase with the high dislocation density and the cell interior component represents, correspondingly, the areas enveloped by the dislocation walls with the low dislocation density. The cell structure is modelled as a 3D periodic configuration of cuboid cells formed by three mutually perpendicular sets of planar cell walls (Figure 1).

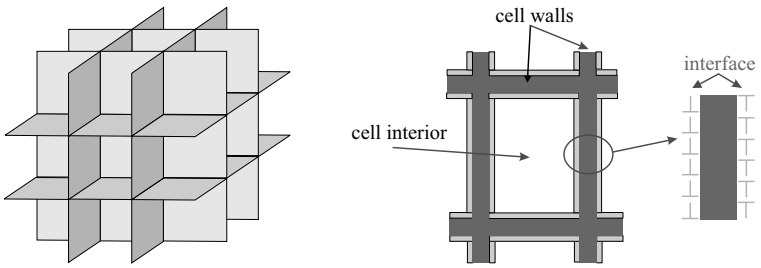

Figure 1. Morphology of the dislocation cell structure: 3D geometry (right), cross section (left).

The heterogeneous distribution of dislocations in the composite structure causes, during external loading, a non-uniform field of plastic strains. To ensure compatibility of the plastic deformation across the interface between the hard and soft phases, polarised layers of geometrically necessary dislocations (GND) will develop at the interface between cell walls and cell interior. It is known that the dislocation network in the material substantially affects the mechanical behaviour by creating internal stresses. In the cell structure model the statistically stored dislocations in the wall and cell interior phases are randomly distributed and therefore induced stress fields will compensate each other. These dislocations do not produce long-range effects. On the contrary the geometrically necessary dislocations are polarised in the interface layers and are, therefore, the source of resulting internal stresses in the material. To compute the internal stresses $\boldsymbol{\beta}$ created by the geometrically necessary dislocations, first, the density of the GND is quantified using the second order Nye's tensor $\boldsymbol{\Lambda}$, and, next,the equilibrium problem for a material with a dislocation distribution $\boldsymbol{\Lambda}(\mathbf{x})$ is solved by the method of Green's functions. In the case of the composite considered here the internal stresses was found analytically as a function of the plastic incompatibility and the composite geometry.

In the presence of the internal stresses the actual stresses $\mathbf{S}$ experienced by the material is the combination of the stresses $\boldsymbol{\sigma}$, applied externally, and the internal stresses $\boldsymbol{\beta}$, induced by the dislocation network. The actual stresses $\mathbf{S}$ are determined by the local material behaviour of the components of the cell structure. As the composite model represents the average behaviour of the entire cell structure developed through a polycrystal, the material behaviour of the cell interior component represents the average material behaviour of all cell interiors in the specimen and the material behaviour in the walls is representative for the average material behaviour of all cell walls. Therefore, the details of the material behaviour as described by dislocation dynamics, slip anisotropy, etc, are assumed to cancel out by averaging and are not taken into account. Thus the material behaviour of the components is modelled to be uniform inside the components and is described by continuum elastoplasticity in the context of geometrical nonlinearity with finite deformations. The material behaviour of the cell and wall components are distinguished by different values of the yield stress related to the local density of dislocations statistically stored in the components.

The macroscopical mechanical behaviour of the entire composite, namely the average applied stress and strain, is determined by spacial averaging of the local quantities. Additional assumptions about the mechanical coupling of the composite components are done to provide deformation compatibility along the interface and stress continuity across the interface.

To summarise, the homogenised mechanical response of the material with the dislocation cell structure can be computed by the following procedure. For a given macroscopic deformation, the actual stresses $\mathbf{S}$ and the plastic deformation of each composite component are determined by the averaging procedure and the elastoplasticity equations for each material component. Then the internal stresses created by the geometrically necessary dislocations are calculated for the found distribution of the plastic deformation. The applied stresses in each composite component can be found by subtracting the internal stresses from the actual stresses and then averaged over the composite to give the macroscopic response of the composite.

RESULTS

To validate the model sequences of two uniaxial tensile tests performed in different directions were considered. The material parameters determining the morphology of the cell structure were identified for copper at room temperature. Calculations proved that significant internal stresses $\boldsymbol{\beta}$ develop through the cell structure and lead to the strain path change effect. The dependence of the reloading yield stress σ^y_Φ (Figure 2) on the amount of prestrain and the angle Φ between the current and previous tension axes are shown in Figure 3.

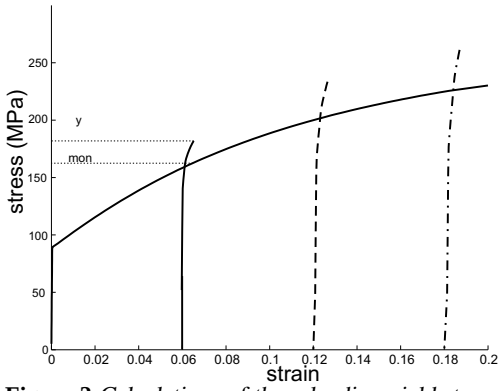

Figure 2 *Calculations of the reloading yield stress. The angle between the two successive tension axes $\Phi = 45^\circ$; prestrain in the first tension $\varepsilon_{pre} = 0.06; 0.12; 0.18$.*

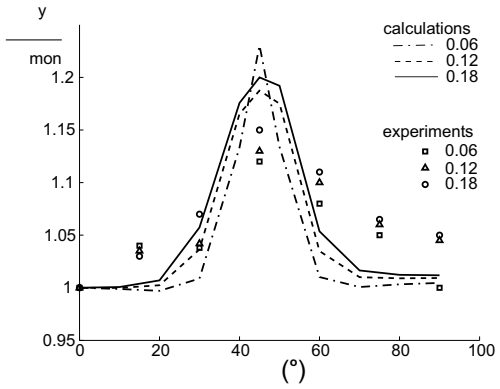

Figure 3 *Strain path change effect. Dependence of the normalised reloading yield stress on the angle between the two successive tension axes Φ. Experimental data from [4].*

CONCLUSIONS

To describe non-uniform deformation of metals a composite model for the dislocation cell structure is proposed. The model takes into account the internal stresses created by the dislocation network during deformation. The model predicts strain path change effects: the increased reloading yield stress, the influence of the direction of the strain change, the influence of the amount of prestrain. To improve the model a physically based evolution of the cell structure geometry should be considered.

References

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