Micro-structural Evolution in Strain Gradient Crystal Plasticity

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ABSTRACT

It is well known that dislocations arrange in wall and cell structures, within the grains of ductile crystalline materials, when subject to plastic deformation. Recently published electron backscatter diffraction (EBSD) measurements on a nickel single crystal, subject to plane strain wedge indentation, show distinct dislocation patterns (see e.g. [1]). These patterns represent highly non-uniform distributions of geometrically necessary dislocations (GNDs) arranged in distinct GND wall and cell structures, producing discontinuities in the lattice rotations. However, existing continuum models of the micro-structural evolution tend to show a much smoother GND field. Predicting the experimentally documented micro-structural behaviour, within a framework based on continuous field quantities, poses obvious challenges, since the evolution of dislocation structures is inherently a discrete and discontinuous process. Nevertheless, continuum theories are powerful tools in computational mechanics and the present work aims to contribute to this class among micro-structurally based models.

In multi-scale mechanics problems where deformation gradients become large, so-called higher order strain gradient plasticity theories are needed in order to obtain accurate results. The present study focusses on single crystal plasticity and adopts the non-work conjugate type higher order extension of conventional crystal plasticity theory proposed by Kuroda and Tvergaard [2;3]. In this theory, apart from the conventional field equations, a separate set of differential equations account for the evolution of GND densities, where these appear as free field variables. This scale-dependent theory has several advantages. One of them is that the back stress, which accounts for the gradient effects and is related directly to the gradients of GND densities, can be formulated in line with the work conjugate theories (e.g. [4]) based on a gradient energy relation, but can also be formulated based solely on phenomenological considerations. This property forms the basis for formulating a constitutive equation for the back stress, which can give rise to non-uniform distribution of GNDs.

The work presents ways to sharpen the micro-structural response through the back stress formulation, as well as an approach to the forming of GND walls through the slip resistance potential, within a phenomenological continuum mechanics framework. The influence of model parameters on the GND density distribution as well as the macroscopic response is demonstrated through a parametric study.

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