INTRAGRANULAR KINEMATIC HARDENING MODELLING AND VALIDATION

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Summary Various deformation induced dislocation microstructures can appear in metals and alloys. Each is composed of a soft phase (cell interiors, channels) and a hard phase (dense walls). They induce backstresses, which gives kinematic hardening on the specimen scale. The Berveiller-Zaoui localization rule is applied for computing these intragranular backstresses. It is validated using experimental results on the single crystal scale. Polycrystal intragranular and intergranular backstress magnitudes are then compared.

BACKSTRESSES

Experimental studies of polycrystal deformation showed the existence of backstresses. At least three experimental techniques permit the evaluation of these long-range stresses at different scales. First, the study of the hysteresis loops gives the kinematic stress (centre of the elasticity unloading domain) on the specimen scale [1]. Second, TEM observations permit the measure of dislocation radii, the computation of the corresponding line tension stresses and of the backstresses (dislocation equilibrium) [2]. Third, X-ray line broadening measurements give backstress measures in single crystals or polycrystals [3].

INTER- AND INTRAGRANULAR BACKSTRESSES

The kinematic stress obtained for a deformed polycrystal is the macroscopic result of both inter- and intragranular backstresses. Numerous experimental studies on single crystals demonstrated the existence of backstresses, particularly after the appearance of deformation induced dislocation microstructures (cell, wall/channel microstructures which included both hard and soft phases). Other experiments of neutron diffraction showed that backstresses on the grain scale could be measured even if no dislocation microstructure had appeared in the grains studied [4]. Both these inter- and intragranular backstresses are due to plastic heterogeneities which involve residual stresses either between the hard wall and soft channel phases inside a grain (intragranular) or between neighbouring grains in a polycrystal (intergranular). According to the experimental results, the relative magnitude of the intragranular backstress initialy seems to increase with the applied strain level and finally both the relative intra- and intergranular backstresses seem to stabilize [4].

Two approaches of the modelling of intragranular backstresses have been used in the past. The first of these is based on on inclusion problems. The soft phase is considered to be surrounded by the matrix or by an elastic wall and by the matrix. Hypotheses concerning the localization rule, which links the macroscopic scale to the cell or wall/channel scale, are used. Pedersen's model uses Eshelby's transition rule [5] and the Lemoine et al. model considers a cell interior surrounded by a wall and embedded in a matrix [6]. The Lemoine et al. model permits us to take into account the geometry and the wall volume fraction which characterize the dislocation microstructure. Generally, the walls are assumed to be elastic, the soft phase is elastoplastic and the matrix is elastic or elastoplastic. The soft phase backstress depends on the soft phase plastic slip. Using Eshelby's coefficients, it is possible to compute the 3D backstress tensor induced by a given microstructure geometry and by given plastic slips on several slip systems. However, these models are thermoelastic, suppose a pure elastic interaction between phases and use no plastic accommodation factor. That is why the computed backstresses are too high as soon as the plastic strain is higher than a few 10^{-4} [7], except for the specific case of Persistent Slip Bands [5].

The second approach, suggested by Mughrabi, proposed a well-known composite model based on the hypothesis that both the hard and soft phase are plastically deformed at maximal load [2]. In this model, the soft phase backstress depends on the dislocation densities in the two phases but not on the plastic slip. This has been developed more recently by Feaugas in order to evaluate both intra- and intergranular backstress for deformed polycrystals [8]. According to his calculations, the intergranular component of the backstress decreases to zero at high strain. This disagrees with neutron diffraction measurements. Therefore, there is at present no agreement between experiment and modelling of intragranular backstresses [4].

Improved modelling of the intragranular backstress is needed, which could be validated on the single crystal scale. Such work is important for understanding and predicting the polycrystal behaviour with a small number of material parameters and for varied loading conditions. This could help to evaluate the type II and III stresses (grain scale and cell scale) and to better understand the propagation of short fatigue cracks which greatly depends on the local backstresses (cyclic loading).

HYPOTHESES AND COMPUTATIONS

An inclusion approach has been used in order to take into account the dislocation microstructure geometry (except the enrobed character) [9,10]. For the sake of simplicity, a single crystal is considered in this part. The soft and hard phases are assumed to be embedded in the matrix. Crystalline plasticity is assumed in both the matrix and soft phase. The average plastic strain tensor is decomposed as a sum of plastic shear tensors. The average plastic slip slip is denoted as γ^p_i and n_i, m_i are respectively the slip normal and the slip direction of the i^{th} slip system. There are N slip systems (N=12 for CFC and N=24 for CC). Because of their high dislocation densities, the walls are assumed to be purely elastic. Following the Berveiller-Zaoui approach [11], a two-phase model is applied, using the macroscopic secant modulus and the Berveiller-Zaoui accommodation factor. This permits the calculation of backstresses with a physical order of magnitude even for large strains. For a spherical cell, the following soft phase backstress is obtained:

$$\underline{\underline{x_c}} = \frac{f_w}{1-f_w}\mu(1-\beta)\frac{1}{1+\frac{3}{2}\mu\frac{\varepsilon^p_{eq}}{\sigma_{eq}}}\sum_{i=1}^{N}\gamma^p_i\frac{1}{2}\left(\underline{n_i}\,\underline{m_i^T}+\underline{m_i}\,\underline{n_i^T}\right)$$

with μ the elastic shear modulus, $\beta=2(4-5\nu)/15(1-\nu)$ (Eshelby's analysis for a spherical elastoplastic inclusion), ν the Poisson ratio and f_w the wall volume fraction. In this equation, all mechanical values are defined on the single crystal scale (matrix). The single crystal kinematic stress is denoted as x_c which is equal to the soft phase backstress.

Spherical cells have been observed for large cyclic or monotonic strains. Other formulae have been obtained for infinite hard cylinders embedded in soft phase (veins/channels microstructures observed for small cyclic strains).

RESULTS

This model is validated by comparison with many backstress measurements on single crystals for which the backstresses are only intragranular. Even for large strains, the computations agree rather well with the experiment measures, except for very small plastic strains. Microstructure parameter and mechanical values are taken from the literature (hard phase volume fraction, geometry, aspect ratios). These parameters allow the calculation of backstresses on single crystals tested using cyclic or monotonic loadings (pure copper, aluminium, AISI 316 stainless steel…) for comparison with experiment. It should be noticed that no adjustable parameter is used.

The backstress model presented here has been used to compute the division of the backstress into inter- and intragranular parts for deformed polycrystals. The ratios between these two kinds of backstresses have been computed on both grain and polycrystal scales. The two macroscopic polycrystal backstress components are assumed to be equal to those of well-oriented grains because these grains seem to glide first during unloading; this corresponds to the definition of the macroscopic backstress. The evolution of the computed backstresses is now described. Once deformation induced dislocation microstructures appear, the intragranular part increases more rapidly than the intergranular part. However, for large strains, both inter- and intragranular backstresses stabilize. These results agree once more with experimental measurements on the grain scale in polycrystals.

Work is in progress concerning improved modelling considering enrobed inclusions (three phase model [12]).

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