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ON SLIGHTLY DISORDERED QUASI RATE-INDEPENDENT VISCOPLASTIC FCC-POLYCRYSTALS

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Summary Geometry and kinematics of intragranular as well as intergranular plastic deformation of polycrystals are discussed. Elastic strain is covered by the effective medium homogenization method inside a representative volume element (RVE). Evolution equation formed by tensor representation is derived from very simple micro-evolution equation. It has incremental form obtained by Vakulenko's concept of thermodynamic time. The rate dependence takes place by means of stress rate dependent value of the initial yield stress. Following [3] strain geometry is based on constrained micro and free macro rotations in intermediate reference configuration. This leads to the fact that evolution equation for plastic spin of RVE is an outcome of evolution equation for plastic stretching. The theory is applied to slightly disordered fcc-polycrystals. For some characteristic given stress histories (with low, medium and high strain rates) the micro-meso transition is tested and number of active slip systems grains are found and compared with so-called J2-approach.

INTRODUCTION

Background

a1) *Rabotnov's delay*. An incremental evolution equation accounts for diverse process speeds by means of dependence of initial yield stress on stress rate. Here the notion of Rabotnov's plastic strain initiation delay is employed.

a2) *Incrementality* is based on almost exact experimentally observed proportionality of equivalent stress rate and equivalent plastic strain rate. It is given by an universal material constant constituting most important part of hereditary Rabotnov's kernel. The constant holds for diverse multiaxial stress histories and a wide range of strain rates - as it has been found in [1].

a3) *Non-associate flow rule*. The equation is not necessarily of associate type i.e. plastic stretching could be not perpendicular to loading surface. However, if it is of associate type, then only four material constants suffice for very high correlation coefficient when calibrating it for processes mentioned in a2-property.

a4) *Tensor function representation* has been extensively used in [1,4,5,6,7] for its development along the line developed by Sawczuk, Murakami and Boehler in the field of inelasticity. Such an approach makes question of induced anisotropy logical and easy.

a5) *Thermodynamic background* fits into the Vakulenko's concept of thermodynamic time [2]. However, it has been necessary to extend his concept of steady aging introducing either accelerated or decelerated aging in order to cover creep-plasticity interaction. Most specifically the Langevin ageing function is shown to describe all three known regimes of creep behavior.

a6) *Plastic spin issue*. The controversial issue of plastic spin has been solved in the mentioned papers by the concept of fixing of orientations of intermediate reference configurations [3]. Thus we have not needed any new material constants apart those already appearing in the evolution equation for plastic stretching [4].

Problems treated previously

b1) *Localized instability of stainless steel sheets.* Nonproportional dynamic stress histories at wide range of plastic strain rates have been analyzed in [5]. The a1-a6 model has shown considerable stability at very large strains and gave smooth transition to localization commence. However, the J2-based associate flow rule with the so-called universal flow curve has been shown to be too stiff for a reliable prediction of advanced strains particularly for localization onset giving rise to unrealistically low failure strains and forming limit diagrams with vertical asymptotes.

b2) *Thermo-ratchetting with 3D viscoplastic strain*. A rectangular block made of AISI 316H austenitic stainless steel with one of its sides is loaded by constant normal stress whereas two lateral side surfaces are acted upon by harmonically variable shear stress [6]. It is known from experiments that such temporal variation induces progressive but saturated increase of axial strain in the direction of tension stress components. The strain rate is of the order of [0.001, 1000] s^{-1}. The model with 6 material constants (plastic stretching is second order polynomial in stress and linear in plastic strain) is compared with extended Perzyna-Chaboche's model (with 8 material constants) having incorporated evolution equations for back stress and equivalent flow stress. Comparison with experiments has shown better agreement of a1-a6 model.

b3) *The Hopkinson bar apparatus* consisted of two elastic long bars enclosing much smaller specimen [7]. Unlike traditional viscoplasticity where only elastic wave speeds are met, the quasi rate-independent model permitted visco-plastic wave speeds in the obtained hyperbolic wave equation. The numerical analysis gives experimentally observed homogeneous stress as well as inelastic strain up to 50%-strains.

EVOLUTION AND CONSTITUTIVE EQUATIONS

Geometric preliminaries

The total deformation tensor of an representative volume element (RVE) consists (according to Kroener's rule) of two incompatible constituents – plastic and elastic distortion tensors. It is essential that according to [3] plastic rotation of natural state reference configuration elements is arbitrary. On the other hand, RVE is composed of N monocrystal grains, such that each grain has N slip systems (for instance, for fcc crystals N=12). Comparing a RVE in natural state initial and current configurations we may write Kroener's formula for micro-distortions. However, there is an essential difference – micro-plastic (and accordingly micro-elastic) rotations of individual grains are constrained. Since arbitrary plastic meso-rotation is assumed to be unity. This has two important consequences: 1. an improved Taylor's procedure in numerical treatment of polycrystals and 2. abundance of new material constants in evolution equation for plastic spin.

Hooke's Law By Homogenization Approach

For treating elastic meso and micro-strains the effective medium variant of the self-consistent method [8] is applied with an assumption that for monocrystals residual microstrains they are negligible. Moreover for considered fcc-polycrystals slight disorder is assumed such that all the grains are almost aligned giving rise to anisotropy. Then the effective Hooke's tensor has the approximate simplified form:

$$D_\Lambda^{eff} = D_M \left\{1 + D_\Lambda \left(1 + \langle S \rangle D_\Lambda - \langle SD \rangle\right)\right\} \tag{1}$$

where D is stiffnes tensor (subscript M stands for the imagined matrix – average of grains and Λ for a grain) and S is the Eshelby tensor. Angular parentesses denote spatial averaging like in [8]. It is worth noting that the simplest linear approximation for the effective grain stiffnesses is worthless since it does not include Eshelby tensor at all.

Evolution equation – micro to meso transition

A special attention is paid to associativity of flow rule based on loading function and derived by Rice. The experimental evidence (cf. [1]) has shown that real time has to be replaced by a thermodynamic Vakulenko's time ζ [2]. If such a time is the same for all the grains then normality could hold. In such a case the meso evolution equation reads (**T** is the stress, $\mathbf{e}_P$ – plastic strain and $\mathbf{M}_\Sigma$ – Spenser-Boehler's tensor describing anisotropy type):

$$\mathbf{D}_P = \partial_T \Omega\left(\mathbf{T}, \mathbf{e}_P, \mathbf{M}_\Sigma\right) D\zeta / Dt\ . \tag{2}$$

In the sequel a special type of tensor representation described in [1] is used. When thermodynamic time is a nonlinear function of plastic power (i.e. non-steady aging happens) the above equation covers creep-plasticity interaction as well.

Some numerical experiments

In order to explore whether a simple micro-evolution equation leads to tensor representation such an equation is integrated for some characteristic strain histories and calibration of an assumed meso-evolution equation is performed. Meso-micro transition is used for computer simulation in two cases of a RVE composed of N=1000 as well as N=125 fcc-grains with slightly disordered crystal orientations and 12 potential slip systems.Residual stresses and number of active slip systems are found. The RVE was loaded by slow and fast stresses with three typical stress states: uniaxial tension, uniaxial shear (with one principal stress vanishing and the other two being opposite) and equibiaxial shear. In all cases smooth increase of active slip systems has been remarked during stress growth.A comparison with J_2-theory is given.

CONCLUSIONS

a) Meso-evolution equation is derived from simple micro-evolution equation. Conditions of associativity of flow rule are derived and connected to concept of thermodynamic time.
b) Plastic spin isue is discussed and clarified.
c) Vakulenko's thermodynamic time must be extended to include non-steady ageing property if we want to describe coupled inelastic processes like plasticity-creep interaction.
d) The constitutive model proposed here has shown much smaller number of active slip systems than J_2-model. Moreover J_2-model was unable to distinguish among fast and slow processes being in such a way rate independent by its very nature.

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