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Microstructural Pattern Formation in Finite-Deformation Single-Slip Crystal Plasticity under Cyclic Loading: Relaxation vs. Gradient Plasticity

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Abstract

We investigate microstructure formation and evolution during cyclic loading in rate-dependent crystal plasticity at finite strains. The non-quasiconvex free energy density in multiplicative single-slip crystal plasticity leads to fine-scale microstructure whose characteristics and resulting effective stress-strain response are studied by two independent approaches: (i) using an incremental formulation based on variational constitutive updates we approximate the quasiconvex hull by *lamination*, i.e. by constructing an energy-minimizing first-order laminate microstructure, and (ii) a *strain-gradient plasticity* model applied to a representative unit cell whose effective properties are obtained from homogenization. In the lamination model, three different formulations for updating the accumulated plastic strains are compared and discussed with a specific focus on identifying a suitable description to account for hardening due to changes of the laminate volume fractions. The gradient-plasticity model also predicts a first-order laminate microstructure to form at a comparable stress level upon microstructure initiation. However, the energy associated with the dislocation network is shown to affect the microstructure evolution, leading to considerably higher strain levels at laminate initiation and a stress overshoot. In both models, cyclic loading leads to a degeneration of the stress-strain hysteresis which ultimately experiences elastic shakedown. The amount of work hardening significantly depends on how fast the degeneration occurs. To allow for a comparison, we consider cyclic loading after pre-deformation in the gradient model which delays the degeneration of the stress-strain hysteresis. For low hardening, the two models predict differences in the stress-strain hysteresis, mainly owing to laminate migration in the gradient-plasticity model. As work hardening increases, this phenomenon is restricted and the agreement of the effective stress-strain response is excellent between the two models. Accounting for the energy stored in domain walls leads to a delayed lamination which is in agreement with the gradient plasticity model.

Key words: microstructure, plasticity, finite deformation, cyclic loading, relaxation,

1. Introduction

The mechanical behavior of most materials of engineering interest is determined by a present or emergent underlying microstructure which is a direct result of physical mechanisms occurring at lower length scales. Sufficiently large levels of deformation or a combined thermo-mechanical history result in a permanent reconfiguration of microstructural defects. In particular in crystalline solids such as metals or ceramics, such plastic deformation is linked to the motion and interaction of the complex network of dislocations, point defects, and grain boundaries, to name but a few. Under sustained loading, the microstructure evolution process can eventually result in a spatially heterogeneous deformation field at the macroscale, when high plastic deformation localizes e.g. in shear bands or persistent slip bands. Such heterogeneous deformation results from the thermodynamically-driven self-organization of dislocations to reduce the stored energy in the crystal. Theoretically, this behavior has been explained by energy relaxation: the non-quasiconvexity of the energy density leads to the formation of fine-scale patterns of minimal energy,

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