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Constitutive modeling of strain rate effects in nanocrystalline and ultrafine grained polycrystals

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ABSTRACT

We present a variational two-phase constitutive model capable of capturing the *enhanced rate sensitivity* in nanocrystalline (nc) and ultrafine-grained (ufg) fcc metals. The nc/ufg-material consists of a grain interior phase and a grain boundary affected zone (GBAZ). The behavior of the GBAZ is described by a *rate-dependent* isotropic porous plasticity model, whereas a *rate-independent* crystal-plasticity model which accounts for the transition from partial dislocation to full dislocation mediated plasticity is employed for the grain interior. The scale bridging from a single grain to a polycrystal is done by a Taylor-type homogenization. It is shown that the *enhanced rate sensitivity* caused by the grain size refinement is successfully captured by the proposed model.

1. Introduction

The inelastic deformation behavior of polycrystalline materials, in particular the influence of grain size (d) on material properties and active deformation mechanisms, has long been the subject of intensive research. After the synthesis of polycrystalline materials with grain sizes lower than ~100 nm, which are often denoted as nanocrystalline (nc) materials, the research efforts in this area have further grown and numerous review articles have been published; comprehensive lists of literature may be found in recent reviews (Dao et al., 2007; Gleiter, 2000; Koch, 2007; Kumar et al., 2003; Meyers et al., 2006; Saada and Dirras, 2009; Weertman, 2007; Wolf et al., 2005) and monographs (Cherkaoui and Capolungo, 2009; Ramesh, 2009). Nc-materials are known to posses several distinct features when compared to coarse grained polycrystals. These include high strength and fatigue resistance, low ductility, pronounced rate and temperature dependence, tension–compression asymmetry and susceptibility to plastic instability. In this paper we will focus on the pronounced rate dependence of nc-fcc metals.

The strain rate sensitivity of metals is often described as the variation of flow stress with strain rate at constant temperature for a given strain level. The non-dimensional strain rate sensitivity exponent is also defined as (Asaro and Suresh, 2005; Wei et al., 2004)

$$m = \frac{\sqrt{3} k_B T}{\sigma_y V}, \tag{1}$$

where k_B is the Boltzmann constant, T is the absolute temperature, σ_y is the flow stress and V is the activation volume, i.e., the derivative of the activation enthalpy with respect to the effective shear stress (Asaro and Suresh, 2005; Kocks et al., 1975; Wei et al., 2004). The rate sensitivity exponent m and the activation volume V can be measured from quasistatic tensile experiments as (Caillard and Martin, 2003; Wei, 2007)

$$m = \frac{\partial \ln \sigma_y}{\partial \ln \dot{\varepsilon}} \quad \text{and} \quad V = \sqrt{3} k_B T \frac{\partial \ln \dot{\varepsilon}}{\partial \sigma_y}, \tag{2}$$

where $\dot{\varepsilon}$ is the applied tensile strain rate. Conventional fcc metals have a large activation volume, e.g. $V \sim 100 - 1000b^3$ where b is the Burgers vector, which leads to lower values for the rate sensitivity exponent m through the relation (1). The strain rate sensitivity m is approximately 0.002–0.006 for most coarse grained fcc metals (Dalla Torre et al., 2005; Wang et al., 2006; Zehetbauer and Seumer, 1993; Zhang et al., 2009). These large values for the activation volume are associated with running dislocations cutting through existing forest dislocations in grain interiors. On the other hand, the activation volumes for grain boundary (GB) diffusion and sliding processes are much lower, e.g. $V \sim 1 - 10b^3$, representing a lower bound for the activation volume in polycrystalline materials. Therefore, GB-diffusion mediated diffusional creep and the GB-sliding mechanisms entail rate sensitivity exponents of $m = 1.0$ and $m = 0.5$, respectively (Wang et al., 2006). Note that although there is a marked reduction in activation volume with grain size refinement as reported in Chen et al. (2006), Guduru et al. (2007), Wang

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