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Plane-strain discrete dislocation plasticity incorporating anisotropic elasticity

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ABSTRACT

The increasing application of plane-strain testing at the (sub-) micron length scale of materials that comprise elastically anisotropic cubic crystals has motivated the development of an anisotropic two-dimensional discrete dislocation plasticity (2D DDP) method. The method relies on the observation that plane-strain plastic deformation of cubic crystals is possible in specific orientations when described in terms of edge dislocations on three effective slip systems. The displacement and stress fields of such dislocations in an unbounded anisotropic crystal are recapitulated, and we propose modified constitutive rules for the discrete dislocation dynamics of anisotropic single crystals. Subsequently, to handle polycrystalline problems, we follow an idea of O'Day and Curtin (J. Appl. Mech. 71 (2004) 805–815) and treat each grain as a plastic domain, and adopt superposition to determine the overall response. This method allows for a computationally efficient analysis of micro-scale size effects. As an application, we study freestanding thin copper films under plane-strain tension. First, the computational framework is validated for the special case of isotropic thin films modeled by means of a standard 2D DDP method. Next, predictions of size dependent plastic behavior in anisotropic columnar-grained thin films with varying thickness/grain size are presented and compared with the isotropic results.

1. Introduction

Understanding mechanical size effects has become a central topic in materials science and engineering due to the recent trend of miniaturization in numerous technological applications, e.g. MEMS. Among various mechanisms leading to a strong size dependency in micro-scale crystalline solids, the most known and well-explored sources are plastic strain gradient, geometrically necessary dislocations and constraints/freedoms on motion/nucleation of dislocations due to grain boundaries/free surfaces or any other internal interfaces. Conventional continuum plasticity is length-scale independent and is based on the concept of homogeneous deformation, precluding size effects, thus inappropriate to solve micro-scale problems accurately. On the other hand, a micro-scale problem is too large for fully atomistic modeling, while small enough that individual dislocation effects are important and cannot be averaged into a classical continuum plasticity constitutive law. Although many attempts have been made to reproduce size effects in nonlocal plasticity theories (e.g. Fleck and Hutchinson, 2001; Gurtin, 2002; Acharya and Bassani, 2000), an alternative technique, the discrete dislocation dynamics has effectively captured micro-scale size dependency.

The discrete dislocation plasticity (DDP) adopts a continuum description of the elastic lattice and retains individual dislocations as carriers of plastic deformation. DDP has received a significant area of applications after development of the superposition method by Van der Giessen and Needleman (1995) for solving a boundary value problem (BVP). In such a DDP framework, long-range interactions between dislocations are directly accounted for through their linear elastic fields, while short-range phenomena, including dislocation motion, nucleation, annihilation and pinning at obstacles, are incorporated through constitutive rules. Although the framework is fully three dimensional, it has been used mostly in solving two dimensional plane-strain BVPs. Past studies include the analysis of micro-scale plasticity near cracks (e.g. Cleveringa et al., 2000; O'Day and Curtin, 2004; Deshpande et al., 2002) or indenter tips (e.g. Widjaja et al., 2005, 2007) and investigations of microstructural size effects in bulk (Cleveringa et al., 1997; Balint et al., 2008; Guruprasad et al., 2008) and thin film materials (Nicola et al., 2003, 2005b; Shishvan and Van der Giessen, 2010; Shishvan et al., 2010).

By construction, DDP describes anisotropic plasticity, as defined by the available slip systems in the crystal, but so far all applications have assumed elastic isotropy. However, real crystals are anisotropic and it remains unclear how important this is. The

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