Accepted Manuscript

Obstacles and sources in dislocation dynamics: Strengthening and statistics of abrupt plastic events in nanopillar compression

S. Papanikolaou, H. Song, E. Van der Giessen

PII: S0022-5096(16)30411-2
DOI: 10.1016/j.jmps.2017.02.004
Reference: MPS 3061

To appear in: *Journal of the Mechanics and Physics of Solids*

Received date: 16 June 2016
Revised date: 31 January 2017
Accepted date: 9 February 2017

Please cite this article as: S. Papanikolaou, H. Song, E. Van der Giessen, Obstacles and sources in dislocation dynamics: Strengthening and statistics of abrupt plastic events in nanopillar compression, *Journal of the Mechanics and Physics of Solids* (2017), doi: 10.1016/j.jmps.2017.02.004

Obstacles and sources in dislocation dynamics: Strengthening and statistics of abrupt plastic events in nanopillar compression

S. Papanikolaou [a,*], H. Song[a,b], E. Van der Giessen [b,*]

[a] *Department of Mechanical Engineering, The Johns Hopkins University, 3400 N Charles St, Baltimore, Maryland, 21218*
[b] *Zernike Institute for Advanced Materials, University of Groningen, 9747 AG Groningen, the Netherlands*

Abstract

Mechanical deformation of nanopillars displays features that are distinctly different from the bulk behavior of single crystals: Yield strength increases with decreasing size and plastic deformation comes together with strain bursts or/and stress drops (depending on loading conditions) with a very strong sensitivity of the stochasticity character on material preparation and conditions. The character of the phenomenon is standing as a paradox: While these bursts resemble the universal, widely independent of material conditions, noise heard in bulk crystals using acoustic emission techniques, they strongly emerge primarily with decreasing size and increasing strength in nanopillars. In this paper, we present a realistic but minimal discrete dislocation plasticity model for the elasto-plastic deformation of nanopillars that is consistent with the main experimental observations of nano pillar compression experiments and provides a clear insight to this paradox. With increasing sample size, the model naturally transitions between the typical progressive behavior of nanopillars to a behavior that resembles evidence for bulk mesoscale plasticity. The combination of consistent strengthening, large flow stress fluctuations and critical avalanches is only observed in the depinning regime where obstacles are much stronger than dislocation sources; in contrast, when dislocation source strength becomes comparable to obstacle barriers, then yield strength size effects are absent but plasticity avalanche dynamics is strongly universal, across sample width and aspect-ratio scales. Finally, we elucidate the mechanism that leads to the connection between depinning and size effects in our model dislocation dynamics. In this way, our model builds a way towards unifying statistical aspects of mechanical deformation across scales.

Keywords: pillar compression, dislocation dynamics, size effect, abrupt plastic events, avalanches, depinning

1. Introduction

The dynamical character of crystal plasticity at the nanoscale has been under scrutiny for more than a decade (Uchic et al., 2003, 2004, 2005; Dimiduk et al., 2006; Uchic et al., 2009; Kraft et al., 2010; Greer and De Hosson, 2011). This interest is driven by the identification of unconventional plasticity size effects in the uniaxial deformation of samples made by the focused ion beam technique. Experiments of nanocrystalline pillar tension and compression have convincingly shown apparent strengthening with decreasing pillar width w, with the yield strength varying as $\sigma_Y \sim w^{-n}$ with $n \in (0.4, 0.8)$ (Uchic et al., 2009; Greer and De Hosson, 2011), and a mild decrease with slenderness $\alpha = h/w$ (Volkert and Lilleodden, 2006; Kiener et al., 2008; Senger et al., 2011). The mechanism of strengthening in nanopillars has been attributed to the exhaustion of typical dislocation mechanisms and to a transition from typical Frank-Read sources in the bulk to the predominance of atypical sources such as surface sources (Gall et al., 2004; Park et al., 2006; Diao et al., 2006) and single-arm sources (Weinberger and Cai, 2008; Oh et al., 2009; Zheng et al., 2010; Lu et al., 2010; Ryu et al., 2015).

*Corresponding authors
Email address: spapanikolaou@jhu.edu, E.van.der.Giessen@rug.nl (E. Van der Giessen)