International Journal of Solids and Structures 51 (2014) 4519–4530

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

A stochastic model for the temporal aspects of flow intermittency in micropillar compression

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ARTICLE INFO

Article history:
Received 26 February 2014
Received in revised form 20 August 2014
Available online 16 September 2014

Keywords:
Crystal plasticity
Intermittency
Finite element simulation
Micropillar
Stochastic nature

ABSTRACT

Systematic experimental investigations have demonstrated that the plastic deformation of micropillar proceeds through a sequence of intermittent bursts, the sizes of which follow power-law statistics. In this study, a stochastic model based on the power-law distribution of burst size is formulated in the framework of crystal plasticity in order to investigate the temporal aspects of flow intermittency in micropillar compression. A Monte Carlo simulation scheme is developed to determine the burst size when a burst activity is captured. This burst size is considered as the displacement boundary condition of burst deformation. Three-dimensional finite element analysis of the model is performed and its predictions are validated by comparison with results from both micro-compression experiments and simulation tests of bulk crystals using the classic crystal plasticity finite element method (CPFEM). The model provides a reasonable prediction of stress–strain responses both at the macroscopic and microscopic scales. Finally, the capability of this model is shown with applications to the intermittent plastic deformation in micropillar compressions, in particular for their burst time durations and burst velocities. The results from such stochastic finite element analysis are shown to be consistent with earlier experimental findings and results of mean-field theory.

1. Introduction

The intermittent characteristic of plastic deformation is considered to be an intrinsic feature (Csikor et al., 2007) that is characterized by a series of burst activities, as shown in the compression tests of single crystalline micropillars (Dimiduk et al., 2006a; Ng and Ngan, 2008; Uchic et al., 2004). The characteristic sizes of the burst activities in micropillar plasticity have already been studied by many researchers and it has been demonstrated that the burst sizes range over at least two orders of magnitude and follow a power-law behavior with an exponential cut-off (Brinckmann et al., 2008; Csikor et al., 2007; Papanikolaou et al., 2012a; Zaiser and Aifantis, 2006). There have been fewer studies on the temporal aspects of burst activity, such as burst time duration and burst velocity. Among such studies, recent experiments have reported that larger burst size is generally associated with longer burst duration (Dimiduk et al., 2010; Maaß et al., 2013; Zaiser et al., 2008). This suggests that the distributions of burst size and burst time duration may be characterized by similar scaling functions.

The micro-compression tests provide a means for direct quantitative description of the statistical attributes of burst sizes as well as burst time durations. However, this type of experimental methodology is facilitated by small volumes of samples. Mesoscope scale investigations (larger than ~20 μm diameters) face the problem of requiring long milling times for preparing micro-samples (El-Awady et al., 2013), particularly for purposes of statistic investigations that require larger number of samples. Furthermore, because of the limited time resolution of apparatus and the frequency of data recorded, the accuracy of measurements is often a concern (Dimiduk et al., 2010; Maaß et al., 2013; Papanikolaou et al., 2012b).

There have been many simulation studies to complement experimental investigations on intermittent plasticity. These simulations include three-dimensional (3-D) dislocation dynamics (DD) simulations (3D-DDS) (Csikor et al., 2007), Monte Carlo (MC) simulation (Ng and Ngan, 2008), molecular dynamics (MD) (Xu et al., 2012) and other numerical algorithms (Greer and Nix, 2006; Zaiser and Aifantis, 2006; Zhang and Aifantis, 2011). These simulations mainly focus on the intermittent deformation of single-crystal metallic

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http://dx.doi.org/10.1016/j.ijsolstr.2014.08.028
0020-7683/

samples in submicrometer and nanometer ranges. For mesoscale plasticity, dislocation-dynamics methods continue to be a formidable challenge.

For the micropillars of larger sizes, the reported experimental stress–strain behavior appears to remain in stage I glide throughout the test, similar to those of bulk crystals (Dimiduk et al., 2007, 2005). Thus, the employment of continuum crystal plasticity theory to obtain a better understanding of micropillar plasticity may be warranted (Kuroda, 2013; Zhang and Shang, 2014). Some attempts have been made to directly correlate appropriate constitutive models to finite element (FE) analysis that can handle complex geometry easily, apply boundary conditions accurately and compute efficiently. In most cases, FE simulations using the phenomenological (Jérusalem et al., 2012; Maaß et al., 2009; Raabe et al., 2007; Zhang and Shang, 2014) and dislocation-based crystal plasticity theories (Hurtado and Ortiz, 2012; Kuroda, 2013) are employed to study micropillar plasticity because they can analyze microscopic heterogeneity associated with plastic deformation in materials and address the issue of high strain rate in dislocation dynamics simulations.

Some FE analyses using crystal plasticity models have already been employed to study size-dependent flow strength (Hurtado and Ortiz, 2012), microplastic deformation mode (Kuroda, 2013) and smoother transition to plasticity observed in micro-compression tests (Jérusalem et al., 2012). A general introduction of strain bursts into the crystal plasticity finite element framework that is capable of capturing the strain bursts in the macroscopic stress–strain behavior of single crystalline micropillar compressions, has been described in Zhang and Shang (2014). This model can calculate the burst time duration for a certain amplitude of strain burst.

In this paper, we propose a stochastic model for the intermittent plastic process in the compression of single crystal pillars with diameters in the range from ~10 μm to 3 mm. The aim is to study the temporal aspects of flow intermittency with various magnitudes of strain bursts, such as burst time duration and burst velocity. For this purpose, the present model incorporates the observed power-law distribution of strain burst into a crystal plasticity framework (Zhang and Shang, 2014). In order to reproduce the power-law behavior of strain bursts, a Monte Carlo (MC) stochastic method is employed to determine the burst size (if a burst activity is captured in the model). In this case, the simulation results (i.e. burst time duration and burst velocity) account for the scaling behavior of strain bursts. The results of our analysis show that the distribution of burst time durations exhibits a power-law behavior with an exponential cut-off, suggesting the same scaling behavior as burst sizes. Analysis of the burst velocities from different sized samples show that they follow a power-law behavior and the derived scaling exponents are consistent with that derived from mean-field theory.

The paper is organized as follows. In Section 2 we begin by a presentation of the plastic flow process in the context of burst activities, followed by an introduction of the stochastic behavior of displacement burst. Its probability density function (PDF) in the form of power-law with cutoff, is reproduced by using a Monte Carlo stochastic method, which can approximately determine the burst size once a burst activity occurs. Section 3 briefly reviews the basic equations of crystal plasticity and develops the crystal plasticity framework that takes into account the stochastic nature of strain burst. In Section 4, we describe an implementation of above constitutive model into the finite element system ABAQUS, and verify this model by comparing its predictions with those from the CPFEM (Huang, 1991; Kysar, 1997) at macroscopic scales and with the experimental observations (Dimiduk et al., 2005) at microscopic scales. Section 5 presents a stochastic finite element study on the temporal aspects of flow intermittency in the compression tests of nickel micropillars with diameters larger than ~10 μm. The simulation results including distribution of burst time durations and burst velocity, are discussed in detail. Finally, Section 6 summarizes the results.

2. Flow intermittency in micropillar deformation

2.1. Flow process

We study the micropillar deformation under the hybrid loading mode (HLM). This testing method controls the displacement rate of indentation platen at a constant value and does not obviously decrease the load imposed by the nanoindentation system during a rapid strain burst. Fig. 1 is a schematic plot of micropillar displacements, shear stress vs. time from the experimental observations under the HLM (Dimiduk et al., 2006a) and a complete description of the flow process in micropillar deformation is provided elsewhere (Zhang and Shang, 2014). From this figure one may observe that the plastic flow expressed in the form of the displacement–time curve includes three distinct parts: burst slip part (Δt^b), holding stage (Δt^h) and loading stage (nearly elastic loading, Δt^l). The burst slip part and holding stage together constitute a strain burst as shown in Fig. 1.

The burst slip part is represented by a line segment with a slope larger than that of the imposed displacement by the nanoindentation system. This is because a burst slip can lead to a rapid sudden displacement on the top surface of specimen, and render the cumulative displacements larger than the imposed value. At the same time, the burst slip can cause the springs that suspend the indentation platen to be suddenly elongated. Since these springs are very compliant, the load drop could be neglected when compared with the total cumulative load applied on the specimen. In the case of very low feedback frequency, the stress is always observed to be nearly constant within a burst slip from experimental force–displacement curves (Dimiduk et al., 2005; Uchic and Dimiduk, 2005).

The holding stage is ideally represented by a horizontal line segment in the displacement–time curve (Fig. 1). It occurs because the burst slip results in a small load drop in the total applied force, causing its value to be smaller than the internal stress of specimen. In fact, as such a process proceeds, there are always finite plastic displacements occurring in terms of quiescent avalanches (Ispánovity et al., 2010; Maaß et al., 2013; Papanikolaou et al., 2012a) induced by cross-slips or other slower relaxation processes (Dimiduk et al., 2006b; Papanikolaou et al., 2012a). These displacements appear to be negligible since the displacement vs. time curves within the holding sections always exhibit small positive slopes (Dimiduk

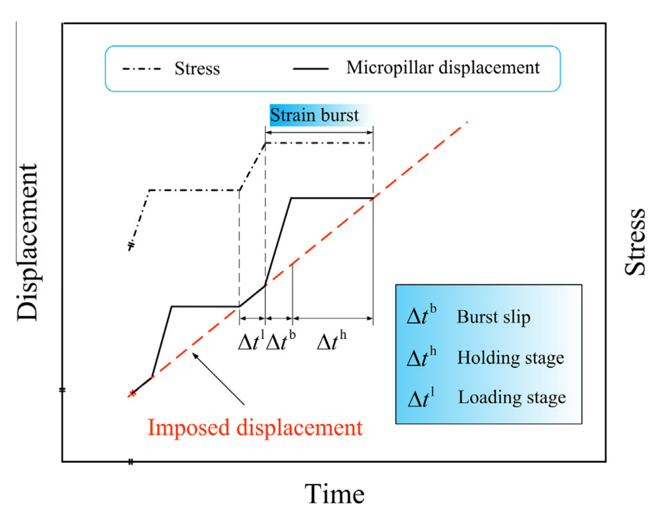

Fig. 1. Schematic drawing of cumulative displacements and stress vs. time curves in micropillar compression under the HLM.