International Journal of Plasticity 85 (2016) 110–129

Contents lists available at ScienceDirect

International Journal of Plasticity

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

Spatial distribution of the net Burgers vector density in a deformed single crystal

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ARTICLE INFO

Article history:
Received 5 December 2015
Received in revised form 30 June 2016
Available online 16 July 2016

Keywords:
B. Crystal plasticity
C. Finite elements
A. Dislocations
B. Constitutive behavior
Single crystal

ABSTRACT

A two-dimensional deformation field on an indented single crystal, where the only non-zero lattice rotation occurs in the plane of deformation and only three effective in-plane slip systems are activated, is investigated both experimentally and numerically. Electron Backscatter Diffraction (EBSD) is utilized to probe the lattice rotation field on the sample. The lattice rotation field is utilized to calculate the two non-zero components of Nye's dislocation density tensor, which serves as a link between plastic and elastic deformation states. The enhanced accuracy of EBSD enabled measurements of the net Burgers vector density, and a new quantity β, which monitors the activity of slip systems in the deformed zone. The β-field is compared to the slip system activity obtained by analytical solution and also by crystal plasticity simulations. A qualitative comparison of the three methods confirms that the β-field obtained experimentally agrees with the slip system activity obtained analytically and by numerical methods.

1. Introduction

The Burgers vector, **b**, is a fundamental quantity in the study of dislocation-mediated plastic deformation that denotes the magnitude and direction of discrete atomic-scale plastic slip events on a slip plane with unit normal vector **n** due to the motion of a single dislocation. As illustrated in Fig. 1 (a) and (b), the Burgers vector is determined by taking a Burgers circuit on the crystal lattice around an area pierced by an isolated dislocation line. Sustained plastic deformation requires the creation of a great many dislocations that move and ultimately come to rest in the crystal lattice. The final dislocation content is a signature of the plastic deformation that created it. As illustrated in Fig. 1(c) and (d), a Burgers circuit to characterize the final dislocation content will, in general, contain many dislocations from several different slip systems. The closure failure vector, denoted as $\mathbf{b}^p_{net}$, is the sum of the Burgers vectors piercing the circuit. The net Burgers vector density is the normalization of the closure failure vector by the area A, which is bounded by Γ as illustrated in Fig. 1.

The geometric relations in crystalline solids with line defects have been studied by means of a dislocation density tensor. This revealed a direct connexion between the elastic and plastic portions of the deformation gradient tensor (Nye, 1953). The dislocation density tensor (Nye, 1953; Kröner, 1958; Bilby et al., 1958), also referred to as Nye's dislocation density tensor, is a second-rank tensor, and determines the state of dislocation in a deformed crystal. It can also be defined as a linear transformation of a unit tangent vector to the net Burgers vector density. The geometric relations defined by Nye (1953) relate to the lattice curvature calculations, and to the geometrically necessary dislocations that are necessary to form a lattice

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http://dx.doi.org/10.1016/j.ijplas.2016.07.005
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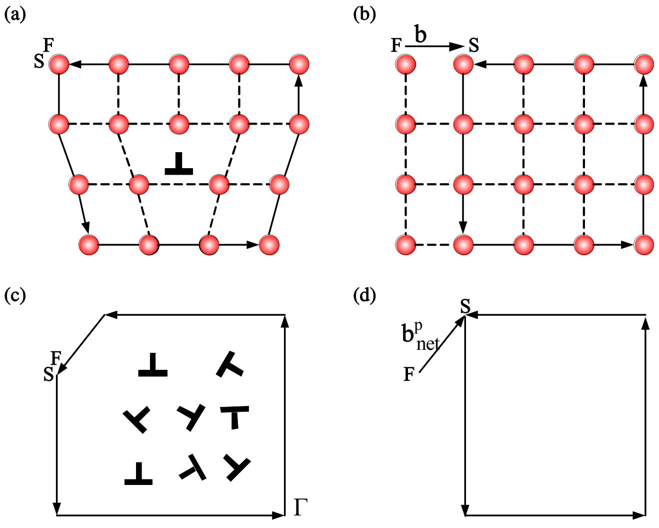

Fig. 1. Crystal lattice and the Burgers circuits: (a) Crystal lattice with a single dislocation, (b) the Burgers vector, **b**, (c) Crystal body with multiple dislocations (d) the net Burgers vector, $\mathbf{b}^p_{net}$.

curvature. The geometrically necessary dislocations (GNDs) contribute to Nye's dislocation density tensor, and can be estimated using some minimization scheme (Arsenlis and Parks, 1999; Kysar et al., 2010). The rest of the dislocations, which make no contribution to Nye's dislocation density tensor, are called the statistically-stored dislocations (SSDs). SSDs accumulate in single crystals during a plastic deformation process (Ashby, 1970).

Nye's dislocation density tensor can be measured from the elastic portion of the deformation gradient tensor, which is associated with the lattice rotation and strain of the crystal lattice. The gradient of the lattice rotation measurements about the three perpendicular axes gives the lattice curvature tensor. There are several ways to accomplish the measuring of lattice rotations. The common method is to measure the orientations of the crystal lattice using Orientation Imaging Microscopy (OIM) (Adams et al., 1993; Adams, 1997), also known as Electron Backscatter Diffraction (EBSD). The method essentially employs a fully-automated scanning technology and EBSD-patterns to obtain 2D-images of lattice distortions (Gardner et al., 2010). Sun et al. (2000) reported the lattice curvature patterns of a plastically deformed high purity Al bicrystal using lattice orientations measured by conventional EBSD. El-Dasher et al. (2003) also measured the lattice curvature through conventional EBSD to estimate GNDs, and discussed the principal limitations of the conventional EBSD method. Orientation gradients of deformed Al single crystals and polycrystals have been measured by other researchers (Field et al., 2005; Pantleon, 2008) using this method. Pantleon (2008) addressed the limitation of the conventional EBSD method in which there is no possibility to measure the curvatures along the third direction. Beausir and Fressengeas (2013) used EBSD orientation mapping to quantify rotational defects in polycrystalline materials. To eliminate the disadvantages associated with angular and spatial resolution, High Resolution Electron Backscatter Diffraction (HR-EBSD) has been used by researchers to measure elastic strains, lattice rotations and GNDs (Britton and Wilkinson, 2011; 2012; Maurice et al., 2012; Ruggles and Fullwood, 2013; Jiang et al., 2015). The problem of quantifying the out-of-plane components of the elastic deformation gradient tensor can be eliminated using different methods. The first method is to use X-ray microbeam diffraction method to measure lattice rotation and lattice strains (Larson et al., 2004, 2007; Ice et al., 2005; Ohashi et al., 2009; Hofmann et al., 2013; Pang et al., 2014). With X-ray microbeam diffraction, it is possible to probe GNDs and lattice distortions much deeper in the sample. A comprehensive study has been performed by Field et al. (2010) to compare the strain measurements in deformed crystals using both EBSD and X-ray microbeam diffraction. The second method is to use EBSD or Transmission Electron Microscopy (TEM) to measure lattice rotation fields via serial sectioning of the sample by Focused Ion Beam (FIB) (Kiener et al., 2006; Zaafarani et al., 2006; Rester et al., 2007; Demir et al., 2009). The third method is to introduce a two-dimensional plane strain deformation state where all out-of-plane lattice rotations are negligible, in other words, the nonzero components of the lattice curvature tensor can only be obtained from the in-plane lattice rotations (Kysar and Briant, 2002; Gan et al., 2006; Kysar et al., 2007, 2010).

The objective of the present study is to define a new variable, β, for validation of existing elastic–plastic constitutive models and obtain direct information about the state of the material (N.B. In the present study, the authors will not suggest a new constitutive solution, and will not extend the existing constitutive models in any way with the use of the β-variable defined herein). To do so, a Scanning Electron Microscopy (SEM) and EBSD method was used to measure in-plane lattice rotations. The gradient of in-plane lattice rotation field gives the non-zero components of the lattice curvature tensor, which correspond to non-zero components of Nye's dislocation density tensor. Nye's dislocation density tensor, which is a linear