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Shielding effects of disclinations on the elliptical blunt crack

Yingxin Zhao [a], Qihong Fang [a,b,*], Youwen Liu [a], Chunzhi Jiang [a,c]

[a] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, PR China
[b] School of Mechanical and Manufacturing Engineering, The University of New South Wales, NSW 2052, Australia
[c] Department of Physics and Electronic Information Engineering, Xiangnan University, Chenzhou 423000, PR China

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ABSTRACT

The influence of the disclinations is of great importance in deformation behavior and structure formation of strongly deformed materials. By introducing to the disclination approach in the description of defect structure development in strongly deformed materials, a theoretical model to study the elastic interaction between a wedge disclination dipole and the elliptical blunted crack is considered. Using the complex variable method, the complex potential and stress field have been derived near the tip of the elliptical blunt crack. From the stress fields, the stress intensity factors (SIFs) at the crack tip are obtained with the effect of a wedge disclination dipole. The influence of the morphology and blunting of the elliptical blunt crack, and the features of the disclination dipole on the SIFs at tip of the elliptical blunt crack is examined in detail. The results show that disclinations exhibit great influence on the mechanical field around elliptical blunted crack tips. Duo to the disclination shielding, the disclination dipole might induce to improve the toughness of crystalline materials. The shielding effect to SIF increases with increasing the crack length, the relative dipole arm and the rotation strength of disclination dipole, and the effect of the shielding effect to SIF is distinctly stronger with the increment of them. There exits critical crack blunting to make the maximum shielding effect to SIF. For both modes I and II blunt cracks, the shielding or anti-shielding effect to SIF becomes more pronounced with different location angles and rotational deformation orientations.

1. Introduction

Analysis of deformations and stresses at crack tips is a fundamental issue for understanding the failure behavior of engineering materials and structures (Huang, Zhang, Belytschko, Terdalkar, & Zhu, 2009; Ovid'ko & Sheinerman, 2010). In physical nature, most crack tips are not ideally sharp but blunt with a finite curvature radius, e.g., on the order of microns or nanometers. First, only when the spacing between the two surfaces of a crack is larger enough beyond some physical limits (e.g., the cutoff radius of Lennard–Jones potential), are the surfaces free from atomic interaction. Second, the atoms near a crack tip experience a local environment different from those in the bulk, and their tendency to minimize the system free energy may also cause blunting of the crack tip (Wang, Feng, Wang, & Gao, 2008). Hence, crack blunting plays an important role in the fracture process. The fracture behavior of crystalline materials by considering the ongoing competition between dislocation nucleation and crack injection in blunt crack tip configurations has been assessed in recent years (Beltz, Lipkin, & Fischer, 1999; Fischer & Beltz, 2001; Kanaun & Levin, 2009; Li, Ji, Li, & Xu, 2007; Schiøtz, Canel, & Carlsson, 1997; Sen, Thaulow, Schieffer, Cohen, & Buehler, 2010; Yang & Yang, 2009). They suggest that blunting of a sharp crack tip can significantly

* Corresponding author at: State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, PR China. Tel.: +86 731 89822841; fax: +86 731 88822330.
E-mail addresses: Fangqh1327@tom.com, Qi-hong.fang@unsw.edu.au (Q. Fang).

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modify the stress field around the crack tip and/or change the favorability of crack advance or dislocation nucleation, and then influence the ductility/toughness mechanism of composite materials. In order to identify the sensitivity of crack blunting processes in composite materials, we pay our attention on physically realistic crack geometries by assuming that the crack geometry is elliptical, which has the primary advantage that the stress fields are available in closed form. In order to build up a fracture theory which describes the plastic deformation based on the behavior of various defects, such as dislocations, disclinations, etc., near the crack tip, the elastic interaction between these defects and elliptical blunt cracks has prompted many investigations (Fang, Liu, Liu, & Huang, 2009; Huang & Li, 2004; Kachanov & Karpetian, 1997; Kiris & Kachanov, 2012; Li & Li, 2007; Li, Li, & Sun, 2006; Song, Fang, & Liu, 2009, 2010; Yu, Liu, Song, & Xie, 2010).

Recently, disclinations have been recognized as typical defects and the sources of characteristic singularities in the fields of displacement and rotation (Lei, Wang, Li, & Wei, 2011; Ovid'ko & Sheinerman, 2008; Romanov, 2003; Valiev, Islamgaliev, & Alexandrov, 2000). The disclination dipole is a low-energy self screened defect configuration which is directly observed in severely deformed solids (Murayama, Howe, Hidaka, & Takaki, 2002; Rybin, 1986). A wedge disclination represents a rotational line defect located strongly deformed materials, such as a grain boundary or a triple junction of grain boundaries, characterized by disclination strength (Ovid'ko & Sheinerman, 2008; Ovid'ko, Sheinerman, & Skiba, 2011). It has been used to describe the structures and mechanical properties and to explain a variety of physical phenomena in solids (Bobylev, Gutkin, & Ovid'ko, 2004; Feng, Fang, Zhang, & Liu, 2013; Gutkin & Ovid'ko, 2004; Luo, Xiao, & Zhou, 2009; Luo, Zhou, & Xiao, 2009; Wu, Zhou, & Nazarov, 2007; Zhao, Fang, Liu, & Zhang, 2013; Zhou, Nazarov, & Wu, 2007, 2008; Zhou & Wu, 2010; Zhou, Wu, & Nazarov, 2008). Plastic deformation can be localized into a kink or misorientational band emitted from the crack tip. The disclination dipoles distribute uniformly inside the misorientation band, but with different rotation strength corresponding to stress and strain gradients (Romanov & Vladimirov, 1992). In the analysis of the effect of disclination plasticity on the crack growth, the flow stress is expressed by a spatial coupling in terms of a second-order gradient of the rotation strength of disclination dipoles (Ovid'ko & Sheinerman, 2007; Zhang, Jeffrey, & Mai, 2004). Wedge disclinations can form in grain boundaries (GBs) and their junctions during the compaction of nanopowders to obtain nanostructured materials (Gryaznov & Trusov, 1993). The special rotational deformation also can occurs through the formation of immobile wedge disclinations whose strengths gradually increase during the formation process conducted by grain boundary sliding, diffusion and nanoscale deformation twinning (Fang, Feng, Liu, Lin, & Zhang, 2012; Kuo, Mura, & Dundurs, 1973; Morozov, Ovid'ko, Sheinerman, & Aifantis, 2010; Zhou, Nazarov, & Wu, 2006). They all show that the introduction to the disclination approach to the description of defect structure development in strongly deformed materials is significant and workable to estimate the effect of the mechanical properties of various deformation materials.

To the best of our knowledge, the effect of disclinations on the blunt crack has not been well quantitatively studied. Thus the main work of this paper is to present a theoretical model to investigate the elastic interaction between a wedge disclination dipole and an elliptical blunt crack. The influence of the morphology and blunting of the elliptical blunt crack, and the orientation, the dipole arm and the location of the disclination dipole on the SIFs at tip of the elliptical blunt crack is evaluated. Based on our results, they manifest that the proposed mechanism to express the improved fracture toughness in nanocrystalline materials is the disclination shielding effect on the crack tip mechanical field. These studies enable an improved understanding of the mechanisms controlling crack nucleation and growth in this complex, hierarchical microstructure, and help the analysis of deformation behavior of NCMs and other nanostructured materials including small atom number clusters, nanosize crystalline particles and nanorods.

2. Problem statement and solution

In this paper we will take a deformed nanocrystalline specimen for example to extend the suggested theoretical disclination approach to a description of the effects of deformation behavior of the strongly deformed materials on the deformations and stresses at crack tips. The physical problem to be considered is shown in Fig. 1. Let a nanocrystalline solid consisting of nanoscale grains divided by grain boundaries and containing an elliptical blunt crack, where a and b are, respectively, the lengths of the major semi-axis and minor semi-axis of the ellipse. The specimen is assumed to be an elastically isotropic solid having the shear modulus μ and Poisson's ratio ν. For simplicity, we restrict our consideration to a two-dimensional grain structure (that serves as a good model for columnar nanoscale structures of films and a first-approximation

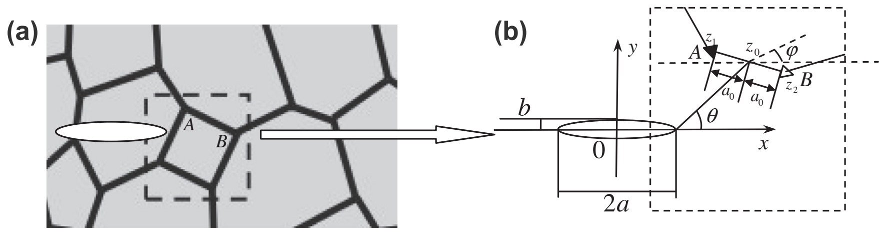

Fig. 1. An elliptical blunt crack locates in a deformed nanocrystalline specimen: (a) general view and (b) the magnified inset highlights a wedge disclination dipole near the elliptical blunt crack tip.