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Effect of coherent twin boundary in nanotwinned materials on fatigue crack growth based on dislocation emission

Yanan Zhou[a], Jianqiu Zhou[a,b,*], Tongyang He[a]

[a] Department of Mechanical Engineering, Nanjing Tech University, Nanjing, Jiangsu Province, PR China, 210009
[b] Department of Mechanical Engineering, Wuhan Institute of Technology, Wuhan, Hubei Province PR China, 430070

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ABSTRACT

A theoretical model to describe the dislocations emitted from the crack tip and penetrating the coherent twin boundary (CTB) in nanotwinned materials under cyclic far field shear stress was proposed in this paper. The dislocations emitted from the tip are subjected to four stresses: the shear stress on the primary slip plane generated by applied stress, the image stress which drives the dislocation glide to the surface of the crack, the back stress from the other dislocations and the lattice friction stress. Combining the theory of continuously distributed dislocation, we developed a method to analyze the dislocation movement from the crack tip under cyclic far field shear stress and derived the calculation method of fatigue crack growth rate in nanotwinned materials. It can be figured out that the fatigue crack growth rate is dependent on the applied stress, the lamellae thickness and the angle between slip system and CTB. When the critical conditions are satisfied, the dislocation piling up around the CTB will penetrate the CTB, the critical stress can be calculated as a function of the misorientation angle and the lamellae thickness.

1. Introduction

Nanocrystalline (NC) materials with the grain size below 100 nm show high strength, high diffusivity, superplasticity at low temperatures and high strain rates (Belova and Murch, 2003; He et al., 2015; Khan et al., 2008a, b; Marek et al., 2015; Wang et al., 2014). Due to a series of wonderful mechanical properties, nanotwinned metals and alloys are novel emerging materials, attracting a great number of researchers (Alkan et al., 2016; Lu et al., 2009b, 2012; Yuan et al., 2014). Recent years, the fracture and fatigue properties of NC have been observed (Kim et al., 2012; Pan et al., 2013; Shute et al., 2009). The properties of NC materials depend significantly on the interactions between dislocations and two-dimensional defects including conventional grain boundary (GB) and twin boundary (TB) (Lu et al., 2009a, b; Ni et al., 2012). In NC materials, GB has a limited capacity to accumulate dislocations, which leads to low ductility (Lu et al., 2004, 2009a). Otherwise, TB acts not only as barriers to dislocation motion but also as sites for dislocation nucleation and accumulation, which leads to a simultaneous increase in both strength and ductility(Lu et al., 2004, 2009a, b; Wang et al., 2010; Zhao et al., 2006). Therefore, it is meaningful to study the factor that affects the interaction between dislocation and TB in materials design.

Some models based on the Mott's assumption (MOTT, 1958) ware proposed to account for the crack growth. These models, however, are rather qualitative and fail to yield any systematic. Mura et al. (1981) and Xie et al. (2015) tried to propose a dislocation model to quantitatively solve the dislocation movement in the slip band. Such studies have a same assumption that the TB blocks the all dislocation movement. However, the interaction between dislocation and TB is complicated and still remain not well understood.

For the case of the interaction of dislocation-GB, researchers have done a series of research to propose the dislocation penetrating GB criterion. Livingston and Chalmers (1957) proposed a geometrical criterion which is about the dislocation to penetrate GB. That the angle between the slip surface of the adjacent grain and the intersection line of GB is minimal, meanwhile the angle between the paths of the dislocation slip in the adjacent grain is minimal. Shen et al. (1988) and Lee et al. (1989) put forward the criterion with other conditions: first, the shear stress of the dislocation which penetrating GB should reach the maximum value; second, the Burgers vector of the residual dislocations in GB should be minimal.

For nanotwinned materials, grains are subdivided into nanometer thick twin/matrix lamellar structure by the coherent twin

* Corresponding author.
E-mail address: zhouj@njtech.edu.cn (J. Zhou).

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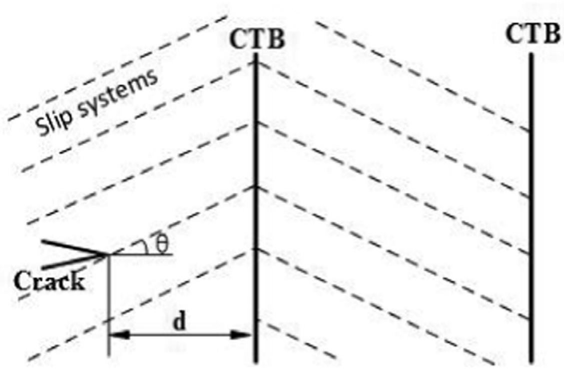

Fig. 1. Schematic drawings of the proposed model.

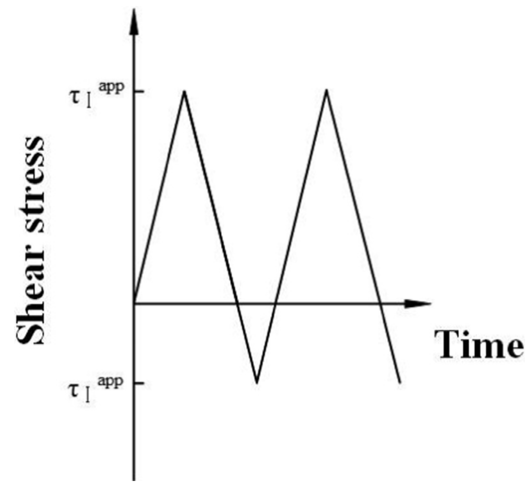

Fig. 2. Cyclic farfield shear stress on the primary slip plane.

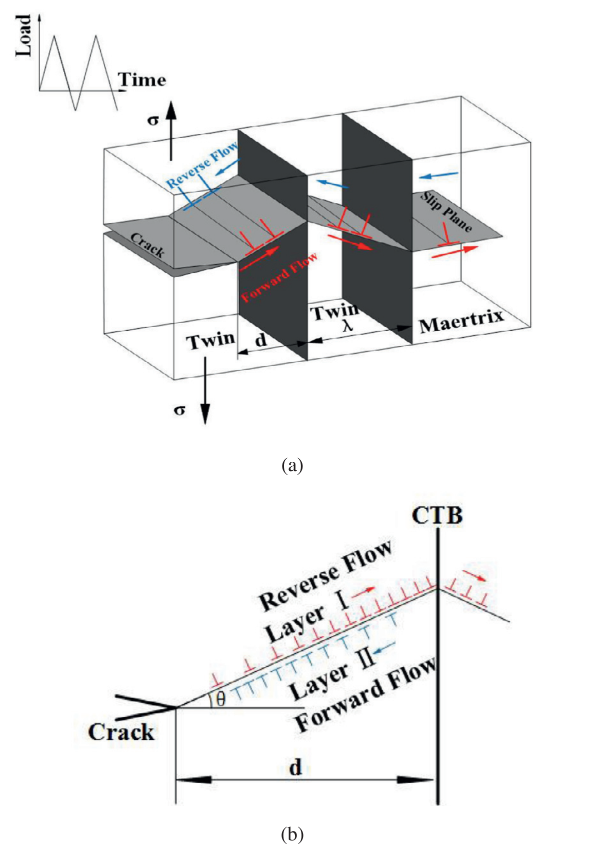

Fig. 3. Schematic diagram of dislocations emitted from crack tip (a) three dimensional graph, and (b) two dimensions.

boundaries (CTBs) (Lu et al., 2005, 2009, 2012; Ovid'Ko, 2011; Yoshida et al., 2014). As the deformation goes ahead, dislocations begin to pile up at the twin boundary (Gutkin et al., 2008). Ovid'Ko (2007) pointed out that if the stress intensity near the crack tip, the crack induces plastic shear through the emission of lattice dislocations from the crack tip. Fang et al. (2013) has investigated the special rotational deformation on the emission of lattice dislocations from the crack tip.

In the above-mentioned works, the researchers have separately studied the effect of the twin near the crack tip or the dislocation pile-up. In this paper, we considered the coupled effect of the twin near the crack tip and the further dislocation pile-up under cyclic far field shear stress for the first time. We will study the interaction of dislocation-coherent twin boundary on fatigue crack growth in nanotwinned materials based on the geometrical criterion more comprehensively, which has never been reported by other papers. First, a method to analyze the dislocation movement from the crack tip under cyclic far field shear stress is established. And then, a calculation method of fatigue crack growth rate in nanotwinned materials will be derived. Finally, the critical conditions, which will be used to judge whether the dislocation piling up around the CTB penetrate the CTB or not, will be analyzed and discussed.

2. The model of dislocations emitted from crack tip

Fig. 1 illustrates the configuration of the nanotwinned crystal. A coherent twin boundary(CTB) are placed ahead of a nanometer sized crack (Itype crack). We denote the perpendicular distance by d between the CTB and the crack. Dislocations glide along the slip systems which intersect the CTB at the angle of θ. Cyclic farfield shear stress on the primary slip plane is applied on the system, where $T_{\mathrm{I}}{}^{\mathrm{app}}$ is the maximum shear stress and $T_{II}{}^{app}$ is the minimum shear stress as shown in Fig. 2.

2.1. Dislocation accumulation

Under the forward flow of the cyclic farfield shear stress, a series of dislocations are emitted from the crack tip and move along the slip band, which is donated as layerI. Finally,the dislocations pileup against the CTB. The reverse flow is expected to take place near the layerI, donated as layer II. It is assumed that the positive dislocation movement formed by forward flow is irreversible and the negative dislocations pileup during the reverse flow causes a positive back stress on layerI. The back stress strengthens the pileup of dislocations during the forward flow of next cycle. Considering the independence of slip band, we neglect the distance of two vicinal layers compared with the length of the pileup layers. Fig. 3 shows the dislocation movement in the nanotwinned crystal for the first cycle under the applied shear stress.

In our model, the theory of continuously distributed dislocation is applied, and the dislocations on the same layer in per circle are regarded as a whole and the dislocations are subjected to several force as follow: (1) shear stress on the primary slip plane, τ^{app} which drives the dislocation away from or toward the crack tip, (2) image stress, τ^{image} which drives the dislocation glide to the surface of the crack, (3) dislocation stress(back stress), τ^{pileup} which hiders the movement of the dislocation, generated from the dislocations of any location(Chowdhury et al., 2014b), (4) lattice frictional stress, τ^{p}, which objects the dislocation moving. When the