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Effect of grain size and misorientation angle on fatigue crack growth of nanocrystalline materials

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ABSTRACT

It is known that the unique microstructure and deformation mechanism of nanocrystalline (nc) materials make the crack initiation and propagation different from the conventional coarse grained materials. The research of fatigue crack propagation (FCP) in nc metals has remained an empirical field. A theoretical model for I type crack growth was established to address the physical processes. The model describes the crack initiation and propagation and discusses the important topic of the role of the grain size and misorientation angle on the fatigue crack growth on the interface of the nc materials. We make the major research that fatigue crack growth is governed by the irreversibility of displacement at the crack tip and the dislocation glide resistance. The characteristics are observed that the dislocation glide suffer larger resistance from ultrafine grain size and large misorientation angle. It can be found that the critical stress of dislocation penetrating grain boundary and the misorientation angle of the grain boundary are positively correlated. The resent experiment found that grain refinement serves to reduce the extent of crack path tortuosity and cause an increase in fcp. The model results demonstrate the crack growth rate increases with the decrease of the grain size and the misorientation angle increases with the crack growth rate decreasing, in agreement with experimental discovery.

1. Introduction

Nanocrystalline (Nc) metal materials which the size is 1–100 nm [1] have been researched in the past few years, because of which have special properties [2–6]. In coarse grain, grain refining which affects the fatigue behavior has attracted a great number of researchers. It is well known that the fatigue endurance will be improved when grain size is decreased with high fatigue stress amplitude for the materials which have higher stack fault energy (SFE) [7,8]. The fatigue endurance will not be affected by changing the grain size when the SFE is low, such as Cu or Al. But for some other materials of brass, possessing low SFE, stress fatigue life will be improved when grain size decrease. In recent years, the fatigue property of ultrafine grained and nc materials have attracted a great number of investigators [9–14]. The research results illustrated that the high cycle fatigue life and fatigue limit stress of ultrafine grained and nc materials are better than those of coarse grain materials, however, the performance of plastic deformation is not well [12,14]. Hanlon [14] researches the fatigue response of nc Ni. The stress life fatigue behavior and fatigue crack growth characteristics of pure Ni were studied as a function of grain size, which ranges from tens of nm to tens of um. It was found that grain refinement in the true NC regime generally leads to a significant increase in total life under stress controlled fatigue conditions and cause an increase in fatigue crack growth. The reason is that the volume fraction of grain boundary increases rapidly after grain refining, and the strength of the materials also increases, the resistance of fatigue crack nucleation increases, meanwhile, the fracture surface asperities decrease.

Many studies have explained the deformation mechanism of nanocrystalline materials under circulating load [15–19]. In the case of coarse grained materials, the fatigue limit of Nc materials and Twined materials are higher. Singh et al. [20] who researched the fatigue crack propagation of nano-twinned Cu show that the higher the twin density, the lower the crack growth rate is, when the grain size remains constant. Zhang et al. [21–23] who systemically study on the fatigue crack mechanism of the twin boundary found that the fatigue crack can crack in the slip band, and also can crack in the twin boundary. Xie et al. [24] found that the width of the shear band increase with the increase of crack size by observing the change of the shear band width in the nanocrystalline materials. They further concluded that the expansion of the tip crack was mainly influenced by the dislocation deformation of the shear band. Michael [25] characterize the

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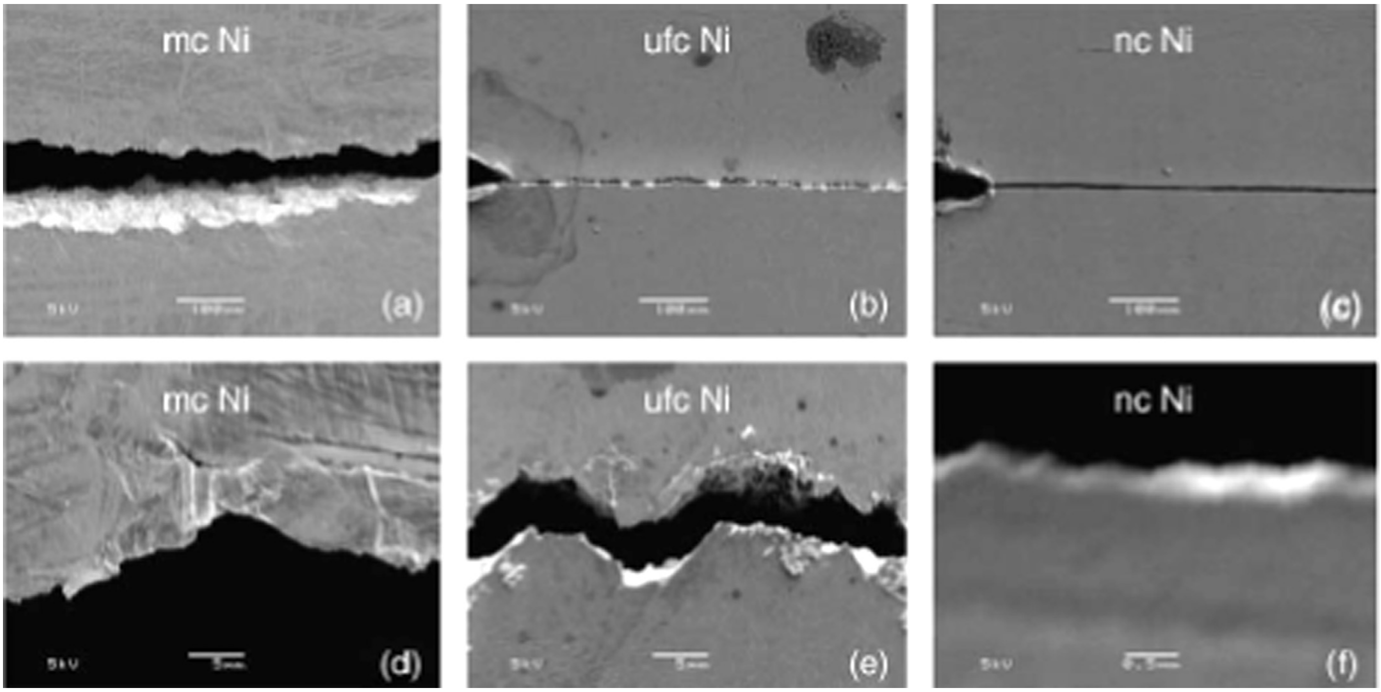

Fig. 1. Scanning electron micrographs of mc, ufc, and nc Ni subjected to sinusoidal fatigue loading [16].

microstructure of a NC electro-deposition (ED) Ni–Co alloy that displays superior FCG resistance compared with CG materials. That explains the fatigue irreversibility and damage resistance of this material and observes the FCG of Ni–Co alloy by scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

The fatigue life of nc materials mainly include fatigue crack Initiation and fatigue crack growth. Most cycle load is used to promote crack Initiation. Crack growth rate is not representing fatigue life. A fatigue crack initiation is because of stress concentration by the dislocation pill-up. Grain refinement can reduce the stress concentration compared with coarse grain, and improve the resistance of crack Initiation. Hanlon [14] found that a reduction in grain size cause an increase in FCP by compared with nanocrystalline pure Ni, ultrafine crystalline pure Ni and microcrystalline Ni. The reason is that grain refinement serves to reduce the extent of such crack path tortuosity, and the roughness of fatigue fracture drop. The reduced roughness reduces the resistance of FCP, and the FCP rate increase when grain size reduces. The experiment result researched by Hanlon [14] is shown in Fig. 1.

The predecessors observed the fatigue growth of nc materials or nano-twined materials by experiment, however, the theoretical model of the fatigue crack propagation problem based on the interface of nc materials is less studied. This paper mainly discusses the fatigue crack growth rate problem which is affected by the grain size and misorientation angle on the interface of the nc materials.

2. Materials and methods

2.1. Dislocation penetrating grain boundary

A brief summary of the grain boundary penetration is represented. Livingston and Chalmers [26] proposed a geometrical criterion which is about the dislocation to penetrate the grain boundary. That the angle between the slip surface of the adjacent grain and the intersection line of the grain boundary, and the angle between the sliding direction of the dislocation and the direction of the dislocation slip are minimum. Defining parameter M,

$$M = (l_1 l_i)(g_1 g_i) + (l_1 g_i)(g_1 l_i) \tag{1}$$

In the formula: l_1 is the normal direction of slip surface and g_1 is the slip direction of dislocation slip plane; l_i and g_i identify the slip surface normal direction and slip direction of all potential dislocations in the adjacent grains. the parameters M is minimum when dislocation penetrate grain boundary. Based on above, Shen et al. [27] and Lee et al. [28] put forward two other conditions: one is that the shear stress which is in the position of the dislocation slip should reach the maximum value; the other one is that the burgers vector of the residual dislocations in the grain boundaries should be minimum. Dislocation penetrating through grain boundary are governed by the above three criteria.

As shown in Fig. 2, the grain A and B are separated by grain boundaries. There are two slip systems on the arbitrary side of the grain boundary. When the dislocations in the grain A along slip system S_1 to the grain boundaries between B and A, the dislocation in the grain A cannot be smoothly slip into the grain B. Grain boundaries play an large obstacle to dislocation slip, and then

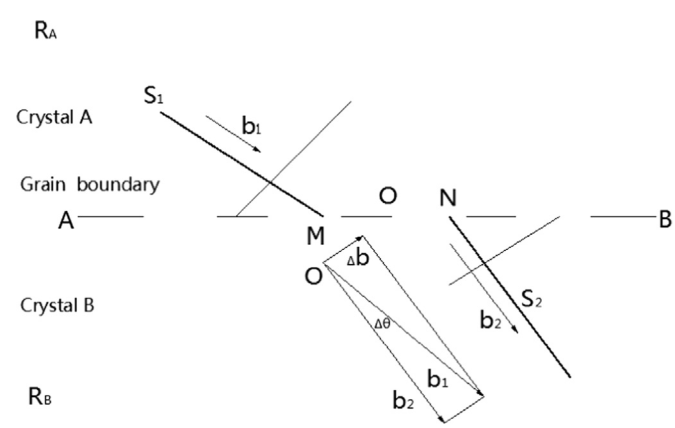

Fig. 2. Two-dimensional sketch map of dislocation penetrating grain boundary.