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Influences of surface grain size and gradient variation along depth on fatigue life of metallic materials

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ABSTRACT

The Navarro–Rios (N–R) model was used to investigate the effects of surface grain size and the grain size gradient along depth (characterized as parameter g) induced by surface nanocrystallization (SNC) on the fatigue damage of the metallic materials in this paper. Two equations were deduced and the results showed that the crack arrest of metallic materials decreased when the surface grain became nanocrystalline. Nevertheless, the crack arrest of the SNCed materials increased as the top layer grain size decreased and it rose with the increase of the value of g when the surface grain size was smaller than 100 nm. The transition stress diminished with the increase of the surface grain size and the decrease of the value of g. The short crack growth rate descended with the decrease of surface grain size and grain size gradient. It explained why the SNC could improve the fatigue life of the metallic materials effectively.

1. Introduction

The majority of failures of engineering materials are very sensitive to the structures and properties of the materials surface. In most cases, material failures like fatigue and wear occur on the surface. Therefore, the optimization of the surface structures and properties may enhance the global behaviors of materials effectively. Surface nanocrystallization (SNC) of the metallic materials is an advanced method to improve the properties and behaviors of materials by the surface modification to generate a thin nanostructured surface layer [1]. It is expected to greatly enhance the surface properties without changing the chemical compositions and the shape of materials. It is also a flexible approach to realize specific structure requirements localized on the surface of materials [2].

Most of the conventional surface mechanical treatments could be potentially used for the SNC by the surface severe plastic deformation of the materials. To date, shot peening [3], ultrasonic shot peening [4], surface mechanical attrition [5], ultrasonic impact treatment [6] and laser shock processing [7,8] have been successfully applied to produce nanostructure on the surface of different kinds of metals and composites.

Different surface treatments induce different surface microstructures of the materials, like different grain sizes on the surface and different deformation layer thickness along depth, which would have influences on the fatigue life of the materials [9]. To investigate the relationship between the fatigue life of metallic materials and their surface microstructures, the Navarro–Rios (N–R) model is used in this paper. The N–R model which is based on the continuous distribution of dislocations as proposed by Bibly et al. [10] is successfully applied to analyze short cracks growth which is several times longer than the microstructural dimension defined by the length of a grain [11]. The N–R model has been used to study the transition between short cracks and long cracks [12]. It is found that the value w defined as fatigue limit dividing cyclic yield stress could affect the transition of the short and long crack essentially. The influence of the average grain size of the polycrystalline on the fatigue life of materials is also investigated [13]. The model is adopted to research the effect of controlled shot peening on fatigue damage of aluminum alloys. The results reveal that the compressive residual stress can decrease the growth rate of the short crack, but the roughness induced by the treatment increases the growth rate [14]. As mentioned above, the surface treatments could induce SNC of materials. But the effects of surface grain size and the grain size gradient along depth on the fatigue damage of the metallic materials are not investigated. In this paper, N–R model is used to study these factors on the fatigue life of metallic materials.

2. Modeling

2.1. N–R model

In short, the N–R model considers the plastic slip produced ahead of a crack to be represented by a continuous distribution of dislocations [15]. It divides the crack system into three zones:

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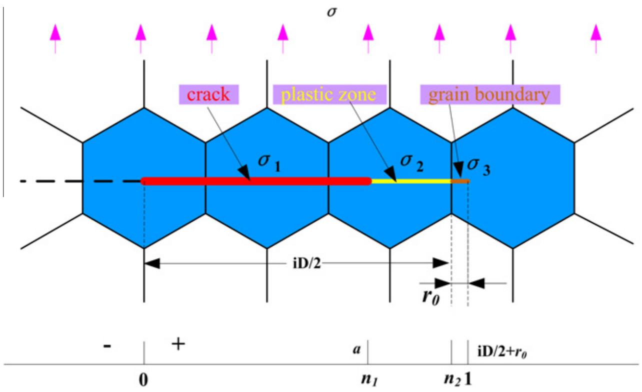

Fig. 1. Schematic representation of the crack, the plastic zone and the barrier zone.

the crack, the plastic zone, and the barrier zone (grain boundary), as shown in Fig. 1. In each of these three zones, there are resistances reacting to the applied load. The stress only depends on the position of the crack tip relative to the grain boundary. According to the material resistance to crack propagation, there are three kinds of stress acting on the crack including: (1) σ_1, closure stress on the crack flanks; (2) σ_2, the stress of material resistance to plastic deformation at the plastic zone (cyclic yield stress); (3) σ_3, the reaction stress developed on the barrier due to the blocking of the persistent slip band (PSB) at the grain boundary of width r_0 [12,16].

When a crack propagates, slip initiates in the next grain when the stress ahead of the plastic zone is large enough to move new dislocations. Based on the equilibrium of dislocations along the three zones, the constraint stress σ_3, ahead of the slip band at the grain boundary for an opening model loading, is given as follows by [11,12]:

$$\sigma_3 = \frac{1}{\cos^{-1} n_2}\left[(\sigma_2 - \sigma_1)\sin^{-1} n_1 - \sigma_2 \sin^{-1} n_2 + \frac{\pi}{2}\sigma\right] \tag{1}$$

$$n_1 = \frac{a}{iD/2 + r_0}, \quad n_2 = \frac{iD/2}{iD/2 + r_0} \tag{2}$$

The parameters n_1 and n_2 represent the crack length and the fatigue damage size in a dimensionless form (as shown in Fig. 1), respectively. The parameter r_0 is the grain boundary width, a is the length of half surface crack (or the length of corner crack), $i = [2a/D]$ is the number of half grain spanned in the crack (The function "$[x]$" is Gauss function which means rounding up x), and $iD/2$ is the zone of the fatigue damage [12]. The demonstration of above effects of the microstructure and the microstructural barriers on the early stages of crack growth is given by the experiments in Ref. [17]. The Eq. (1) is also justified in Ref [18] through the test of 2024-T351 alloy treated by shot peening in which σ_1 is induced by the residual stress and σ_2 is changed for the microhardness variation induced by the treatment.

In N–R model, the crack is supposed to grow along a slip plane at all times [13]. The crack tip plastic displacement ϕ is determined by:

$$\phi = \frac{2(1-\upsilon)\sqrt{1-n_1^2}}{\mu n_1}\sigma a \tag{3}$$

where σ is the applied load, a is crack length for a corner crack or half crack length for the surface crack, μ is the shear modulus, υ is Poisson's ratio, and n_1 is a dimensionless parameter as mentioned above. The crack growth rate is proportional to the crack tip plastic displacement [11]. Then the crack growth rate is given as:

$$\frac{da}{dN} = f\phi \tag{4}$$

where N is the load cycles number and f, depending on the applied stress and the material, is representative of the fraction of dislocations ahead of the crack that participates in the crack propagation process.

The crack growth rate decreases when the crack tip approaches the grain boundary for the slip band blocked by this microstructural barrier. The crack will propagate when the stress is sufficient to overcome the barrier and initiate a new slip band in the next grain. If not, the crack will stop. Above critical condition occurs for the ith half grain at a critical value of n_1 equal to:

$$n_c^i = \cos\left(\frac{\pi}{2}\frac{\sigma - \sigma_c^i}{\sigma_2}\right) \tag{5}$$

where i is the sequence number of consecutive half grains ($i = 1, 3, 5 \ldots$). σ_2 is the resistance to plastic deformation of the crack tip same as in the Eq. (1), σ_c^i is minimum stress required for crack propagation represented by:

$$\sigma_c^i = \frac{\sigma_{FL}}{\sqrt{i}}\left(\frac{m_i}{m_1}\right) \tag{6}$$

where σ_{FL} is the fatigue stress and m_i is the ratio of grain orientations. The grain orientation factor, (m_i/m_1), has been experimentally estimated to follow the progression [14] for aluminum alloy:

$$\frac{m_i}{m_1} = 1 + 0.35\ln(i) \tag{7}$$

where $1 \leqslant m_i \leqslant 3.07$ .When a new slip band initiates in the next grain, the plastic zone is supposed to span the entire new grain, and therefore, n_1 decreases from n_c^i to:

$$n_s^i = \frac{i-2}{i} n_c^{i-2}, \quad i > 1 \tag{8}$$

$$n_s^{i=1} = 0.2 \tag{9}$$

which is a rescaling of the old value of n_1 by the new value of c. The condition for $n_s^{i=1}$ is justified in Ref. [11].

The number of cycles spent in the grain (or over parts of a grain) could be given by integrating the growth rate Eq. (4) over that grain as:

$$\Delta N_i = \frac{\mu}{f(1-\upsilon)}(\arcsin n_c^i - \arcsin n_s^i) \tag{10}$$

The total number of cycles is then obtained by summing over all grains. The using of the N–R model could effectively describe the behavior of the short crack growth, and it could explain some experiments results that could not be explained by other models [17,18].

2.2. Microstructure model of the SNCed materials

In N–R model, all the grains are assumed to be equal in size. It has to be modified to the situation of the SNCed materials that have a grain size gradient region on their surface, in which the grain size varies from tens of nanometers to tens of micrometers, and a coarse grained interior with grain size of tens of micrometers [19,20]. According to previous studies [2,19–21], the grain refinement process of SNC of metallic materials includes three steps: development of dislocation tangles (DTs) and dense dislocation walls (DDWs) in the original grains and in the refined cells by the sequence of elongated microbands; transformation of DTs and DDWs into subboundaries; and evolution of subboundaries to highly misoriented grain boundaries. The SNC technologies can produce nanostructural layer on the surface of the materials in the depth varying from a few to about 15 – 25 μm depending on different treatment processes, and the corresponding grain size gradually increases from about 10 – 30 nm at the top layer to more