International Journal of Fatigue 70 (2015) 270–277

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Microscopic inhomogeneity coupled with macroscopic homogeneity: A localized zone of energy density for fatigue crack growth

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ARTICLE INFO

Article history:
Received 25 May 2014
Received in revised form 5 October 2014
Accepted 6 October 2014
Available online 16 October 2014

Keywords:
Fatigue crack growth
Microscopic effect
Non-equilibrium and non-homogeneity (NENH)
S–N curve
Energy density zone (EDZ)

ABSTRACT

Fatigue failure problem is a typical multi-scale problem that passes at least two different scales of micro-scale to macro-scale. Moreover, the microscopic effects play an important role in a fatigue process. However, the microscopic non-equilibrium and non-homogeneity (NENH) is grossly incompatible with the classical concepts of equilibrium used in mono-scale fracture mechanics. Localized energy density zone (EDZ) is used to describe the fatigue crack growth from a micro-flaw to macro-crack. The term EDZ is used to redeem the formalism of using segmented linearity in previous works. In this way, the segmented local linearity would not be confused with the macroscopic fracture mechanics. The EZD term clears the way for describing micro and macro effects in the same model. Micro and macro effects can thus be included in the *S–N* curves of LC4 aluminum alloy. Specifically, the scatter of the fatigue test data is shown to be contributed by the material microscopic effects.

1. Introduction

It is well known that the fatigue test data for specimens exhibit considerable scatter. This is to say, a group of the same specimens under the same loading conditions differs in fatigue lives. This is caused by the difference in material microstructure that is not accounted for in the conventional fatigue crack growth model. The effect of micro-structure is different from specimen to specimen and should be included. The microscopic effects of materials have a notable influence on the fatigue failure behavior. Fatigue failure is usually triggered from a micro-defect or a weak point (known as the site of initiation) in the material under the cyclic loading. The fatigue process undergoes initiation, microcrack growth, the appearance of macro-cracking until to final breakage. Fatigue cracking is a multi-scale problem that involves at least two different scales, say micro-scale and macro-scale. "Micro-scale" stands for the scale of the micro-structures of a material (usually, micron, μm in the order for metals) in contrast to the atomic scale or nano-scale. In addition, "macro-scale" refers to size visible to the naked eye. The fatigue process is a continuous process in physics. However, this continuous process has been traditionally modeled into two different segments, initiation and propagation, using two different approaches. The shortcoming of classical continuum mechanics to treat multi-scale problems is that the microscopic effects cannot be compatible with the macroscopic continuity and homogeneity [1]. The non-equilibrium and non-homogeneity (NENH) effects have been neglected at in the classical continuum mechanics theories by invoking continuity and homogeneity as a rule. Efforts have been made to include local non-homogenous effects without change in material properties. Some of these works are cited. Dugdale [2] proposed a crack tip strip yielding zone. Barenblatt [3] developed a crack tip cohesive stress model. Wells [4] suggested a fracture criterion by using the crack tip opening displacement (CTOD criterion). When the cohesive stress in the cohesive model is equal to the yielding stress in the Dugdale model, two models become identical. Chan [5] gave a review for the microstructure role played in the fatigue crack initiation. Sangid (2013) [6] gave a review for all of the above models are based on homogeneous physical properties. Vernerey et al. (2007) [7] developed a multi-scale micromorphic theory for hierarchical materials. The treatment of full NENH in fatigue crack growth was made by Sih (2009) [8] who developed the crack tip mechanics approach based on the progressive damage with directional consideration. Hierarchy of singularities was established to invoke the change in material homogeneities for multi-scale segments. In addition, the recent works [8–10] have removed the formalism of using segmented linearity [11–21] to elucidate the effects of micro–macro inhomogeneity. The term energy density zone EZD [22] was suggested to clarify any possible misinterpretation.

As mentioned early, fatigue problem is a multi-scale problem in which the non-equilibrium and non-homogeneity (NENH) effects are present. The EDZ is no more than a reinterpretation of the

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http://dx.doi.org/10.1016/j.ijfatigue.2014.10.003
0142-1123/

use of segmented linearity while micro–macro effects are retained. This is not the same as those models that assume homogeneity of material properties at large. Moreover, non-equilibrium has also been invoked such that the physical properties of the material change with time and location.

2. Energy density zone (EDZ)

For the polycrystal materials, the damage types at the micro-scale (i.e., the scale of material micro-structures) include the intergranular cracking and transgranular cracking as shown in Fig. 1 [23]. Thus, the micro-defect can be simplified to a microscopic V-notch as illustrated in Fig. 2 where d_0 is the characteristic length of crystal grains. d_0 is an important parameter that denotes the microscopic inhomogeneity of a material. Three possible microscopic boundary conditions are free–free, fixed–free and fixed–fixed as shown in Fig. 2. The singularity of the micro-stress field in the vicinity of the micro-V-notch tip may be stronger or weaker than the normal $r^{-1/2}$ singularity for a line macro-crack depending on the micro-defect boundary conditions (see Ref. [14] by Tang and Sih, 2005). In general, the singularity of a micro-V-notch is related to the loading, material property and geometry [14].

A typical fatigue failure process for smooth plate specimens is illustrated in Fig. 3. The fatigue failure starts from a micro-flaw known as the fatigue source as shown in Fig. 3(a) when the fatigue loads are applied. Then, the fatigue micro-crack gradually forms and slowly propagates as exhibited in Fig. 3(b). The initiation and growth of a fatigue micro-crack is invisible at the macro-scale. After a microscopic development period, the fatigue crack can be seen by naked eyes. This indicates the macro-crack forms and growth as shown in Fig. 3(c). After a stable growth period, the fatigue macro-crack would lose the stability. The plate specimen would finally break down. The a versus N curve for a typical fatigue process is depicted in Fig. 4 in which a is the fatigue crack length, N the cycle number, a_0 the size of the micro-flaw, a_{cr} the critical length of the fatigue macro-crack, and N_f the fatigue life of the plate specimen.

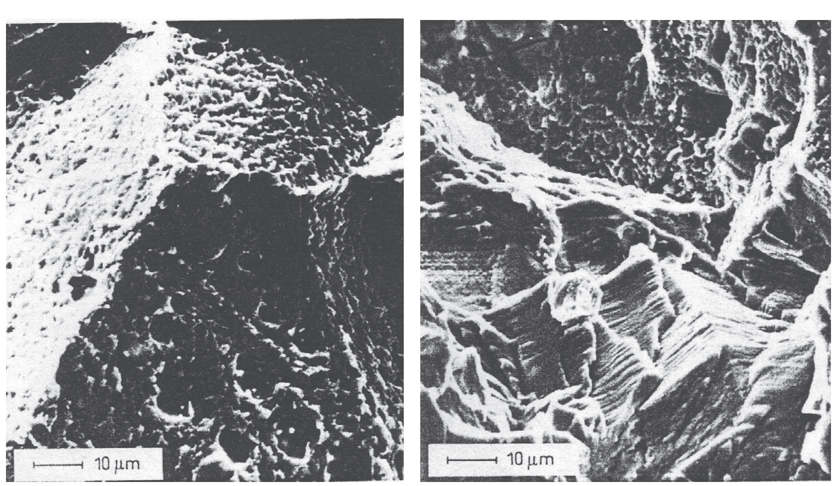
The energy density theory founded by Sih has a wide application from equilibrium to non-equilibrium cases and can apply to different scales from nano-scale to macro-scale and large structural scale. A schematic diagram for the energy density zone (EDZ) [22] is depicted in Fig. 5. For a fatigue failure problem, the failure starts from a micro-defect. A localized energy density zone would prevail in the fatigue source area with the length a. In addition, a microscopic damage zone (or a micro-V-notch) with the length d is attached to the EDZ tip to reflect the microscopic inhomogeneity, and $c = a + d$. The effective stresses should have a non-uniform distribution. The average value of effective stresses in the EDZ is denoted by σ_0. The effective stress can vary with the material damage in the EDZ during the material failure process. At the beginning, $a = a_0$, a_0 is the size of micro-defect in the fatigue source. Then, the effective stress σ_0 decreases while the length a increases with the time t (or cyclic number N). This means the material damage increases with the time t. Meanwhile, the material property in the EDZ would also vary with time t because the material is damaged and the scale is changed. When the effective stresses vanish and the size a increases to the order of millimeters, the EDZ becomes a real macro-crack and can be seen by naked eyes. Therefore, the EDZ model can describe the whole failure process from a micro-defect to the final fracture. In addition, the model can consider the microscopic effects in quantity as demonstrated below. Here, we emphasize that when the fatigue loads $\sigma_\infty(t)$ vary with time t, all parameters in the EDZ would also vary with time t (i.e., functions of time t) including material property, effective stresses, lengths a, d and c as shown in Fig. 5.

3. Formulation of fatigue crack growth

As shown in Fig. 5, the fatigue crack growth is dominated by a localized strain energy density field. The strength of the localized energy density field is represented by a strain energy density factor S^{macro}_{micro}. Here, the superscript "macro" and subscript "micro" simultaneously appear and indicate that the quantity S^{macro}_{micro} is a multiscale parameter involving two different scales of both macro-scale and micro-scale. The expression of S^{macro}_{micro} has been solved for the case of uniform distribution of effective stresses in the EDZ [22]. It should be noted that the effective stresses distributed in the EDZ need not be uniform and constant as shown in Fig. 5. It has been tested that for the different distributions of effective stresses, the expression of S^{macro}_{micro} has little difference. In general, the expression of S^{macro}_{micro} can be concluded as [8–10]

$$S^{macro}_{micro} = Aa\sigma^2_\infty \mu^* \sqrt{d^*}\left(1 - \frac{2}{\pi}\sigma^*\right)^2 \sqrt{\frac{d_0}{r}} \quad (1)$$

where A is a constant related to the material property. d_0 is the characteristic length of crystal grains referring to Fig. 2. r is the



(a) Intergranular cracking damage (b) Transcrystalline cracking damage

Fig. 1. Fractographs in a nickel-based alloy taken from Ref. [23].