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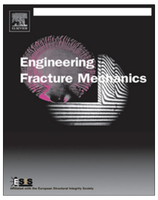

A multi-scale damage model for fatigue accumulation due to short cracks nucleation and growth

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ABSTRACT

A multi-scale fatigue damage evolution model is proposed for describing both the behaviour of short fatigue cracks nucleation and growth in micro-scale and fatigue damage evolution reflecting the progressive deterioration process of metal components and structures in macro-scale. The model is verified through the experimental data of fatigue damage. It was found that, the model can offer a new reasonable explanation of the effect of load sequence on fatigue life, and also can predict the fatigue life during fatigue damage accumulation due to short cracks nucleation and growth in metal components and structures.

1. Introduction

The fatigue failure of metal components and structures due to the cumulative fatigue damage is the most common form of engineering failures. Therefore, the monitoring and evaluation of fatigue damage accumulation for fatigue life prediction play a vital role in structural design and maintenance. Over the past few decades, though there is a mass of research on fatigue, the accurate evaluation on fatigue damage accumulation and fatigue life prediction is still a challenge up to now, especially evaluation on fatigue accumulation due to short crack nucleation and growth. Nucleation and growth of short cracks are the two main processes of fatigue damage accumulation, and which spend a high ratio of life cycles in metal components and structures that do not have inherent defects before entering the long crack growth stage [1–5]. For low cycle fatigue (LCF) the estimates of life spent in nucleation and short crack growth regimes vary from 70–90% of fatigue life, and for high cycle fatigue (HCF) it even exceeds 95% of fatigue life [6]. Therefore, the accurate evaluation of fatigue damage accumulation of metal components and structures depends on the degree of understanding of the behaviour of short fatigue cracks. However, accurate quantification of fatigue damage accumulation due to short cracks nucleation and growth becomes a difficult problem since traditional method of research on fatigue damage accumulation during the stages of nucleation and growth of short cracks is carried out in a single scale of micro- or macro-scale.

In micro-scale, the behaviour of a few single short fatigue cracks was studied at the beginning of the 1980s by many researchers [7–25]. Taylor [7] observed the behaviour of short crack growth and pointed that there is an approximate correlation between the critical size for short crack and the dominate length of the microstructure scale. Bu [8] and Kaynak et al. [9] compared the growth behaviour of short and long cracks and found that, in the same material, the growth rate of short cracks can be greater than the corresponding growth rate of long cracks under the same driving force. In order to describe the growth behaviour of short fatigue cracks, several analytical models for describing short fatigue crack growth rate were

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Nomenclature

a	length of short crack
a_0	initial length of crack in nucleation
$\dot{a}$	crack growth rate
d_0	dominate length of the microstructure scale
$\mathrm{D}_{\mathrm{diam}}$	diameter of the armored vehicle transmission shaft
D	damage variable
n	number density of short cracks
n_i	number of cycles of the ith stress range
n_N	short crack nucleation rate per cycle
N	number of cycles
N_f	number of cycles to failure
N_T	total number of cycles
S	sectional area
$\tilde{S}$	effective value of sectional area
T	torque
V_{RVE}	volume of RVE
x	distance from the location of crack nucleation to the first microstructural barrier
L, A, α, m	constants of model parameters
$\Delta\gamma$	plastic shear strain range
σ	nominal stress
$\tilde{\sigma}$	effective stress
$\Delta\sigma_{ef}$	effective stress rang
τ	shear stress
$\Delta\tau$	shear stress range

demonstrated by Miller [10], Delosrios [11], and Angelova [12] by analysis on the experimental data from micro-scale testing. Hussain [13] reviewed many analytical models of short fatigue crack growth behaviour and summarized a lot of micro characteristics of short crack growth. He pointed out that, the resistance to short crack growth is much influenced by microstructure, and linear elastic fracture mechanics (LEFM) is unsuitable for application in the analysis of short crack growth. Miller [14–15], Plumtree [16] and Demulsant et al. [17], followed by micro-scale observations, performed a series of experiments for metals. Their results show that the microstructural barrier, e.g. grain boundary, inclusion, second phase particle, can retard the growth of short fatigue cracks. In most of cases, short fatigue cracks were arrested at those microstructural barriers. Ke [18] proposed a model for analyzing the evolution of microdamage (e.g. short crack) and reviewed several models for describing short crack nucleation behaviour (e.g., the short crack nucleation rate decreases with increasing of nucleation size). Polák [19] studied the behaviour of short crack nucleation and growth and reported that the nucleation of short fatigue cracks is due to strain hardening and strain localization and short crack growth depends strongly on the plastic strain amplitude. Hong et al. [20–21] presented an analysis of collective damage for short cracks and showed that the nucleation size of most short fatigue cracks is less than the average grain size, and there is almost not a short fatigue crack in nucleation with size larger than several grain sizes.

In macro-scale, when the cumulative fatigue damage theories were studied at the beginning of the 1950s by many researchers [26–33], e.g. Miner [26], Miller [27], Manson [28], Chaboche [29], Kujawski [30], Fatemi [31], Franke [32] and Lemaitre [33], many cumulative fatigue damage models based on a large amount of experimental data, which describe the progressive deterioration processes of material fatigue before the macroscopic crack initiation by means of a damage variable, were proposed previously. In 1945, Miner [26] proposed the Palmgren-Miner linear damage hypothesis to predict the fatigue life of specimens based on the assumption of linear accumulation damage. However, it was found that fatigue damage accumulation during the early stage of life is different from later stage, which is frequently evidenced by summation factors being less than unity when the load sequence is from high to low stress levels, but greater than unity when the load sequence is from low to high stress levels. Although the linear damage rule is most widely used, the Palmgren-Miner linear damage rule can be dangerous or over-conservative. For improving fatigue life prediction accuracy, Manson [28], Kujawski [30] and Franke [32] et al. introduced modifications into the Palmgren-Miner rule. A classical non-linear model of fatigue damage was proposed by Chaboche [29] and applied to various loading situations and different types of metal. And non-linear fatigue damage theories were developed quickly. Lemaitre [33] brought the continuum damage mechanics (CDM) into the framework of thermodynamics to describe the collective effect of distributed micro-defects such as short cracks by defining a damage variable, and established a fatigue damage model based on the theoretical basis. Fatemi [31] provided a review of cumulative fatigue damage theories and grouped them into different categories. Miller [27] proposed a hypothesis of explanation for effect of load sequence by setting the fatigue damage to crack length and developed a double exponential law for fatigue damage during the initiation and stage I fatigue crack growth stages based on the hypothesis.