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Multi-scale fatigue model and image-based simulation of collective short cracks evolution process

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ABSTRACT

Multi-scale fatigue model and image-based simulation method are developed in this study to describe collective short cracks evolution process in micro-scale and continuous fatigue damage evolution in macro-scale based on the concept of continuum damage mechanics (CDM). The relationship between the micro-scale and macro-scale fatigue is explored to enhance the understanding the nature of fatigue phenomenon. A case study is carried out to verify the developed multi-scale fatigue model and image-based simulation method. The results show that it is more effective and clear to reveal metal fatigue failure mechanisms from the viewpoint of multi-scale.

1. Introduction

Fatigue is a leading cause of failure for steel structures during their long-term service [1–3]. Generally, the fatigue damage process of metal can be subdivided into two phases [4,5]: short-crack regime and long-crack regime, in which most of the fatigue life is spent in the short-crack stage before entering the long crack stage [6–8]. Fatigue damage accumulation is strongly related to the short cracks initiation and growth [9–11]. Therefore, a great deal of work has been devoted in the past to studying the short-crack behavior [12].

In fact, metal fatigue accumulation is a multi-scale phenomenon (i.e. reduction of material stiffness or strength referred to as *damage* in the macro-scale, which corresponds to the structural level, and short cracks nucleation and growth in micro-scale, which corresponds to the material level). It can be described at different scales and from different viewpoints, depending on which processes to focus on [13]. Current methods for studying fatigue problems can be mainly classified into two classes. The first class methods focus on macroscopic fatigue analysis in structural level, which are used to describe the continuous fatigue accumulation in terms of a damage variable by many researchers, e.g. Manson [14] and Chaboche [15] among many others. The first class methods are actually a phenomenological approach based on the concept of continuum damage mechanics (CDM) which was probably first presented by Kachanov [16]. The second class methods focus on microscopic fatigue analysis, which are used to describe the short cracks nucleation and growth behavior by many researchers, e.g. Miller [17], Beretta [18] and Alaoui [19] among many others, with resort to modern experimental equipment such as scanning electron microscopy.

It has long been regarded as a very important issue to establish the micro–macro relationship for the fatigue accumulation process [20] because such a relationship can enhance our understanding of the fundamental nature of fatigue mechanisms, but it is still a challenging task up to now. Researchers found that the fatigue accumulation process is actually caused by collective behavior of a large number of short cracks [7,21,22], but the current monitoring and analysis of short crack behavior focus on only a few single cracks, which could not reflect collective evolution behavior of a large number of short cracks [21]. Meanwhile, researches indicated that the random microstructure, such as grain size and boundary, plays a key role in fatigue accumulation of metal [5,7,20,23,24]. Short cracks keep nucleation and growth processes within grain domains, which seldom overcome grain boundary obstacles [5,7]. And grain boundary is considered to be one of the main factors controlling fracture in metals [20]. Polycrystalline orientation distribution can affect the short fatigue crack nucleation and propagation processes [23,24]. So, in order to better understand fatigue mechanisms, the construction of random microstructural model is necessary for accurate micromechanical analysis. However, there

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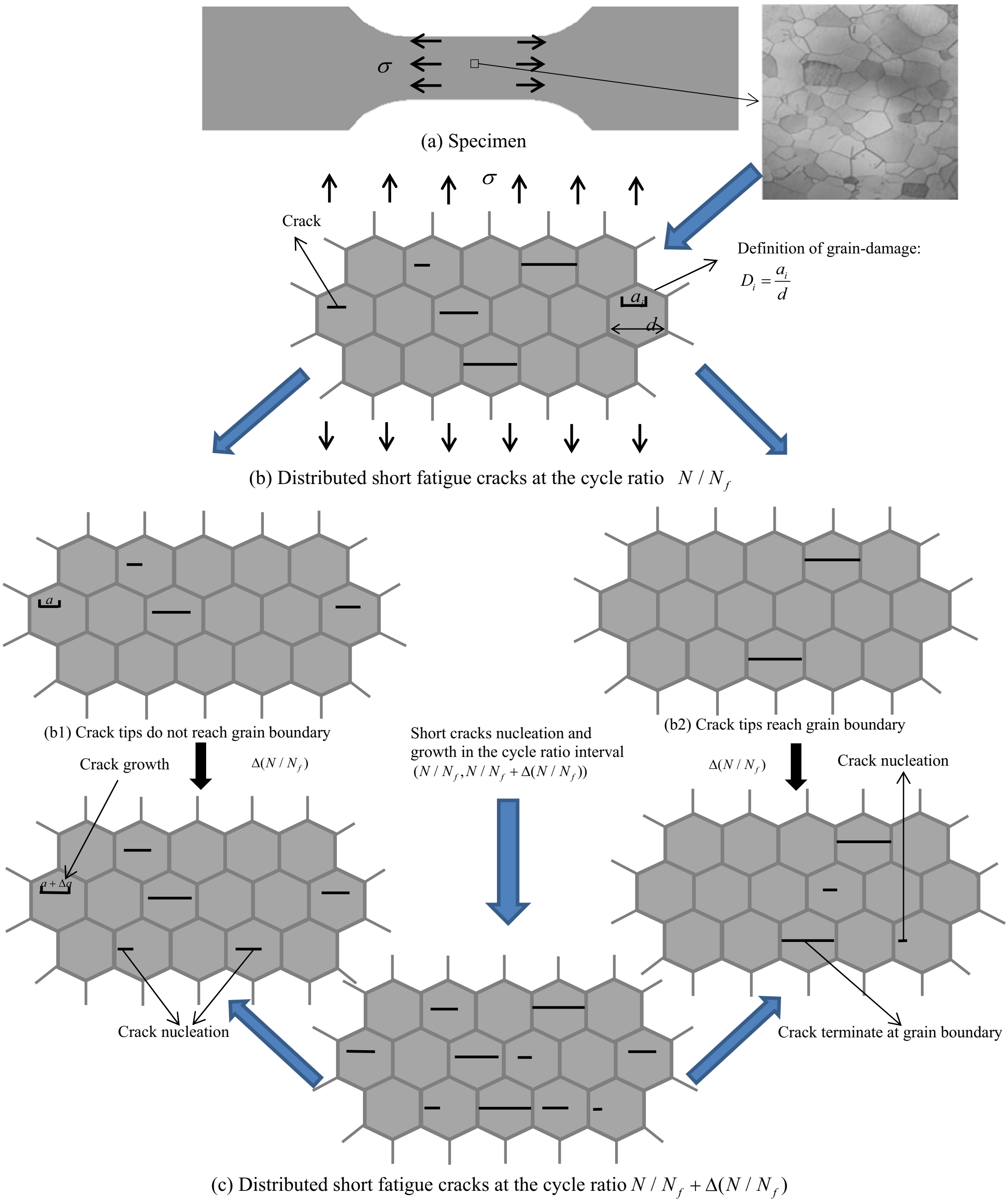

Fig. 1. Schematic diagram of the developed multi-scale fatigue damage model.

is a paucity of image-based models which can consider the real microstructural morphology [25].

In this regard, this paper aims to develop a multi-scale fatigue model and image-based simulation method to link short cracks collective evolution process in micro-scale to continuous fatigue damage evolution in macro-scale in terms of the concept of CDM. The proposed model and method provide a useful tool to establish the micro–macro relationship in fatigue process for better understanding the fundamental nature of the fatigue mechanisms.

2. Multi-scale model for fatigue damage accumulation due to short cracks nucleation and growth

2.1. Definition of macroscopic continuous damage variable by number density of microscopic short cracks

Short-crack regime occupies a large portion of total fatigue life, and for high-cyclic fatigue it can exceed 95% of the total fatigue life [6]. In the short-crack regime, most short cracks nucleate and grow