International Journal of Fatigue 75 (2015) 205–212

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Microstructural influence on the scatter in the fatigue life of steel reinforcement bars

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ARTICLE INFO

Article history:
Received 3 September 2014
Received in revised form 22 January 2015
Accepted 26 January 2015
Available online 7 February 2015

Keywords:
Short fatigue crack growth
Ferrite–pearlite
Tempered martensite
Scatter above the fatigue limit

ABSTRACT

Fatigue damage accumulation and failure of steel reinforcement bars (rebars) is a stochastic process. Scatter can be influenced by the sensitivity of the short crack growth to the microstructural features, especially near the fatigue limit. This work investigates the scatter inherent to the microscopic conditions near the fatigue limit of ferrite–pearlite and martensite microstructures found in the outer layer of rebars. An adapted Navarro–De Los Rios model within a Monte-Carlo framework is used to simulate the short crack growth in material grains. Grain size variation, grain orientation factor and multiple phases i.e., ferrite–pearlite and martensite were considered in the model. The results are compared with the scatter found in fatigue tests on hot-rolled-cold worked (HR-CW) as well as quenched and tempered (QST) rebars. It is shown that microstructural effects explains part of the observed scatter in the fatigue tests.

1. Introduction

Fatigue life assessment of engineering structures depends on the knowledge of material properties. Fatigue limit is a macroscopic property of the material that is sensitive to microscopic conditions. Since metal fatigue is a random process, fatigue data from testing always exhibit scatter for specimens of the same geometry, under same loading condition, especially near the fatigue limit. Besides, for metallic materials, the crack initiation period often dominates the fatigue life just above this limit. Since fatigue crack initiation is mainly a surface phenomenon, specimen surface roughness, protrusions and microscopic aspects such as grain size, grain orientation, dislocation density can influence the scatter in fatigue lives and fatigue limit stress range. The large scatter observed in fatigue tests lead to high values of confidence intervals (CI) s to get the design S–N curves. Further scatter result from the damage accumulation models used in fatigue life verifications. Most design codes, including those for steel reinforcement bars (rebars), usually consider 95% CIs.

Furthermore, one single design S–N curve regroup rebars produced from hot rolling, cold working and quenching and self-tempering with different surface microstructures, rib patterns and surface roughness, all of which increase the scatter near the fatigue limit and lead to very conservative design values. In order to understand the scatter inherent to microscopic aspects in the fatigue behaviour of rebars, this work proposes a short crack growth model to simulate the initiation period in ferrite–pearlite and tempered martensite grains found on the surface of different types of rebars.

Fatigue crack initiation period in metallic material consists of cyclic slip, crack nucleation and short crack growth [1]. These cracks can behave significantly different from the (long) crack propagation as described by Paris' law [2,3]. Short cracks can grow faster than corresponding long cracks at the same value of stress intensity factor range, ΔK. They can also grow at significant rates for ΔK value smaller than the threshold for long cracks [4].

Surface microscopic investigations in steel specimens have shown that short cracks form on slip bands and propagates along them [3]. The short crack propagation stops when the applied stress is below the fatigue limit; when the stress is just above this limit, the crack accelerates and decelerates due to the interactions with microstructural barriers until it reaches a long crack regime with apparent continuous propagation rate. The crack growth rate decreases as approaching the grain or phase boundary; the crack then accelerates when a slip band is initiated in the adjacent grain [2,5].

Navarro and De Los Rios (N–R) [6,7] proposed a short crack growth model where a crack initiates from slip bands. This model is particularly appropriate to study fatigue limit problems which involve microstructurally short cracks. N–R model considers the interaction between crack and microstructural barriers. It assumes

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http://dx.doi.org/10.1016/j.ijfatigue.2015.01.016

that dislocations are constrained to remain on their original plane and pile up when blocked by grain boundaries. They propagate along slip bands extending through successive grains.

N–R model can be considered as a further development of research in [8,9,3]. Bilby et al. [8] were the first to obtain a bounded solution for the dislocation distribution function representing the crack and the plastic zone (slip band ahead of the crack tip). Taira et al. [3,9] showed that the crack tip plastic zone interacts with microstructural barriers, such as grain boundaries, when the crack is of the order of microstructural features. Taira et al. [9] developed the unbounded solution for the dislocation distribution function.

In its original form, N–R model considers infinitesimal dislocations distributed within two zones: the crack itself a (half crack length) and the plastic zone c as shown in Fig. 1. In this two-zone model, an infinite stress level is sustained by the grain boundary. In [10], the model was extended by considering an additional small zone of length $r_0 \ll D$, (D is the, uniform, grain diameter) representing the interface between neighbouring grains or phases (see Fig. 1). This model eliminates the singularity of the stress field associated to the distribution of dislocations. In physical terms, the three-zone system was argued to be more realistic since the plastic zone is blocked by the grain boundary i.e., its two boundaries, and it remains blocked until the stress in the third zone i.e., the grain boundary, attains a critical level for dislocations to cross this zone.

N–R model has been extensively used (or extended) to predict the fatigue lifetime of metals. In [11], N–R model was applied to predict the short fatigue crack growth behaviour in mild steel. In [12], N–R model was applied for fatigue life prediction of commercially pure aluminium. The model prediction was in good agreement with experimental results. In [13], the effect of textures was investigated in the short fatigue crack growth in Al-Li alloy. An equation for the grain orientation factor was proposed depending on the load axis, slip plane normal and slip direction. N–R model was extended for biaxial fatigue loading case in low and medium Carbon steels; the crack initiation orientation was close to the experimental results [14]. The influence of the grain size variation was introduced in the N–R model by [15] where Voronoi cells were used to represent the grain structure. In [16], a micromechanical model for short crack growth based on successive blocking of monotonic plastic zone and cyclic plastic zone of a crack at grain boundaries was proposed. This model was based on the N–R approach [10]. These models successfully reproduced the short crack growth pattern where the crack decelerates at a grain boundaries and it accelerates when crossing a grain.

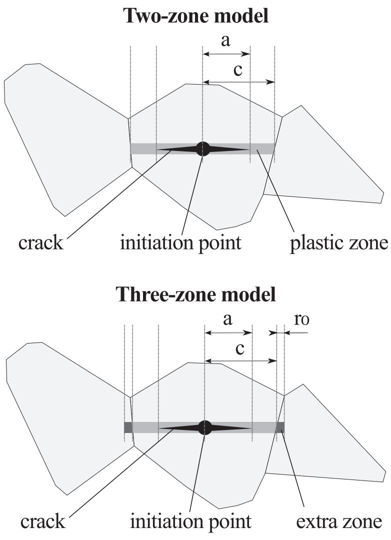

Fig. 1. Two-zone [6,7] and three-zone [10] models.

This irregular behaviour of short cracks due to the interactions with the microstructure can affect the scatter found near the fatigue limit. Factors such as grain size variation [3], grain orientation [13] and different phases [2] are more prominent at low stress levels and consequently influence the fatigue crack initiation period.

In this study, the influence of the microstructure on the scatter observed in experimental data as obtained above the fatigue limit is investigated using an adapted N–R model within a Monte-Carlo framework. The short crack growth is simulated in ferrite–pearlite (F–P) and tempered martensite (TM) grains found on the outer layer of rebars. The grain structure is represented by Voronoi tessellation. In the F–P model, the two phases, pearlite and ferrite, were modelled separately with the area fraction of each phase being obtained from the literature. On the other hand, the parent austenite grain is considered for short crack growth modelling in TM. The parent grain is experimentally determined using Electron Back Scattered Diffraction (EBSD) and ARPGE software [21]. The scatter obtained in the crack initiation phase is compared to experimental data from the literature.

2. Reconstruction of parent austenite grains

The laths of (daughter) martensite are organized within the parent austenite grains. The austenite grain size represents an essential characteristic of martensite steels; fine austenite grain results in the formation of fine martensite and consequently improvement in the mechanical properties of martensite steels [17]. In this work, slip band and short crack growth is simulated in the austenite grains of TM steel.

With the martensite transformation, also called displacive transformation, a vestige of the austenite grain boundary remains in the microstructure [18] and it can be revealed by etching [19]. However, it can be time consuming to find a successful etching to correctly identify the austenite grain boundaries. Instead, in [20], parent grains were successfully reconstructed by post-processing of EBSD data on the daughter grains. This technique was applied in this work to reconstruct the parent austenite grains in the cross section of quenched and self-tempered (QST) rebar from EBSD data obtained on martensite laths. The ARPGE software [21] was used for reconstruction of the parent grains.

2.1. Experimental analysis

EBSD analyses were performed on a polished cross section of QST rebar with 16 mm diameter. The cross section was prepared by mechanical grinding and polishing up to 1 μm followed by polishing with a Vibromet table containing non-crystalline colloidal silica for approximately 3.5 h. ESBD analyses were then conducted using XL30-FEG Scanning Electron Microscopy (SEM) at 20 kV. The cross section was tilted at 70° in the SEM. EBSD map of the martensite grains was obtained from the surface edge to 200 μm towards the centre. A map size of 200 × 200 μm was considered with a measurement step size of 0.2 μm.

EBSD map of the martensite laths is given in Fig. 2a. The orientation of the martensite grains is coded by colours[1] representing the Euler angles; they are a set of three angles which describe the crystallographic orientation of grains relative to a reference (sample) coordinate system.

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[1] For interpretation of colour in Fig. 2, the reader is referred to the web version of this article.