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Small crack formation in a low carbon steel with banded ferrite–pearlite structure

N. Narasaiah, K.K. Ray*

Department of Metallurgical and Materials Engineering, Indian Institute of Technology, Kharagpur 721302, India

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Abstract

The phenomenon of the formation of small cracks in a banded plain carbon steel has been studied on dumble-shaped plate type specimens under varied cyclic stress amplitudes at the load ratio of $R = 0$. The locations at which the cracks were found to nucleate could be classified as: (i) ferrite–pearlite interface (FPI), (ii) ferrite–ferrite grain boundary (FFGB), (iii) ferrite grain body, and (iv) inclusion–matrix interface. The most preferred site for such crack nucleation in the investigated steel was found to be the ferrite–pearlite interface. The orientation of the initiated small cracks was found to vary widely between 0° and 90° with respect to the loading direction unlike some earlier reported results. It is reported here for the first time that the angle between the direction of banding and the loading axis has pronounced effect on the orientation of such small cracks. The lengths of these cracks at FPI and FFGB are found to be larger than the ones nucleated inside ferrite grain body. The preferred site of crack nucleation and the influence of the banding on the size and the orientation of the small cracks have been explained using inhomogeneous distribution of stress/strain in the microstructure and incompatible strains along the interfaces.

Keywords: Fatigue; Crack initiation; Small crack; Banded structure; SA333 steel

1. Introduction

Micro-crack nucleation in structural materials is considered to be the first stage in fatigue damage, which is consequently followed by small/short and macro crack propagation leading to critical fatigue fracture. Any crack with all three dimensions small is defined here as “small crack” [1]; the short cracks, on the other hand, are known to possess two small dimensions and the third one of macroscopic size. A substantial body of evidence, accumulated over the last two decades, un-ambiguously indicates that small or short cracks exhibit faster growth at low stress intensity factor range (ΔK) than what would be predicted from the propagation of macro cracks [1–5]. Such evidences are also well supplemented by a large number of investigations [6–8] related to the possible mechanisms of crack nucleation. By now it is well conceived that a large percentage of fatigue life of smooth specimens are spent in the domain of crack nucleation and small/short crack growth, in the emerging clean (i.e., with very low inclusion content) structural materials especially in high cycle fatigue. It is thus imperative to gather more knowledge about crack nucleation and about small/short crack growth behaviour in such structural materials. In a recent communication, two of the present authors have extended some understanding about the influence of microstructure on the short crack growth behaviour in a structural steel [9], whereas in the present communication the role of microstructure on crack nucleation in a low carbon steel is being addressed.

The pre-macro crack regime of fatigue damage is often termed as “fatigue crack initiation stage”. It is well known by now that the microstructure of a material significantly influences this stage of fatigue damage. But unfortunately it is difficult to demarcate the crack nucleation stage from the stage of small/short crack propagation in this regime. The existing models that describe small/short crack growth behaviour in materials do account for the microstructural features (e.g., grain boundaries, precipitates, second phase particles, etc. [10–12]). The developments related to the mechanisms of crack nucleation, on the other hand, are found to be mostly

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* Corresponding author. Tel.: +91 3222 283278; fax: +91 3222 282280.
E-mail address: kkrmt@metal.iitkgp.ernet.in (K.K. Ray).

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associated with concepts related to sub-structural features (e.g., dislocations, dislocation-vacancy complexes, dislocation dipoles, etc. [13,14]). Information related to the role of microstructure on micro crack nucleation are limited and scattered, and such information have not led to any organised conceptual developments plausibly because of the numerous variety of microstructures encountered in the different investigated materials. The earlier attempts to probe this aspect have usually laid more emphasis either on the investigated material system or on the mechanics of small/short crack growth rather than trying to achieve a generalised perspective on the effect of microstructure on the location of crack nucleation. The present study aims to achieve understanding about the location and characteristics of small cracks in a two-phase material.

In this pursuit, this article deals with the formation of small cracks in a commercial steel exhibiting ferrite–pearlite structure. The material selected for this study is a SA333 grade 6 steel, which is used in the primary heat transport system of pressurized heavy water reactors. The major aim of this report is to identify the preferred crack nucleation sites in this material. In addition, the selected steel of engineering importance exhibits banded microstructure. The existing literature does not indicate the role of such structures on the nucleation of small cracks; this has been examined in this study. This report further aims to reveal the possible mechanisms associated with each type of crack observed in the material.

2. Experimental procedure

The steel used in this investigation is SA333 grade 6, which is used for the construction of piping for the primary heat transport system of pressurized heavy water reactors. The chemical composition of the steel is shown in Table 1. Samples for microstructural studies were prepared on sections oriented both to the longitudinal and the transverse directions of the pipe axis. These samples were initially ground with emery paper and were then polished first using alundum and finally using 0.25-μm diamond paste. The size and the number of inclusions on the polished specimens were found to be so insignificant that quantitative estimations of their size and volume fraction by conventional standard procedure like JIS G0555 [15] were found to be difficult. The polished samples were then etched with 2% nital solution to reveal the microstructure. Optical microscopic examination indicated that the steel contained ferrite and pearlite with prominent banding as shown in Fig. 1. The banding indices were determined following the procedure described in ASTM standard E-1268 [16], and were found to be 0.053 and 0.018 in the longitudinal and the transverse directions, respectively.

Table 1
Chemical composition of the investigated steel (in weight percentage)

Element	Composition
C	0.14
Mn	0.9
Si	0.25
P	0.016
S	0.018
Al	<0.1
Cr	0.08
Ni	0.05
V	<0.01
N	0.01
Cu	0.05
Pb	80 ppm
H	<5 ppm
O	0.03
Fe	Balance

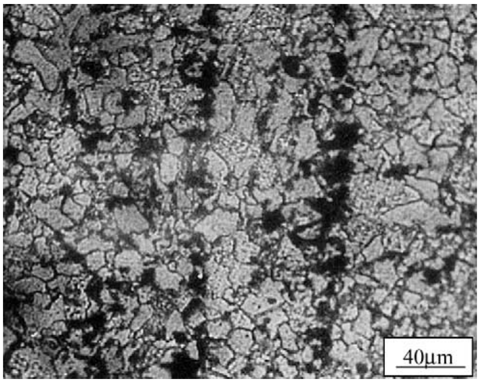

Fig. 1. Typical banded microstructure of the investigated material.

The tensile properties of the material were determined on specimens having their axis parallel to the length of the pipe. Round tensile specimens of 5-mm gauge diameter and 20-mm gauge length were fabricated from the as-received plates following ASTM standard E8-93 [17]. The tests were carried out using a Universal testing machine (Schimadzu, model: AG-5000G) at a nominal strain rate of $4.2 \times 10^{-4}\ \mathrm{s}^{-1}$ at room temperature. The average yield and tensile strength of the material were found to be 292 and 433 MPa, respectively, whereas the uniform and the total elongation were estimated as 23 and 46%, respectively.

The fatigue studies were carried out on small hourglass type flat specimens, made from the as-received material as shown in Fig. 2. One of the flat surfaces of each of these

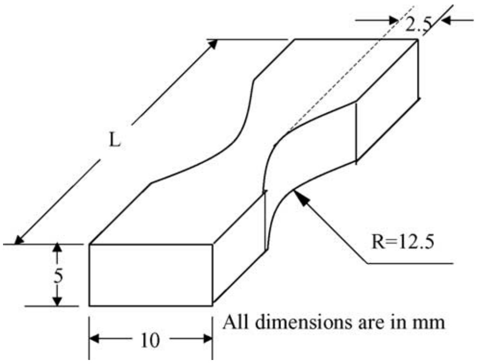

Fig. 2. Specimen configuration used for small crack initiation studies.