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Fatigue crack growth of a railway wheel

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A B S T R A C T

Typically, fatigue crack propagation in railway wheels is initiated at some subsurface defect and occurs under mixed mode (I–II) conditions. For a Spanish AVE train wheel, fatigue crack growth characterization of the steel in mode I, mixed mode I–II, and evaluation of crack path starting from an assumed flaw are presented and discussed.

Mode I fatigue crack growth rate measurement were performed in compact tension C(T) specimens according to the ASTM E647 standard. Three different load ratios were used, and fatigue crack growth thresholds were determined according to two different procedures. Load shedding and constant maximum stress intensity factor with increasing load ratio R were used for evaluation of fatigue crack growth threshold.

To model a crack growth scenario in a railway wheel, mixed mode I–II fatigue crack growth tests were performed using CTS specimens. Fatigue crack growth rates and propagation direction of a crack subjected to mixed mode loading were measured. A finite element analysis was performed in order to obtain the K_I and K_{II} values for the tested loading angles. The crack propagation direction for the tested mixed mode loading conditions was experimentally measured and numerically calculated, and the obtained results were then compared in order to validate the used numerical techniques.

The modelled crack growth, up to final fracture in the wheel, is consistent with the expectation for the type of initial damage considered.

1. Introduction

The paper presents a study of the fatigue crack growth in a high speed train wheel. Its aims are to evaluate the fatigue crack growth (FCG) properties of the material, and to illustrate their use in the prediction of FCG in the wheel, in the presence of an assumed initial defect.

Two main issues are encountered when studying fatigue of Spanish AVE high speed train wheels: (i) near threshold fatigue crack growth (FCG), (ii) mixed mode FCG.

Fatigue crack growth tests involve cyclic loading of notched specimens which have been fatigue pre-cracked. During these experimental tests the crack length (a) is recorded as a function of the number of cycles (N). The obtained results can be represented as a function of the crack-tip stress-intensity factor range (ΔK), in $da/dN = f(\Delta K)$ plots providing results independent from the geometry. This enables comparison of results obtained from a variety of specimen configurations and loading conditions assuming the similitude concept which implies that cracks of different lengths, subjected to the same nominal ΔK value, will grow by equal increments of crack extension per cycle [1].

Several studies of fatigue crack growth rates in wheel and rail steels are published in the technical literature. Among these, El-

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Shabasy and Lewandowski [2] present the effect of changes in load ratio R (min./max load ratio), and test temperature on the fatigue crack growth behavior of fully pearlitic eutectoid steel. This study revealed a significant effect of load ratio on the Paris law slope for a given test temperature and an increase in ΔK_{th} as the test temperature decreases.

The fatigue crack growth threshold is the asymptotic value of ΔK at which da/dN approaches zero, or according to [1] $da/dN < 10^{-10}$ m/cycle, and if the stress intensity factor for a given crack is below the threshold value, the crack is assumed to be non-propagating. At near-threshold levels, several factors, such as microstructure, environment, loading condition, and crack size, significantly affect crack propagation rates, [3].

The fatigue crack growth threshold ΔK_{th} is experimentally defined in [1], where a load reduction methodology is applied. Using this technique it is observed that ΔK_{th} decreases as the (positive) load ratio is increased. Crack closure is generally considered to be the main reason for the load ratio effect on the fatigue threshold value in metallic materials [4]. This could be explained by the fact that the methodology described in the ASTM E647 standard uses a load reduction technique where the maximum and minimum loads are reduced, and, when the threshold is being reached, during the unloading process the crack will close first at some point along the wake or blunt at the crack tip, reducing the load effect at the crack tip [5,6].

According to this interpretation, the K-decreasing (ASTM E647) methodology leads to overestimates of FCG threshold since the load is shed in steps and the amount of crack-wake plastic deformation produced during a test is directly related to the magnitude of previously applied loads leading to remote plasticity-induced crack closure, which could generate artificially high threshold values, [5]. An experimental study on two structural steels (normalized C45 and 25CrMo4 grades) conducted by Carboni and Regazzi to determine the influence of the adopted technique onto the ΔK_{th} value, [7], lead to conclude that in the threshold region, traditional approaches based on K-decreasing tests tend to systematically overestimate the ΔK_{th}.

Despite of this, the test method defined by ASTM is the only standardized test designed to produce the range of fatigue crack thresholds. Among others, the constant K_{max} with increasing K_{min} method, [8], was implemented to solve this problem, as this maintains high R–ratio levels that keep the entire crack open.

Single-mode loading rarely occurs in practice. Under mixed mode loading conditions a crack will deviate from its original direction, *e.g.* Biner, [9]. Several researchers indicate that rolling contact fatigue cracks are subjected to mixed mode I and II loading cycles, see *e.g.* Wong et al., [10]. Wheel shelling and rail squats are examples of defects originated in cracks that cause loss of large pieces of metal from wheel treads and rail head as a result of wheel-rail rolling contact fatigue. Fatigue tests performed to obtain the fatigue crack growth rate under the mixed loading (mode I–II) can be helpful to increase safety and reduce railway industry costs related with maintenance of wheels and rails. Fatigue cracks tend to deviate so that the crack plane is perpendicular to the maximum principal stress direction. This was shown for mixed I + II mode for which the initial crack plane was perpendicular the minimum principal stress direction or under shear only loading, see *e.g.* Qian and Fatemi, [11].

Different specimen geometries and testing methodologies have been used to perform mixed mode tests. Some examples of specimens that can be used to perform mixed mode tests are the compact tension and shear specimen, [12], three- or four-point bending specimens with an offset edge crack [13], plate specimen with inclined central or edge crack loaded under tension, as *e.g.* [14]. These specimens were developed to be tested on uniaxial testing machines. However, there is the possibility to use in-plane biaxial testing machines specially designed to perform this type of tests, and in this case the most used specimen is the cruciform specimen with central crack, see *e.g.* [15].

Until now there is no standard methodology for mixed mode testing, making it difficult to compare experimental results from different specimen geometries or testing apparatus.

Wheel and rail materials were tested by Akama [16] using an in-plain biaxial testing machine. Wong et al., [10] investigated the mechanics of crack growth under non-proportional mixed mode loading using cruciform specimens made by BS 11 normal grade rail steel tested in a biaxial testing machine.

The fatigue crack growth behavior under mixed mode of a 60 kg rail steel, commonly used as a railroad track in Korea, was experimentally investigated by Kim and Kim, [17]. The authors reported that fatigue crack growth rate under mixed mode is slower than under mode I, and this difference decreases with the increase of the load R-ratio. In this study a special loading device proposed by Richard, [12] was used to obtain the mixed mode loading on a uniaxial testing machine. Tanaka, [18] presented a study on sheet specimens of aluminum in which the mixed mode is obtained by using an initial crack inclined to the tensile axis.

Tests in compact mixed mode specimens (CTS) were carried out by Borrego et al. in AlMgSi1-T6 aluminum alloy, for several values of K_I/K_{II}, [19]. AISI-304 stainless steel samples were tested under mixed-mode I–II loading conditions using Compact Tension Shear Specimen (CTS) by Biner [9].

To evaluate the characteristics of mixed mode fatigue crack propagation, it is necessary to introduce a comparative, equivalent, stress intensity factor K_V that considers the effect of mode I (K_I) and II (K_{II}) simultaneously. Several equivalent stress intensity factors have been proposed along times. Among them those presented by Tanaka, [18], Richard, [12,20], Richard/Henn [21] and Henn et al. [22], Tong et al. [23] and Yan et al. [24]. Tanaka [18] dealt with the FCG behavior under mixed mode loadings using the K_V as presented in Eq. (1), which was derived from the dislocation model for fatigue crack propagation proposed by Weertman, [25].

$$K_V = \sqrt[4]{K_I^4 + 8K_{II}^4} \tag{1}$$

Tong et al. [23] and Yan et al. [24] combined mode I and mode II loadings based on maximum tangential stress criterion (MTS) proposed by Erdogan and Sih, [26], as:

$$K_V = K_I \cos^3\frac{\theta}{2} - 3K_{II}\cos^2\frac{\theta}{2}\sin\frac{\theta}{2} \tag{2}$$