Theoretical and Applied Fracture Mechanics 80 (2015) 73–78

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

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

Near threshold fatigue crack propagation in railways' steels: Comparison of two testing techniques

D.F.C. Peixoto [a],*, P.M.S.T. de Castro [b]

[a] INEGI – Institute of Science and Innovation in Mechanical and Industrial Engineering, Rua Dr. Roberto Frias, 400, 4200-465 Porto, Portugal
[b] Department of Mechanical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

ARTICLE INFO

Article history:
Available online 6 August 2015

Keywords:
Railway
Steels
Fatigue
Crack
Threshold

ABSTRACT

Mode I fatigue crack growth thresholds of steels for rail and wheel used in railways were determined according to two different procedures. Although fatigue crack propagation data in the Paris regime is usually straightforward to obtain, the same does not apply to the threshold regime, where crack growth rates are very small up to inexistent, and therefore tests are very time consuming. Furthermore, the very small fatigue crack growth rates involved in testing for threshold determination require very thorough and careful experimental procedures if extraneous effects – as for example interaction effects such as crack retardation or acceleration – are to be avoided. Two methods for evaluation of fatigue crack growth threshold value of the range of stress intensity factor were used: load shedding and constant maximum stress intensity factor with increasing load ratio R (R = minimum load/maximum load), taking into account the ASTM standard E647 prescriptions. The obtained results and lessons learned in conducting these tests are discussed, and the data generated is compared with data published.

1. Introduction

Fatigue crack growth rate tests involve cyclic loading of notched specimens which have been pre-cracked in fatigue. During these experimental tests the crack length (a) is recorded as a function of the number of cycles (N), together with the maximum and minimum values of the applied load. Using the recorded data and an appropriated methodology it is possible to obtain the fatigue crack growth rates (da/dN) and the corresponding values of the crack-tip stress-intensity factor range (ΔK). The obtained results can be represented as $da/dN = f(\Delta K)$ plots which provide results independent from the geometry. This enables comparison of obtained results 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-Shabasy and Lewandowski present in [2] the effect of changes in load ratio, R, 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 effect of rail residual stress in fatigue crack growth rates was studied by Skyttebol et al. and presented in [3]. The authors reported that due to the high tensile stresses in the lower part of the rail head a very high stress ratio is observed, $0.7 \leqslant R \leqslant 0.9$, implying that existing cracks are fully open during the load passage. The fatigue crack growth behavior of a premium rail steel was studied using the modified crack layer theory by Aglan and Gan [4]. In that work, the fatigue test specimens were sliced longitudinally from the head of a new rail near the web which represents the microstructure of the base material, avoiding the vertical microstructure gradient inside the rail. Bulloch presents in [5] a study of fatigue crack growth in welded rail steels concluding that the deformed rail steel exhibited fatigue crack growth rates that are slightly faster than undeformed rail steel and weld metal growth data are appreciably faster than rail steel growth results. Zain et al. [6], tested compact tension specimens ($C(T)$) made from rail steel with a load ratio of 0.1 while simultaneously recorded the acoustic emission signal in order to obtain the acoustic emission count rate associated with the stress intensity factor. Baseline fatigue crack growth data at $R = 0$ of different rail materials which were in service in the U.S. in 1978 have been generated by Feddersen and Broek [7], in order to develop a correlation of mechanical and metallurgical factors affecting crack behavior in rail steels.

---

* Corresponding author.
E-mail address: dpeixoto@inegi.up.pt (D.F.C. Peixoto).

http://dx.doi.org/10.1016/j.tafmec.2015.06.008
0167-8442/© 2015 Elsevier Ltd. All rights reserved.

In welded construction initial defects of considerable size may occur; but in most rail and wheel applications cracks develop in service from crack free material, and may be identified as very small cracks if adequate NDT is used. Therefore, further to the more common determination of Paris law constants it is important to characterize the near-threshold regime and determine the fatigue crack growth threshold, because for crack propagation in actual service the initial values of ΔK are expected to be rather low. It is considered that the fatigue crack growth threshold is the asymptotic value of ΔK at which da/dN approaches zero, or according to the ASTM E647 standard $da/dN < 10^{-10}$ 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, [8].

The fatigue crack growth threshold ΔK_{th} is experimentally defined by the ASTM standard E647, 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 principal reason for the load ratio effect on the fatigue threshold value in metallic materials [9]. 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 [10]. This phenomenon is schematized in Fig. 1, adapted from [11].

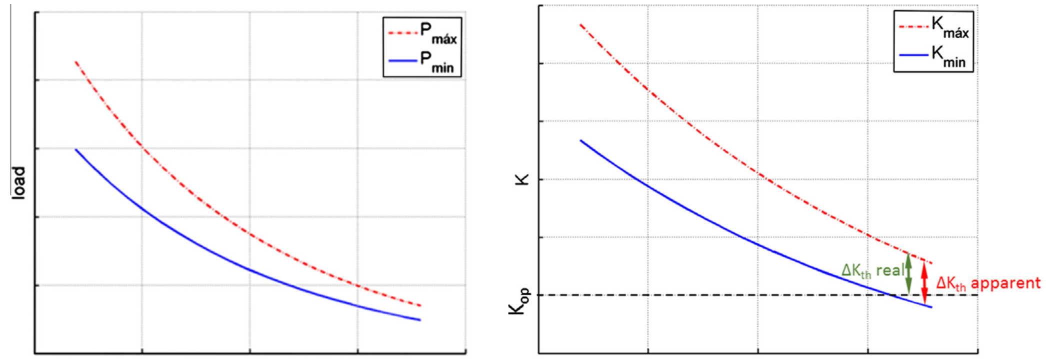
According to this interpretation, [10], the K-decreasing (ASTM E647) methodology leads to overestimates of fatigue crack growth (FCG) threshold since the load is shed in steps and the amount of crack-wake plastic deformation produced during a test is directly related to the magnitude of previously applied loads leading to remote plasticity-induced crack closure, which could generate artificially high threshold values. 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, [12], 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, [13], was implemented to solve this problem, as this maintains high R – ratio levels that keep the entire crack open, as schematized in Fig. 2, circumventing the difficulties and limitations mentioned above.

2. Near-threshold propagation fatigue crack growth rates experimental procedure

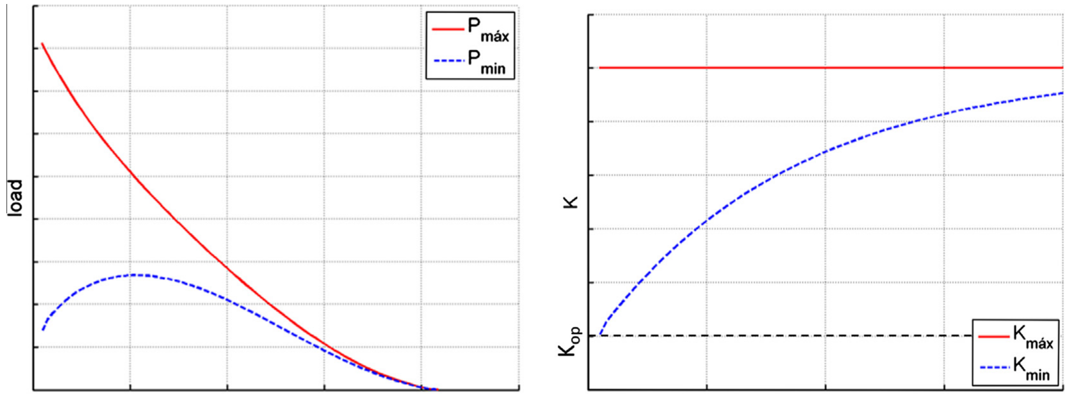
In the present study the K-decreasing test procedure, described in the ASTM E647 standard, and the constant K_{max} with increasing K_{min} procedure were used to characterize fatigue crack propagation near the threshold.

According to the ASTM E647 standard the K-decreasing test procedure is suited for rates below 10^{-5} mm/cycle. The constant



(a) (b)

Fig. 1. Schematic presentation of the ASTM E647 load shedding method for threshold determination.



(a) (b)

Fig. 2. Schematic presentation of nominal values of P_{max}, P_{min}, K_{max} and K_{min} as a function of the crack length a, along the constant K_{max} with increasing K_{min} test.