International Journal of Fatigue 33 (2011) 833–841

Contents lists available at ScienceDirect

International Journal of Fatigue

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

A simple model to predict the very high cycle fatigue resistance of steels

Mirco D. Chapetti

Laboratory of Experimental Mechanics (LABMEX), INTEMA (Research Institute for Materials Science and Technology), CONICET – National University of Mar del Plata, Juan B. Justo 4302 (B7608FDQ) Mar del Plata, Argentina

ARTICLE INFO

Article history:
Received 11 August 2010
Received in revised form 14 December 2010
Accepted 23 December 2010
Available online 5 January 2011

Keywords:
High strength steels
Very high cycle fatigue
Internal cracks
Non-metallic inclusions

ABSTRACT

This work deals with the very high cycle fatigue behavior of high strength steels where fracture origins are mostly at non-metallic inclusions. From the analysis of several features involved in the crack initiation and propagation processes, and since the fatigue resistance usually observed for metals is mainly due to a microstructural threshold for pure fatigue crack propagation, the following expression is proposed to estimate the internal fatigue resistance for a given fatigue life for fractures produced by cracks initiated from an internal inclusion:

$$\sigma_e^{Int} = 444\frac{\Delta K_{th}}{\sqrt{nR_i}}$$

where σ_e^{Int} is given in MPa, the inclusion radio R_i is in μm, n is a dimensionless factor and the pure fatigue crack propagation threshold ΔK_{th} is equal to the lower value given by the following expressions:

$$\Delta K_{th} = 4.10^{-3}(H_V + 120)\ a^{1/3}$$

$$\Delta K_{th-1} = -0.0038\ \sigma_u + 15.5$$

where the pure fatigue crack propagation thresholds ΔK_{th} (function of crack length) and ΔK_{th-1} (a constant value for a given tensile strength or hardness) are in MPa m$^{1/2}$, the crack length a in μm, the Vicker harness H_V in kgf/mm^2 and the ultimate tensile strength σ_u in MPa. Such estimation becomes very important in the assessment of the fatigue resistance of components subjected to very high cycle fatigue, as this might become a very expensive and time consuming task.

1. Introduction

Fatigue of high strength metals in the very high cycle fatigue regime has become of high interest the last decades, mainly for steels [1–15]. Fatigue fracture origins associated to very high cycle fatigue of high strength steels are mostly at non-metallic inclusions [1–5]. Improvement in steel-making technology has led to a reduction of the inclusion size, so the fatigue strength of high strength steels tends to increase year by year. Nevertheless, nowadays inclusion content still causes fatigue fracture and a decrease of the fatigue limit in almost all high strength steels. Thus, a method to estimate such fatigue limit for very high cycle fatigue (VHCF, total number of cycles to fracture $N > 10^7$) is highly necessary, as this is a very difficult property to obtain without sophisticated and expensive equipment that is not amply allowed for industry.

In the case of steels, a dark area is often observed in the vicinity of a non-metallic inclusion at the fracture origin, inside a fish-eye mark for specimens with a long fatigue life (hydrogen assisted fatigue crack initiation) [1–11], which represents the particular morphology associated with the mechanism of failure involved. Murakami and coworkers have named the near area around the inclusion as "Optically Dark Area" (ODA), and the related mechanism of failure as "hydrogen embrittlement assisted by fatigue" [1,3,4].

In a previous work [12], some features related to fatigue crack initiation and propagation from surface and from internal inclusions were analyzed and modeled in high strength steels that present both types of crack initiation. It was concluded, in accordance with previous publications, that any estimation of total fatigue life N associated with the failure produced by cracks initiated at internal inclusions will succeed only if the crack initiation period, an important percentage of N, is properly estimated.

The fatigue crack initiation period could be defined by the number of cycles necessary to create a crack length for which pure fatigue crack propagation can be reached [3–12] (see Fig. 1). The number of cycles to form such a critical crack a_0^{pf} is defined by the type and size of inclusion, the tensile residual stresses around it, the amount of hydrogen, the applied nominal stress range and amplitude, some particular features of the microstructure related to the hydrogen trapping places and the threshold for pure fatigue

E-mail address: mchapetti@fi.mdp.edu.ar

0142-1123/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijfatigue.2010.12.010

Nomenclature

a	crack length
a_0	initial crack length
a_0^{pf}	initial crack length for pure fatigue propagation
$Area^{1/2}$	Murakami's model parameter
$(Area_{ODA})^{1/2}$	Murakami's model parameter for ODA
d	position from the surface of the strongest microstructural barrier to fatigue crack propagation
$\Delta\sigma$	applied stress range
$\Delta\sigma_{eR}$	plain fatigue limit, for a given stress ratio R
$\Delta\sigma_{th}$	stress threshold range for pure fatigue crack propagation (function of crack length)
ΔK	applied stress intensity factor range (applied crack driving force)
ΔK_{dR}	microstructural threshold (defined by $\Delta\sigma_{eR}$ and d)
ΔK_{th}	total fatigue crack propagation threshold (function of crack length)
ΔK_{thR}	mechanical fatigue threshold for long cracks
$\Delta K_{th0.1}$	mechanical fatigue threshold for long cracks, $R = 0.1$
ΔK_{th-1}	mechanical fatigue threshold for long cracks, $R = -1$
H_V	Vicker's hardness
n	dimensionless factor
N	total number of fatigue cycles to fracture (total fatigue life)
N_I	number of cycle for fatigue crack initiation (initiation life)
N_P	number of cycle for fatigue crack propagation (propagation life)
ODA	Optically Dark Area
R	stress ratio (minimum stress/maximum stress)
R_i	inclusion radius
R_i^{max}	maximum inclusion radius
σ_e	surface fatigue resistance amplitude
σ_e^{Int}	internal (or subsurface) fatigue resistance amplitude
σ_u	ultimate tensile strength

crack propagation [1–15]. However, there exists very limited information on how parameters influence the crack initiation period. Thus, the aim of defining a proper model to estimate the fatigue crack initiation life N_I is not an easy task. Nevertheless, a threshold for pure fatigue propagation of internal cracks initiated at inclusions can be defined taking into account the different geometrical and mechanical variables involved in the process.

In this paper, a simple model to estimate the threshold nominal stress to obtain fatigue fracture from cracks initiated at internal inclusions is presented. The defined internal fatigue resistance is obtained from: (a) the threshold for pure fatigue crack propagation and (b) the inclusion size in the material where the crack initiation takes place. Some applications are shown, and a simple procedure to estimate the internal fatigue resistance of the material for a fatigue life of 10^{10} cycles is also proposed.

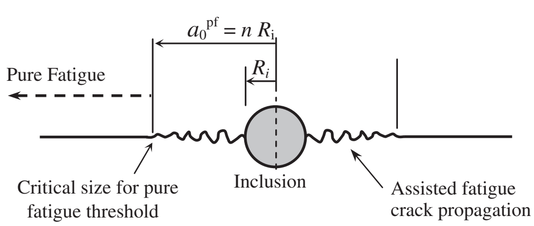

Fig. 1. Schema of the mechanism for very high cycle fatigue failure from internal inclusion with an initial assisted fatigue crack initiation and early propagation stage.

2. The influence of tensile strength σ_u on fatigue resistance σ_e

It is well known that fatigue resistance σ_e increases with tensile strength σ_u (or with hardness, H_V) [16,17]. However, after a given tensile strength, the fatigue resistance shows a different trend and a different fatigue mechanism takes place. Fig. 2 shows schematically the experimental trend. The linear relationship usually observed between σ_e and σ_u at lower strength is related to surface fatigue crack initiation mechanisms, while at higher resistances, a fracture process given by an internal fatigue crack initiation defines the relationship between σ_e and σ_u. Even though both processes have features in common, there are some important differences.

The fatigue resistance and the competition between these two fatigue mechanisms are also shown by the experimental σ–N curves (applied nominal stress amplitude σ as a function of the number of load cycles to failure, N). Fig. 3 shows an example for a JIS SUJ2-QT steel [5], where the low, high and very high cycle fa-

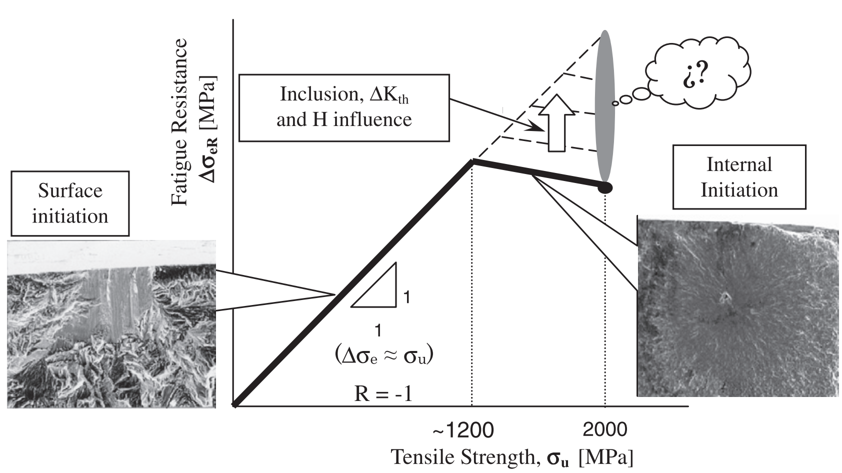

Fig. 2. Schema of the experimental trends of the relationship between fatigue resistance $\Delta\sigma_{eR}$ and tensile strength σ_u for $R = -1$. Typical fractographic appearance of the initiation zones is also shown.