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Surface Versus Internal Fatigue Crack Initiation in Steel: Influence of Mean Stress

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Abstract

Stress-controlled fatigue tests were run at different R ratios (= $\sigma_{min}/\sigma_{max}$) up to at most 3 million cycles on a 2.5%Cr-1%Mo steel (ASTM A182 F22) used in riser tubes connectors for offshore oil drilling. The fatigue lives, as well as the slope of the S-N curves were found to decrease with increasing R and the endurance limit to follow Gerber's parabola. Surface crack initiation without any defect involved, was most often observed for $R = -1, -0.5$ and 0, while an R ratio of 0.25 triggered crack initiation from either surface or internal pores or chemically inhomogeneous areas, leading, in the latter case, to fish-eye patterns for relatively low numbers of cycles. A further increase in R ratio to 0.5 promoted only defect-initiated surface cracks, while no fatigue fracture was observed within 10 million cycles above $R = 0.6$. These transitions in crack initiation mode are discussed based on X-ray diffraction analyses of residual stresses, elastic-plastic FE computations on a unit cell model containing a pore and some fracture mechanics analyses, with a particular attention to environmental effects.

Keywords: Mean stress, internal crack, steel, defects, fish-eye

1. Introduction

Fatigue cracks are known to initiate potentially in steels by a variety of mechanisms: from the surface at machining marks, persistent slip bands, grain/phase boundaries or surface-cutting defects, or from internal metallurgical defects. Surface initiation usually predominates up to 10^6 cycles, while internal crack initiation is common in the very high cycle fatigue (VHCF) (> 10^7 cycles) [1–5]. The switch from surface to internal crack initiation often leads to dual S-N curve [6, 7] with a plateau between 10^6 and 10^7 cycles, which has long been considered as the endurance limit, (since surface-initiated cracks do not propagate below this stress amplitude) until the use of ultrasonic testing machines revealed fatigue failures from internal defects, at even lower stress ranges, i.e. VHCF.

Internal crack initiation is generally accompanied by a "fish-eye" pattern on the fracture surface [8–10] and often, by a rough Optically Dark Area (ODA) [9], also called Fine Granular Area (FGA) [7], surrounding the defect responsible for crack initiation. The formation mechanism of the ODA/FGA has been much debated [9–12]. The formation of an ODA/FGA is known to require at least 10^7 fatigue cycles, under fully reversed loading. Surface residual stresses have been reported to play an important role in the competition between surface and internal crack initiation [13–15]. Compressive surface residual stresses were reported to inhibit surface crack initiation when they are stable and thus to favor internal crack initiation.

Many attempts to use Linear Elastic Fracture Mechanics (LEFM) to predict the endurance limit in case of internal crack initiation, based on the defects size distribution and a threshold ΔK for fatigue crack growth, or to compute the fraction of fatigue life spent in internal crack growth by integration of crack growth kinetics, can be found in the literature [1, 5]. The main difficulty with these approaches is the lack of reliable data on fatigue crack growth threshold

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