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A fracture mechanics approach to interior fatigue crack growth in the very high cycle regime

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ABSTRACT

Growth rates of optically dark areas (ODA) and fish-eyes (FE) were quantified in kHz-ultrasonic fatigue tests on SUJ2 and 17-4PH steels at constant and repeated two-step amplitudes. Sizes of ODAs and FEs depended on the stress intensity factor (SIF) range, and interior fatigue crack growth rates (FCGR) were slower than those of “long” cracks in air, suggesting vacuum as ODA growth environment. Repeated two-step tests on SUJ2 steel served to form beach marks so that, a quantification of ODA sizes, interior FCGRs and SIFs became possible. Additional FCGR measurements of long cracks in vacuum and comparable fracture morphologies allowed estimating the growth rates of ODAs and FEs in 17-4PH steel.

1. Introduction

Due to the demand for longer fatigue lives in technical equipment and constructions, research on fatigue failure has attracted increased attention recently. Responding to this demand, material scientists continually develop new materials with improved fatigue properties, therefore also relying on exact fatigue failure measurements.

As early as 1978, Schijve emphasized the importance of *internally growing cracks* in aluminum alloys and showed that the resulting fatigue lives were determined by such cracks growing in a vacuum under realistic loading conditions [1]. In the 1980s, research on the very high cycle fatigue (VHCF) properties of high-strength steels received a most important input, namely the detection of failures beyond the traditionally assumed fatigue limit in the regime of 10^6–10^7 cycles [2,3]. Moreover, under special conditions (i.e. material properties, surface condition, amplitude of loading, number of cycles, etc.) such VHCF failures were found to originate in the *interior* of the specimen, whereas fatigue cracks in the regime of up to approximately 10^7 cycles usually start from some kind of *surface* imperfections. Since that time, interior fatigue crack initiation has been discovered in other materials than high-strength steels as well. In addition, cracks were found to originate not only from inclusions, but also from interior pores or porous areas in cast aluminum alloys [4] or even from internal persistent slip bands in polycrystalline high purity copper [5].

Numerous investigations were performed to determine how structural features such as grain size, morphology and size of inclusions, surface treatment and pre-straining influence the fatigue strength and fatigue life of different materials such as

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Nomenclature

CT	compact tension
da/dN	fatigue crack growth rate in m
D_f	cumulative damage
N	number of cycles
ODA	optically dark area within fish-eye fracture surface
R	stress ratio
SEM	scanning electron microscope
S–N curve	plot of stress versus number of cycles to failure
ΔK	stress intensity factor in MPa$\sqrt{m}$ (defined by tensile component, i.e. amplitude of cyclic stress at $R = -1$ in this paper)

Austenitic stainless steels [6]. A comprehensive overview of the most important findings by Li [7] was published recently. The study investigates the effects of hydrogen, vacuum, the boundary segregation of fine grains and carbides. According to Li, most of the fatigue life is spent on the formation of a characteristic fracture surface morphology. This characteristic fracture surface is called ODA (optically dark area) [8] because it looks dark when observed with an optical microscope, while the same region is also called FGA (fine granular area) [9] or GBF (granular bright facet) [10] based on the morphology. Thus, the terms correctly indicate the morphological characteristics and the term ODA is used in this paper, because optical microscopy was the main means of determining the sizes of the regions.

Detailed fractography and transmission electron micrographs both led to corresponding roughness values of ODAs [9,11]: compared to the original material microstructure, the grain size of the ODAs' subsurface structure is extremely reduced [12]. Another remarkable characteristic of ODAs is that a similar morphology can be observed for different material systems, i.e. high strength steels [13], titanium alloys [14–16] and aluminium alloys [17]. In addition, such a morphology can also be found on the fracture surface of compact tension (CT) specimens made of these materials for standard FCG tests when tested in a high vacuum environment [13,14,18,19].

Several theories try to explain the formation of ODAs: Murakami [20] emphasizes the influence of hydrogen, e.g. hydrogen assisted fatigue crack growth. Oguma [12] proposes the segregation of extremely fine grains of material as influencing and accompanying ODA formation and Shiozawa et al. [21] emphasize the importance of the segregation of fine carbides and subsequent formation and coalescence of microcracks. At variable amplitude loading, beach marks were formed on the fracture surface of the fish-eye region around the ODA. These were used to characterize the ODA's and fish-eye's growth rate of an ODA using a fracture mechanics approach [22].

Only very few papers using fracture mechanical methods to quantify the areas of fish-eyes and especially ODAs around inclusions manage to give quantitative results for fatigue crack propagation rates and stress intensity factors [9,17,23–30]. In the present study, ultrasonic fatigue tests were performed on high carbon chromium bearing steel, SUJ2, and a precipitation hardened chromium–nickel–copper steel, 17-4PH, at constant amplitudes. Furthermore, two types of two-step amplitude stressing tests were conducted on SUJ2 steel in order to investigate the fatigue damage accumulation and the growth behavior of interior cracks. Based on these results together with those from the literature, a formation mechanism of the ODA is proposed.

2. Material and experimental procedures

The tested materials were SUJ2, a high carbon chromium steel for bearings (Japan industrial standards JIS) and 17-4PH, a precipitation hardened chromium–nickel–copper steel which is often used for steam turbine blades. Their chemical compositions and mechanical properties are presented in Tables 1 and 2, respectively. The SUJ2 steel was oil quenched from 850 °C and tempered at 180 °C for 120 min. The 17-4PH steel was age hardened at 620 °C (condition H1150) and stress relief annealed at 600 °C. The specimen shapes for the SUJ2 steel and the 17-4PH steel are shown in Fig. 1(a) and (b), respectively. The surfaces of the test specimens were polished with abrasive paper in axial direction (final grade 2000 for SUJ2 and 4000 for 17-4PH).

Table 1
Chemical composition (mass%) of SUJ2 and 17-4PH steel.

Material	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	Nb + Ta	O (ppm)
SUJ2	1.00	0.17	0.39	0.017	0.006	0.08	1.40	0.03	–	–	5.00
17-4PH	0.033	0.40	0.49	0.027	0.001	4.37	15.57		3.31	0.23	