Effects of the ENVIRONMENT on the Initiation of CRACK GROWTH

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Foreword

This publication, *Effects of the Environment on the Initiation of Crack Growth,* contains papers presented at the symposium of the same name held in Orlando, Florida, on 20-21 May 1996. The symposium was sponsored by ASTM Committee E-08 on Fatigue and Fracture, G01 on Corrosion of Metals, and Subcommittees E08.06 on Crack Growth Behavior and G01.06 on Stress Corrosion Cracking and Corrosion Fatigue. The symposium was chaired by W. Alan Van Der Sluys, Babcock & Wilcox; Robert S. Piascik, NASA Langley Research Center, and Robert Zawierucha, Praxair, Inc. They also served as editors of this publication.

Overview

The initiation stage of environmentally assisted cracking can have a profound effect on the life of a component. Little is known about the damage mechanisms that occur during the important early stages of crack formation, e.g., nucleation and small crack growth, compared to the crack propagation regime. This Special Technical Publication reviews current understanding on the effects of the environment on the initiation of crack growth relating to specific areas, including: (1) mechanistic modeling, (2) life prediction, (3) nuclear industry environmental cracking, and (4) recent aging aircraft durability issues. The following is a brief overview of the symposium papers included in this topical volume.

Session I: Stress Corrosion Cracking Initiation

Akid discussed the role of stress-assisted localized corrosion on the development of short fatigue cracks. Corrosion experiments were conducted under cyclic and static stress, using low and high strength steels and stainless steels in chloride environments. Surface film breakdown, pit development and growth, pit/crack transition, and environment-assisted Stage I and Stage II crack growth were monitored. Each process is considered to be of primary importance during the early stages of stress corrosion and corrosion fatigue cracking.

Chen, Liao, Wan, Gao, and Wei assess two proposed pit to crack transition criteria: (1) the stress intensity factor for an equivalent crack, equal, or exceeded the threshold stress intensity factor for corrosion fatigue crack growth (CFCG), and (2) the time-based CFCG rate exceeded the pit growth. Validation of a proposed pitting corrosion/fatigue crack nucleation criterion is presented and discussed in terms of open hole alloy 2024-T3 experiments conducted in 0.5M NaCl solution.

Leis and Colwell studied the processes leading to the formation of crack-like features as well as early crack growth of stress-corrosion cracking on the exterior of gas transmission piping. Observations show that cracks with dense spacing tend towards dormancy, whereas the sparsely spaced cracks continue to grow. Fracture mechanics based analysis is used to rationalize the crack pattern observations.

Session II: Crack Initiation in Aging Aircraft

Kolman and Scully examined the effects of a sharp notch or crack tip on cation accumulation—hydrolysis—acidification, potential drop in solution and resulting hydrogen production, and localization on dynamic strain in titanium alloys exposed to 0.6 *M* NaCl. It was shown that the drop in potential down a sharp crack is severe enough to enable hydrogen production, even when the applied potential is more positive than the reversible potential for hydrogen production. The effects of a sharp notch on the interplay of mechanics, film rupture, and hydrogen uptake are also examined.

Schmidt, Crocker, Giovanola, Kanazawa, Shockey, and Flournoy investigated the processes that influence the transition from salt water corrosion pit development to fatigue crack formation in Alcad 2024-T3. Results suggest that the nucleation of corrosion fatigue cracks involves two competing mechanisms: hydrogen effects in the cladding and electrochemical dissolution at constituent particles in alloy 2024. Cracks do not necessarily nucleate at the largest corrosion pit, suggesting that a contributing factor to crack nucleation from a pit may be the creation of a local region of weakness.

Bray, Bucci, Colvin, and Kulak evaluate the effect of prior corrosion on the S/N fatigue performance of 1.60 and 3.17-mm-thick aluminum sheet alloys 2524-T3 and 2024-T3. The fatigue strength of alloy 2524 was approximately 10% greater and the lifetime to failure, 30 to 45% longer than alloy 2024. Two main factors are believed to have contributed to the better performance of 2524: less damaging configuration of corrosion pits and its better fatigue crack growth resistance.

Session III: Stress Corrosion Crack Initiation in Nuclear Environments

Parkins and Mirzai provide a database that will allow prediction of stress corrosion cracking failures in nuclear reactor components exposed to the radiolysis of moist air which produce nitric acid environments. Constant strain stress corrosion tests, at 50 or 100% yield stress, were conducted on welded nickel based steel samples exposed to a mixed nitrate solution for various times. Selective attack at relatively short exposure times was observed where grain boundaries intersected the specimen surfaces.

Kondo, Bodai, Takei, Sugita, and Inagaki studied environmentally assisted cracking of 3.5NiCrMoV low alloy steel under cyclic straining in water at 60°C. Test results showed that higher strain range, lower strain rate, longer strain hold times, and higher electric conductivity caused increased charge transfer, which resulted in shorter crack initiation life. A prediction model for crack initiation life was proposed based on observed charge transfer.

Soloman, DeLair, and Unruh investigated the fatigue crack initiation of WB36, a German low alloy steel (LAS), tested in high-temperature high-purity water. The tests were performed at 177°C, in water containing 8 ppm O_2. H_2SO_4 additions were also used in some tests to raise the conductivity of the water from 0.06 to 0.4-0.5 μS/cm. The crack initiation and growth data are correlated with water chemistry.

Akashi and Nakayama investigated the initiation of stress corrosion cracking in boiling water reactor materials. They suggest that stress corrosion cracking can be divided into six (three deterministic and three stochastic) separate processes. The paper examines the influence of three stochastic processes: (1) nucleation of corrosion pits, (2) initiation of micro cracks, and (3) the coalescence of microcracks, on the stress corrosion cracking initiation process.

Session IV: Modeling

Hall and Symons showed that the initiation of stress corrosion cracking in alloy X-750 exposed to high-temperature-deaerated water occur at a variable distance from the notch or crack tip. The initiation site varies from very near the crack tip, for loaded sharp cracks, to a site that is one grain diameter from the notch, for lower loaded, blunt notches. The existence of hydrogen gradients, which are due to strain-induced hydrogen trapping in the strain fields of the notch and crack tips of the SCC test specimens, is argued to be responsible for variation in the crack initiation site.

O. Jonas presented a corrosion model for iron-based alloys. Interactions of aqueous environments in cracks are expressed as relative bonding energies for individual molecules and other parameters. The results indicate relative aggressiveness of environments, types of chemical/corrosion reactions, and the rate of mass transport to the crack-tip.

Session V and VI: Crack Initiation in Corrosion Fatigue

Atkinson, Zhao, and Yu investigated the effect of dynamic strain aging (DSA) on stress corrosion cracking of reactor pressure vessel steels exposed to 250°C water. Results support the coincidence of temperature and strain rate between the DSA hardening and the susceptibility to environment-assisted cracking of reactor pressure steels. The mechanistic role of DSA and its interpretation with other influential variables in the enhancement of stress corrosion cracking are discussed.

Higuchi, Iida, and Asada studied the effect of strain rate on the fatigue life of carbon steel exposed to high-temperature water containing dissolved oxygen. A series of strain-controlled fatigue tests were conducted with strain rate changed stepwise or continuously. A method using the product of the environmental effect and the strain increment within a unit time interval in a transient period is integrated from the minimum strain to the maximum. This modified strain rate approach method is discussed in detail.

Nakao, Higuchi, Kanasaki, Iida, and Asada investigated the fatigue design of pressure vessel components. They show that decreased fatigue life of STS410 carbon in simulated boiling water reactor water is dependent on temperature and dissolved oxygen. An environment parameter ratio, R_p, is proposed for the estimate of the fatigue life at a certain temperature and dissolved oxygen content.

Chopra and Shack summarized the available data on the effects of various material and loading variables such as steel type, dissolved oxygen level, strain range, strain rate, and sulfur content on the fatigue life of carbon steel and low-alloy steels. The data have been analyzed to define the threshold values of the five critical parameters. Methods for estimating fatigue lives under actual loading histories were discussed.

Kanasaki, Hirano, Iida, and Asada performed strain controlled low cycle fatigue tests of a carbon steel in oxygenated high-temperature water. The corrosion fatigue life prediction method was proposed for changing temperature conditions. The method is based on the assumption that the fatigue damage increased linearly with the fatigue cycle strain increment. The fatigue life predicted by this method was in good agreement with the test results.

Kishida, Umakoshi, and Asada proposed a method for evaluating the environmental fatigue lives for the Class I reactor pressure. A revised simplified method is developed for the determination of a fatigue usage factor for a component in which loading transients include variation of temperature, strain rate, and oxygen content in addition to the strain range. A number of examples are presented in which an environmental effect correction factor is determined for components in a nuclear pressure boundary.

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Stress Corrosion Cracking Initiation

Robert Akid [1]

THE ROLE OF STRESS-ASSISTED LOCALIZED CORROSION IN THE DEVELOPMENT OF SHORT FATIGUE CRACKS

REFERENCE: Akid, R. "**The Role of Stress-Assisted Localized Corrosion in the Development of Short Fatigue Cracks,**" Effects of the Environment on the Initiation of Crack Growth, ASTM STP 1298, W. A. Van Der Sluys, R. S. Piascik, and R. Zawierucha, Eds., American Society for Testing and Materials, 1997.

ABSTRACT: The initial development and growth of defects from 'engineered' surfaces, i.e. fine abraded, polished, shot peened etc., often dominates the resulting component lifetime, particularly for materials of high strength and limited ductility. When subject to the conjoint action of stress and environment this lifetime is impaired and reductions in fatigue strength are often observed resulting from a reduction in defect development time, often termed 'initiation', and enhancement in defect growth rate.

A number of factors exist which influence the rate at which defects, such as pits/cracks, develop. Included in these are; physical and chemical material surface condition, the nature of the loading mode, test frequency and electrochemical micro-climate at the metal/solution interface. Based upon corrosion experiments conducted under cyclic and static stress, using low and high strength steels and stainless steels in chloride environments, the following events; surface film breakdown, pit development and growth, pit/crack transition and environment-assisted stage I and stage II crack growth have been observed. Included in these experiments is that of the Scanning Reference Electrode a technique adapted to evaluate stress-assisted localised corrosion, a process considered to be of primary importance during the early stages of stress corrosion and corrosion fatigue cracking; particularly for actively corroding systems.

KEYWORDS: corrosion fatigue, pitting, scanning reference electrode, microstructural fracture mechanics, short cracks, modelling

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INTRODUCTION

Corrosion processes coupled with the application of an applied stress can have a profound effect on limiting the useful lifetime of structures and components. In this respect a number of procedures are adopted to reduce the risk of corrosion. Included in these methods is the selection of corrosion resistance materials, the application of coatings or the imposition of a potential, more negative than the free corrosion potential, to suppress metal dissolution. In the latter case over protection of a structure can lead to embrittlement through the adsorption of hydrogen. However, this mechanism is principally restricted to components and structures containing pre-existing defects, i.e. cracks which are of a size appropriate for inducing hydrogen embrittlement [1-3]. Where conditions are such that engineering surfaces, i.e. smooth polished or peened, are essentially free from defects the process of metal dissolution can have a marked effect on the fatigue resistance of a metal.

This paper sets out to illustrate through examples from experimental studies including the Scanning Reference Electrode Technique (SRET) and fatigue tests conducted within air and under corrosion conditions, how the anodic dissolution process can modify the early stages of defect development such that the in-air fatigue limit may be eliminated. In addition microstructural fracture mechanics based models adopted to incorporate the influence of variables such as stress state, test frequency and electrochemical condition are discussed.

FATIGUE CRACK DEVELOPMENT IN AIR AND AQUEOUS ENVIRONMENTS

Numerous references within the literature may be cited which emphasise a period of the fatigue process designated as the 'initiation stage'. This term is somewhat misleading as close attention to many of these studies shows that the term initiation refers to a period, prior to which a defect, 'of a specified size', may be observed. The value of this period, as a fraction of total life; is subject to the users ability to find the defect of interest and in many cases little attention is paid to cracking along the boundary of an inclusion or at subsurface inclusions or defects. Recent studies [4-6] have shown that cracks can develop within the first few percent of lifetime and grow microscopically until arrested at some feature associated with the microstructure, e.g. a grain or phase boundary. That cracks develop early in the lifetime and exhibit marked accelerations and decelerations in growth is recognised through the development of Microstructural Fracture Mechanics (MFM) models [7-8].

When smooth specimens are tested within aggressive environments the lifetime is often reduced to a fraction of that observed in air. Observation of the early stages of defect development [9-13] show that for carbon steels in chloride environments, pit development and stress assisted dissolution accelerate the transfer of a stage I shear crack to that of a fatal stage II tensile crack. Typically the processes involved during air and corrosion fatigue are illustrated in Fig. 1.

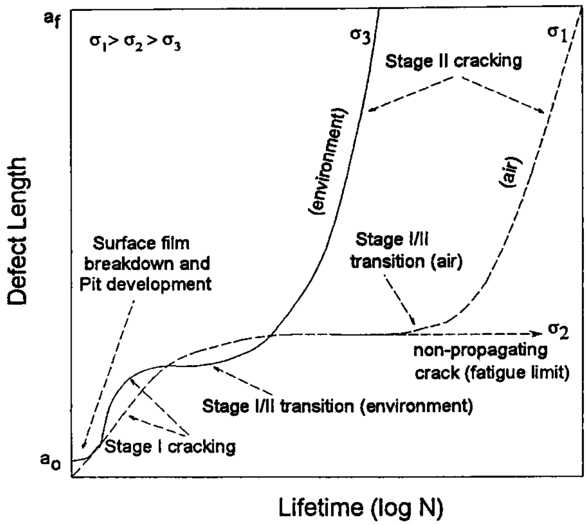

FIG. 1 Schematic of defect development stages in air and an aggressive environment.

The ratio of corrosion fatigue to air fatigue lifetimes varies from approximately unity to less than 0.2 depending upon the applied stress level, test frequency and solution conditions. At high stress levels lifetimes are short and the effects of corrosion are small. As the stress falls below that of the in-air fatigue limit the mechanical crack driving force decreases and the relative, chemical driving force i.e. corrosion, increases. This interaction between mechanics and corrosion is also observed as the defect approaches a microstructural barrier [11]. Furthermore as the crack length increases, and a physically short crack (PSC) develops, the corrosion fatigue and air fatigue crack growth rates merge as the mechanical crack tip stress intensity controls the growth rate at the expense of corrosion assisted growth.

The major events occurring during corrosion fatigue are discussed in detail below and illustrated in fig 1.

MECHANISMS CONTRIBUTING TO INITIAL DEFECT DEVELOPMENT.

(a) Surface film breakdown

Surface film breakdown is dependent upon the nature of the material, solution conditions, the electrochemical state at the material/solution interface and the application of a stress.

Where dissolution is known to influence the fatigue resistance of a material the processes leading to the formation of a pit are extremely important. A delay in the formation of pits through a delay in film breakdown has the effect of increasing corrosion fatigue lifetime. It has been observed during torsional corrosion fatigue tests [14], conducted in 3½% NaCl, using a high strength tempered martensite steel (σ_y = 1440 MPa) that the lifetime was extended on the addition of 0.1M sodium nitrite to the solution, see table 1. In this case the effect was attributed to a delay in the development of pits.

Solution composition	Applied shear stress (MPa)	Fatigue lifetime (cycles)
0.6M NaCl	613	205000
0.6M NaCl + 0.001M $NaNO_2$	613	230000
0.6M NaCl + 0.1M $NaNO_2$	630	3.6×10^6

Table 1 Influence of $NaNO_2$ additions on fatigue lifetime in 0.6M NaCl

Similar effects were reported by Boukerrou & Cottis [15] where it was observed that, despite a tendency to pitting, pits were small and few in number. It should be stressed that this phenomenon is not an increase in initiation time but an increase in the time taken for film breakdown and subsequent pit development, which assuming a given rate constant for film dissolution, may be associated with an increase in the thickness of the surface film in the nitrite solution. Isaacs [16] described equivalent effects when comparing pit half lifetimes for different degrees of surface oxidation although Ambrose and Kruger pointed out that film thickness was not the sole factor in influencing the time to film breakdown [17]. The effect of the addition of a passivating solution on the initial development of pits, using a heat treated low carbon steel, is further illustrated in tests using the scanning reference electrode technique [18].

(b) Pit development and growth

Pit development and growth is similarly influenced by those factors discussed for film breakdown with the nature of the inclusion content within the material microstructure and the magnitude of stress both additionally influencing the rate of pit growth. The inherent nature of material microstructures gives rise to sites at which localised corrosion processes (pitting) can occur [19, 20]. Typical examples include non-metallic inclusions, especially Manganese Sulphide, and inter metallic 2nd phase particles. Depending upon the nature of the environment, for example solution pH, localised corrosion can also take place at slip bands developed during fatigue loading [21]. However it is curious that not all sites give rise to pitting, a feature that may be associated with the tenacity of the surface film and the relationship between inclusion/microstructure, local stress state and distribution of corrosion current over the surface the metal.

The rate of pit growth may be considered to be principally governed by the material, local solution conditions and stress state. For systems in which pitting leads to crack development the relationship between pit propagation rate and stress state is seen to be of paramount importance if realistic models for corrosion fatigue are to be developed.

Experimental methods are available to evaluate pitting rates [22, 23], however these techniques fail to account for the effects of an applied stress.

Several studies have illustrated the influence of cyclic stress on the local corrosion current [24, 25] highlighting the many fold increase in corrosion activity as bare metal is exposed during the fracture of surface films. However, there appears to be no data available in the literature which illustrates the change in pit current density as a function of applied stress. Preliminary SRET studies [26] show that local pit activity increases on the application of an applied stress. Fig. 2 shows that this activity apparently depends upon the electrochemical conditions applied. In this recent study 316 stainless steel was tested in aerated 0.6M NaCl with the specimen being held under either potentiostatic or galvanostatic control. Local pit current density was then measured as the surface stress was changed, in this case to a value of 90% of the material's yield strength. From fig 2a it can be seen that pit current density decreases on the application of a stress under galvanostatic control but increases under potentiostatic control, fig 2b. Under galvanostatic control it is assumed that there is a limiting fixed anodic current available, which is distributed between the pit walls and outer external surfaces.

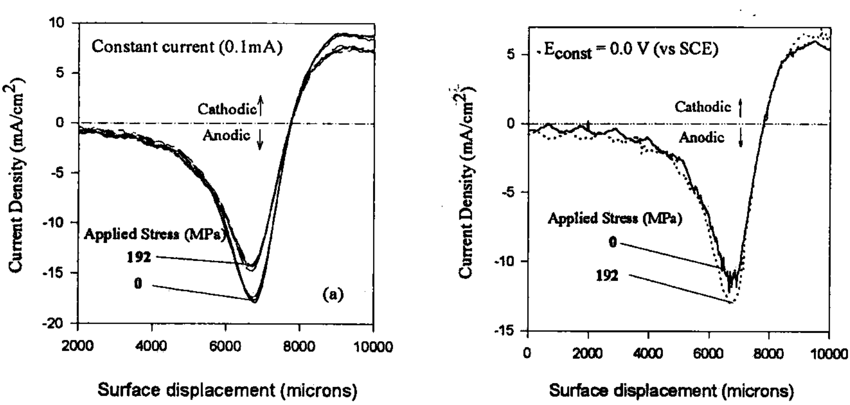

FIG. 2 Influence of stress on pit current density under (a) galvanostatic and (b) potentiostatic control. 316 Stainless Steel, 0.6M NaCl.

On the application of an applied stress corrosion activity on the surface increases at the expense of that within the pit due to the area ratios of the pit and external surfaces and the limited availability of current. However, under potentiostatic no such current restriction exists and the current is free to increase as the applied stress level increases, Fig. 2b.

(c) Pit to crack transition

Previous fatigue studies [27, 28] comparing the development of stage II tensile cracks from stage I cracks, in both air and 0.6 M NaCl solution under torsional loading, show that both the crack size and the fraction of life (N/Nf), at which the stage I/II transition occurs, decreases for corrosion fatigue loading. Typically it was found that in air a transition from stage I to stage II occurred around 120 μm (surface crack length) equivalent to 4 prior austenite grain diameters. Under corrosion fatigue this transition length is reduced to 30-60 μm that is, one to two prior austenite grain diameters. The ability of a crack to transfer, at an early stage, from the shear growth plane to the tensile plane therefore has a marked effect on the resulting fatigue lifetime, as illustrated schematically in fig 1 and experimentally in table 2.. Hence corrosion processes which assist in bypassing or accelerating this stage give rise to a considerable reduction in fatigue resistance; to the extent of eliminating the in-air fatigue lifetime.

Shear stress range (MPa)	Environment	transition length $a_{I/II}$ (μm)	Cycles to transition $N_{I/II}$	Lifetime N_f (cycles)
854	air	no transition	-	∞
920	air	120-150 (stage I/II)	2.6×10^6	4.8×10^6
920	0.6M NaCl	30-60 (pit/stage I)	15000	80000

Table 2 Influence of Stage I/II transition on fatigue lifetime.

Greater attention has recently been given to the pit/crack transition stage, that is, the point at which a crack is clearly established at a pit site. Given this criteria and based upon the analysis of data from a wide range of corrosion fatigue studies, it would seem totally inappropriate to assign a given fraction of lifetime (N/Nf) value to this important stage. Fig 3 summarises the data from several sources [28-34] plotting the fraction of lifetime, at which a crack develops during corrosion fatigue, against the applied stress level.

It can be seen from this figure that no overall trend exists and the transition point can be independent of either the applied stress or fraction of lifetime. If however this data is replotted, as shown in Fig. 4, in terms of the time taken for the pit/crack transition to occur, as a function of applied stress, it is immediately apparent that a correlation exists. The spread of data arises due to three factors, namely the nature of the loading mode, that is, torsion, tension, or bending, the test frequency and the pit depth at which the transition occurs. The effect of frequency on the pit/crack transition is shown in Fig. 5 which plots the time taken for the pit/crack transition to occur against the test frequency for tests conducted under two different loading conditions [28, 29].