

Recent progress in understanding environment assisted fatigue crack growth

R.P. WEI AND G.W. SIMMONS

Lehigh University, Bethlehem, Pa 18015, USA

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ABSTRACT

Metal fatigue has been well recognized as an important cause for failure of engineering structures. In most applications, fatigue damage results from the conjoint actions of the cyclically applied stress and the external (chemical) environment, and is therefore time dependent. Understanding of this load-environment interaction is essential to the formulation of rational life prediction procedures and to the development of realistic materials evaluation and qualification tests.

Research over the past 15 years has led to the suggestion that the rate of fatigue crack growth in an aggressive environment, $(da/dN)_e$, is the sum of three components—the rate of fatigue crack growth in an inert environment, $(da/dN)_i$, which represents the contribution of “pure” fatigue, a cycle-dependent component, $(da/dN)_{ef}$, that requires the synergistic interaction of fatigue and environmental attack, and the contribution by sustained-load crack growth (i.e., stress corrosion cracking) at K levels above K_{Isc} , $(da/dN)_{sc}$. Recent fracture mechanics and surface chemistry studies have provided a clearer understanding of the cycle-dependent term, and, hence, a more complete understanding of environment assisted fatigue crack growth. $(da/dN)_{ef}$ results from the reaction of the environment with fresh crack surfaces produced by fatigue, and is a function of the extent of reaction during one loading cycle. For highly reactive alloy-environment systems, this contribution depends also on the rate of transport of the aggressive environment to the crack tip. The experimental basis and the development of models for transport and surface reaction controlled fatigue crack growth are reviewed. Interpretation of the effects of partial pressure of the aggressive environment and cyclic load frequency in terms of surface reaction and transport processes is discussed. Implications in terms of service performance and life prediction procedures are considered.

1. Introduction

Metal fatigue has been well recognized as an important cause for failure of engineering structures. In most applications, fatigue damage results from the conjoint actions of the cyclically applied stress and external (chemical) environment, and is therefore a time dependent phenomenon. Understanding of this load-environment interaction in fatigue is essential to the formulation of rational life prediction procedures and to the development of realistic materials evaluation and qualification tests. Quantitative characterization and understanding, however, have been hampered by the complexity of the phenomenon, by difficulties in separating the effects associated with crack initiation from those associated with crack growth, and by the influence of external chemical environments on both the initiation and growth processes.

With the increased emphasis placed on fatigue crack growth in many applications since the early 1950's and the development of fracture mechanics technology, separate considerations of the processes associated with fatigue crack growth evolved more or less naturally. This separation has provided better definition and focus, and

has been by and large beneficial in terms of developing understanding of environment assisted fatigue crack growth. In this paper, the background and recent progress in understanding environment assisted fatigue crack growth are described. Implications of current understanding in terms of service performance and life prediction procedures are considered.

2. Background

Studies of the influence of environment on fatigue crack growth began in the mid 1960's and have continued throughout the past 15 years. The results from the various studies have been reviewed and summarized in a number of papers [1-3] and in the proceedings of conferences [4, 5]. Most of the early studies were directed at characterizing fatigue crack growth response, and at examining the influences of different loading variables on environment assisted fatigue crack growth. Results from these early studies served to demonstrate the complexity of the problem, and showed that many of the observed effects of loading variables can be traced directly to their interactions with the environment [2, 3]. It became apparent also that a better understanding of the underlying processes for environment assisted fatigue crack growth is needed to provide a rational basis for the interpretation of fatigue crack growth data. A number of issues began to crystallize by the early 1970's. These issues relate to the reported differences in response to frequency and waveform for aluminum alloys [6-9] and steels [10-12], the relationship between environment assisted sustained-load crack growth (stress corrosion cracking) and fatigue crack growth (corrosion fatigue) [13-15], and the cause or mechanism for environment assisted fatigue crack growth below the so-called stress corrosion cracking threshold (K_{Isc})* [18-19]. The most important issue, insofar as it relates to phenomenological understanding of load-environment interactions, appears to be the identification of the rate controlling process for environment assisted crack growth [19, 20]. The possible sequential processes involved in environment assisted crack growth are illustrated schematically in Fig. 1, for example, for a ferrous alloy exposed to a hydrogenous gas [21]. The need for and development of a fundamental approach for addressing these issues are discussed by Wei and Simmons [19], Wei [21] and Williams, Pao and Wei [22].

Using an integrated interdisciplinary approach, Simmons, Pao and Wei [20] sought to identify the rate controlling process for crack growth in water/water vapor for a high-strength (AISI 4340) steel. To this end, sustained-load crack growth experiments were carried out in hydrogen and in water to determine the kinetics of crack growth as a function of temperature. Companion experiments were carried out on the same steel to determine the kinetics of water-metal surface reactions using Auger electron spectroscopy (AES). These studies were supplemented by detailed fundamental studies of reactions of water vapor with iron single crystals by AES and LEED (low energy electron diffraction) [23], and by AES analysis of the elemental composition of fracture surfaces produced by environment assisted crack growth [24]. Through these coordinated interdisciplinary studies and comparisons of activation energies for crack growth and for surface reactions, the rate controlling process for crack growth was identified to be a slow step in the reaction of water/water vapor with iron and, perhaps, iron carbide [20, 23]. This reaction step is associated with the nucleation and growth of oxide on the surface, and the presumed concomitant

* K_{Isc} is the apparent threshold stress intensity (K) level for stress corrosion cracking and is defined as the asymptotic value of K as the rate of crack growth under sustained load approaches zero [16, 17].

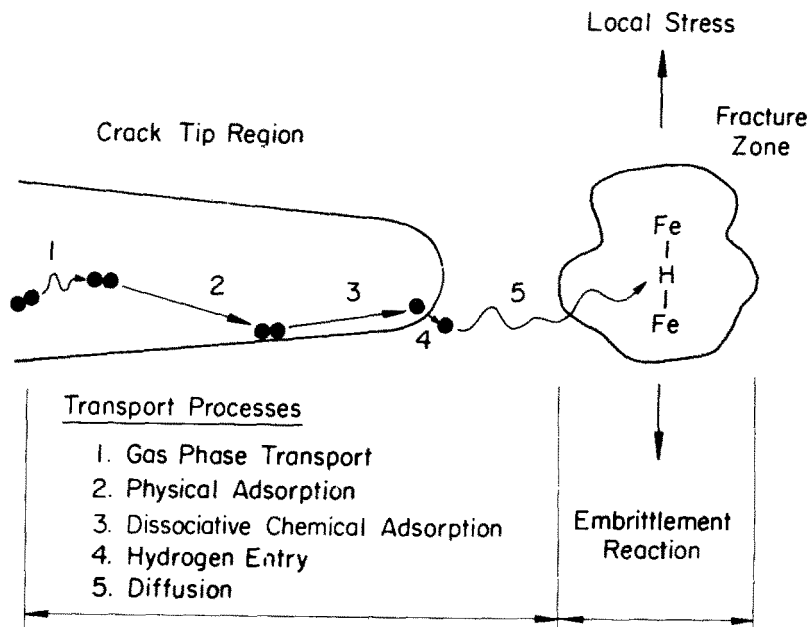


Figure 1. Schematic illustrations of various sequential processes involved in embrittlement by external gaseous environments. Embrittlement reaction is depicted schematically by the iron-hydrogen-iron bond [21].

production of hydrogen [20]. Hydrogen produced by this reaction is believed to be responsible for embrittlement [20].

Having identified the rate controlling process for sustained-load crack growth for this high-strength steel in water/water vapor, Pao, Wei and Wei [25] examined its implication in terms of environment assisted fatigue crack growth response. Their results indicated that both steady-state and nonsteady-state crack growth response can be adequately explained in relation to the kinetics of surface reactions. Based on this success, the integrated interdisciplinary approach has been extended to the study of environment assisted fatigue crack growth response in an aluminum alloy [26]. This later study expands on an earlier suggestion by Bradshaw and Wheeler [6] that the enhancement of fatigue crack growth in aluminum alloys by water vapor is determined by the exposure (pressure \times time) during each load cycle. It has led to the recognition that for highly reactive systems, environment assisted crack growth may be controlled by the transport of the aggressive environment to the crack tip, and has led to the development of transport and surface reaction controlled models for environment assisted fatigue crack growth [26,27]. Additional verification of the transport controlled model has been made also for a hydrogen sulfide-steel system [28].

The experimental evidence that formed the basis for model development is summarized. The models, their implication in understanding environment assisted fatigue crack growth, and their engineering significance are considered.

3. Experimental basis for modelling environmental effect

Pao, Wei and Wei [25] examined the effect of cyclic-load frequency (0.1 to 10 Hz) on fatigue crack growth in a high-strength (AISI 4340) steel tested in water vapor at room

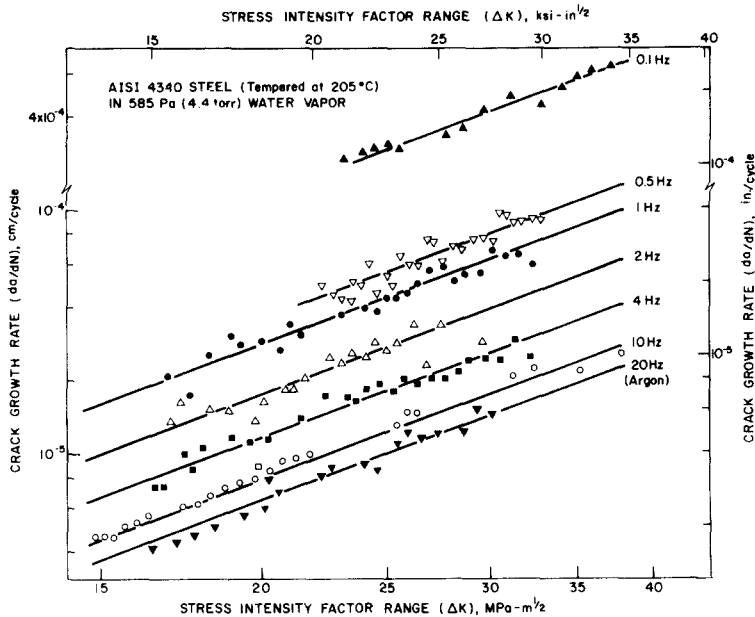


Figure 2. Room temperature fatigue crack growth kinetics on AISI 4340 steel tested in dehumidified argon and in water vapor (below K_{Isc}) at $R = 0.1$ [25].

temperature. A water vapor pressure of 585 Pa was selected to preclude capillary condensation at the crack tip. Steady-state crack growth data from this study are shown in Fig. 2, and confirm the existence of a substantial effect of frequency at K_{max} levels well below that required for producing significant crack growth under sustained loads (that is, below K_{Isc}) [1, 10]. Fractographic data indicated that at the higher frequencies (namely, 10 Hz), the fracture surface morphology corresponded to that for "pure" (mechanical) fatigue. At the lower frequencies (that is, below 1 Hz), on the other hand, the morphology exhibited increasing amounts of intergranular separation along prior-austenite grain boundaries that is typical for sustained-load crack growth in water/water vapor [20]. These observations, taken in conjunction with previous studies, suggested that the steady-state fatigue crack growth rate in an aggressive environment is composed of two components — one for "pure" fatigue and the other representing the environmental contribution. Because the rate controlling process has been identified to be a slow step in the water-metal surface reaction in this case, the environmental component is expected to depend on the time available for this reaction (namely, the cyclic load period) and on the reaction kinetics. In other words, the extent of crack growth during one loading cycle is expected to be proportional to the extent of reaction (or surface coverage) during that cycle. Based on data on the kinetics of surface reactions [20], the environment contribution should vary almost linearly with the cyclic load period or inversely with frequency, over the range of frequencies used in their investigation [25]. At high frequencies, environmental effect should be essentially negligible; at low frequencies, it should reach a maximum or a saturation value. This general trend is consistent with data on AISI 4340 steel [25] and with data reported by Gallagher [11] for fatigue crack growth in a high-strength (HY-80) steel in 3.5 pct NaCl solution, and by Bradshaw and Wheeler [6] on an aluminum (DTD 5070A) alloy in water vapor. Examination of steady-state and nonsteady-state growth data on AISI 4340 steel [25] suggested that the environmental effect is associated with a zone of hydrogen-embrittled material ahead of the crack

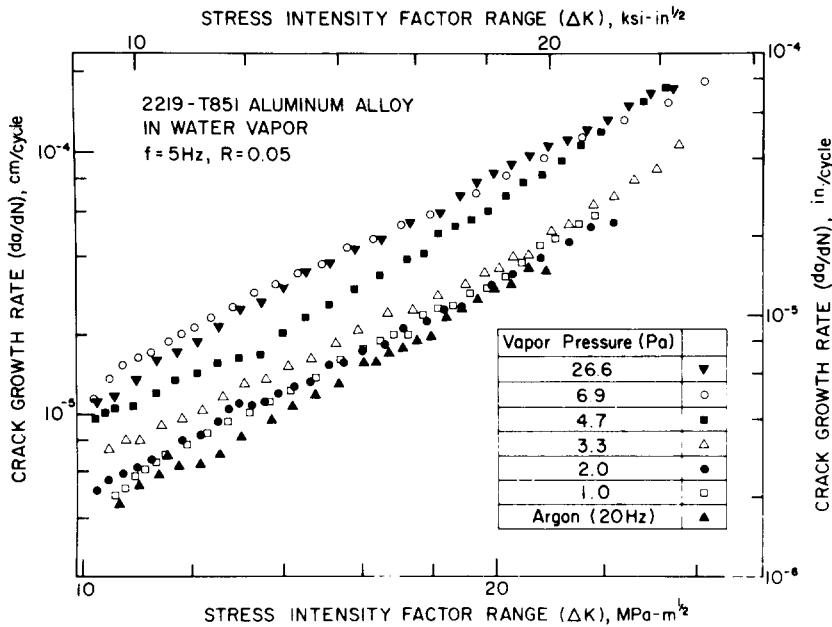


Figure 3. Influence of water vapor pressure on the kinetics of fatigue crack growth in 2219-T851 aluminum alloy at room temperature [26].

tip. The size of this zone and the nonsteady-state crack growth response would be functions of the surface reaction kinetics and frequency.

To further verify the concept of surface reaction control and to follow up on the earlier suggestions by Bradshaw and Wheeler [6] and by Hudak and Wei [8], a combined surface chemistry and fracture mechanics study of fatigue crack growth in water vapor was carried out on an aluminum alloy [26]. Fatigue crack growth experiments were carried out as a function of water vapor pressure at room temperature for an Al-Cu (2219-T851) alloy. The reactions of this alloy with water vapor were also determined by Auger electron spectroscopy (AES) and by X-ray photoelectron spectroscopy (XPS) [29]. Steady-state fatigue crack growth data (for test frequency of 5 Hz) are shown in Fig. 3, and indicate the effect of water vapor pressure and the existence of saturation of environmental effect at the higher pressures. The variations in the fatigue crack growth and surface reaction data with exposures (expressed as pressure \times time or pressure/frequency) showed similar trends, except that the exposures differed by about 3 orders of magnitude. It was recognized that, at the low pressures used in these experiments and for this highly reactive system, the environmental contribution may be limited, in addition, by the rate of transport of the environment to the crack tip* (that is, by step 1 in Fig. 1). This recognition provided the impetus for the formal development of a model for environment assisted fatigue crack growth that incorporates the influences of transport and surface reaction kinetics [27].

4. Modeling of environment assisted fatigue crack growth

Based on these recent experiments and on research over the past 15 years, a rational basis for treating environment assisted fatigue crack growth had been suggested [21]. The rate of fatigue crack growth in an aggressive environment, $(da/dN)_e$, is con-

* Transport limitation has been suggested by the companion fractographic observations [26].

sidered to be the sum of three components.

$$\begin{aligned} (da/dN)_e &= (da/dN)_r + (da/dN)_{cf} + (da/dN)_{sc} \\ &= (da/dN)_r + (da/dN)_{cf} + \int_0^\tau [da/dt(K)] dt \end{aligned} \quad (1)$$

$(da/dN)_r$ is the rate of fatigue crack growth in an inert environment and, therefore, represents the contribution of "pure" (mechanical) fatigue. This component is essentially independent of frequency at temperatures where creep is not important. $(da/dN)_{cf}$ represents a cycle-dependent contribution requiring synergistic interaction of fatigue and environmental attack. $(da/dN)_{sc}$ is the contribution by sustained-load crack growth (that is, stress corrosion cracking) at K levels above K_{Isc} [15].

Detailed examinations of the contribution by sustained-load crack growth, that is, the $(da/dN)_{sc}$ term, have been made previously [13, 15]. For usual engineering applications, however, alloys that are highly susceptible to sustained-load crack growth (stress corrosion cracking) would not be used, and the $(da/dN)_{sc}$ term is primarily of academic interest. The cycle-dependent term, $(da/dN)_{cf}$, on the other hand, is quite important. Its existence has been recognized by researchers for some time [3, 6–11, 14, 30]. With the identification of rate controlling processes and the development of chemical data, it was possible to consider quantitative modeling of this term. The modeling effort was limited to the establishment of a formal framework for estimating frequency and pressure dependence of $(da/dN)_{cf}$ in gaseous environments.

In the model [27], enhancement of fatigue crack growth is assumed to result from embrittlement by hydrogen that is produced by the reaction of hydrogenous gases (e.g., water vapor) with the freshly produced fatigue crack surfaces. More specifically, $(da/dN)_{cf}$ is assumed to be proportional to the amount of hydrogen produced by the surface reaction each cycle, which is proportional in turn to the crack area produced during the prior loading cycle (or to $(da/dN)_e$) and to the extent of surface reaction. The time available for reaction is assumed to be equal to one-half of the fatigue cycle [27]. Transport of gaseous environments to the crack tip is assumed to be by Knudsen flow [31]. The governing differential equations for flow and surface reactions, and the relationship for $(da/dN)_{cf}$ are as follows [27]:

$$\frac{dp}{dt} = -\frac{SN_0RT}{V} \frac{d\theta}{dt} + \frac{F}{V}(P_0 - P) \quad (2)$$

$$\frac{d\theta}{dt} = k_c p f(\theta) = k_c p (1 - \theta) \quad (3)$$

$$\left(\frac{da}{dN}\right)_{cf} \propto \theta \cdot \Delta a = \theta \cdot \left(\frac{da}{dN}\right)_e \quad (4)$$

The terms in the equations are as follows [26, 27]:

$F = 8.72 \times 10^4 \beta (\sigma_{ys}^2/E^2) Bl(T/M)^{1/2}$ (in cm^3/s) = Knudsen flow parameter that depends on dimension and shape of the capillary, molecular weight (M) of the gas and temperature (T). The specific form of this expression reflects an attempt to account for constriction in flow by the real crack, where l is an arbitrary distance (of the order 10^{-4} cm) from the crack tip used in defining a crack opening and β is an empirical quantity to be determined from the crack growth data [27, 31]

k_c = reaction rate constant

N_0 = density of surface sites

p = pressure of gas at the crack tip

- p_0 = pressure of gas in the surrounding environment
- R = gas constant
- S = area of newly created crack surface per cycle = $\alpha(2B\Delta a)$, where Δa = crack growth increment per cycle, B = specimen thickness, and α = empirical constant for surface roughness and crack geometry [27]
- T = absolute temperature
- V = control volume at the crack tip, i.e., volume associated with the distance l
- θ = fractional surface coverage

From Eqn. (2), it can be seen that the rate of change of pressure at the crack tip depends on the decrease in pressure produced by reaction of the environment with the newly created crack surface and on the increase in pressure from the influx of gas from the external environment. Equation (3) incorporates the assumption that the surface reaction is first-order in relation to available surface sites [26–29].

Equations (2) and (3) are nonlinear, coupled equations which can be solved to obtain θ , at least in principle, for specific cases. The values of θ can be then substituted into Eqn. (4) to estimate the influences of key environmental and loading variables on the cycle-dependent component of fatigue crack growth rate, i.e., $(da/dN)_{cf}$. Solutions for Eqn. (2) and (3), with $f(\theta) = 1 - \theta$, have been obtained for two limiting cases, for $0 < \theta < 1$ [27].

Case I: Transport controlled.

$$\theta \approx \frac{F}{SN_0RT} p_0 t \quad \text{for} \quad \frac{SN_0RTk_c}{F} \gg 1 \tag{5}$$

Case II: Surface reaction controlled.

$$\theta \approx 1 - \exp(-k_c p_0 t) \quad \text{for} \quad \frac{SN_0RTk_c}{F} \ll 1 \tag{6}$$

In the transport controlled case, because of the rapid reactions of the environment with the freshly created crack surfaces (high k_c) and the limited rate of supply of the environment to the crack tip, significant attenuation of gas pressure takes place at the crack tip. The extent of surface reaction (θ) during one cycle is controlled by the rate of transport of the aggressive environment to the crack tip, and thus varies linearly with time (see (5)). For the surface reaction controlled case, the reaction rates are sufficiently slow so that the gas pressure at the crack tip is essentially equal to the external pressure. The extent of reaction, for the case considered (3), becomes an exponential function of time (6).

If t is taken to be equal to $\tau/2$ or $1/2f$, and l in the expression for F is chosen to be equal to the growth increment per cycle at saturation (i.e., for $\theta \approx 1$), then the following expressions are obtained from Eqns. (4) and (5):

Transport Controlled:

$$\left(\frac{p_0}{2f}\right)_s \approx \frac{SN_0RT}{F} = \left[4.36 \times 10^4 \frac{\beta}{\alpha} \frac{\sigma_{ys}^2}{N_0RTE^2} \left(\frac{T}{M}\right)^{1/2}\right]^{-1} \tag{7}$$

$$\frac{\left(\frac{da}{dN}\right)_{cf}}{\left(\frac{da}{dN}\right)_{e,s}} \propto 4.36 \times 10^4 \frac{\beta}{\alpha} \frac{\sigma_{ys}^2}{N_0RTE^2} \left(\frac{T}{M}\right)^{1/2} \frac{p_0}{2f} \tag{8}$$

$$\frac{\left(\frac{da}{dN}\right)_{cf}}{\left(\frac{da}{dN}\right)_{cf,s}} = \frac{(p_0/2f)}{(p_0/2f)_s} \tag{9}$$

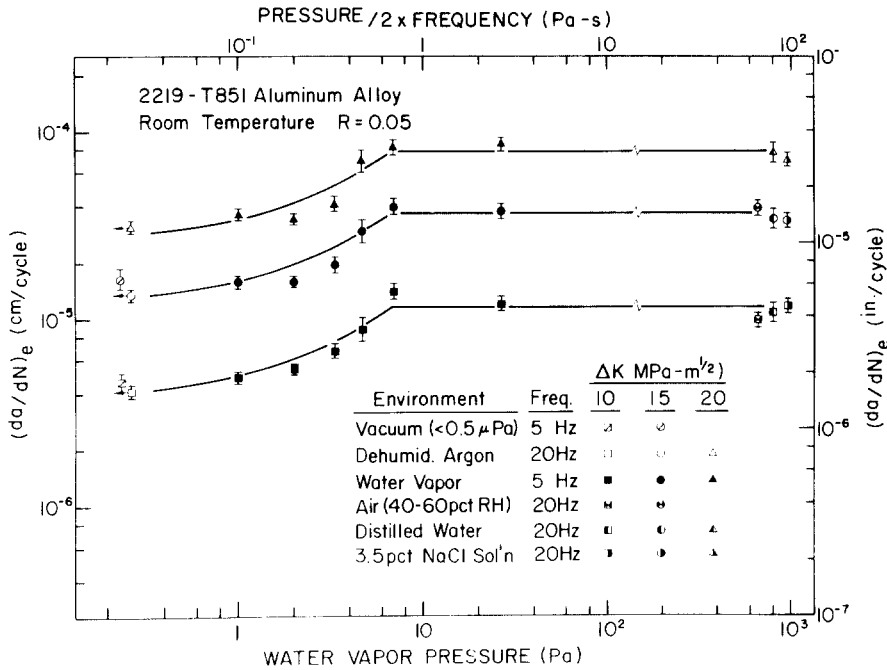


Figure 4. Influence of water vapor pressure (or pressure/2 x frequency) on fatigue crack growth rates in 2219-T851 aluminum alloy at room temperature. Solid lines represent model predictions. [26].

Subscript *s* is used to denote the corresponding value at saturation. From Eqns. (4) and (6), one obtains the following expressions for the surface reaction controlled case:

Surface Reaction Controlled:

$$\frac{\left(\frac{da}{dN}\right)_{cf}}{\left(\frac{da}{dN}\right)_e} \propto 1 - \exp(-k_c p_0/2f) \tag{10}$$

$$\frac{\left(\frac{da}{dN}\right)_{cf} / \left(\frac{da}{dN}\right)_e}{\left(\frac{da}{dN}\right)_{cf,s} / \left(\frac{da}{dN}\right)_{e,s}} = 1 - \exp(-k_c p_0/2f) \tag{11}$$

Equation (7) gives the value of $p_0/2f$ at which “saturation” in environmental effect can be expected in terms of the properties of the alloy, molecular weight of the aggressive gas, and temperature for the transport controlled case. Fatigue crack growth response is given, for this case, as an explicit function of $p_0/2f$ below saturation by Eqns. (8) and (9). For the surface reaction controlled case, the dependence of fatigue crack growth response on $p_0/2f$ is given by (10) and (11). It should be noted that Eqns. (8) to (11) deal only with relative rates. The actual growth rates depend on the interactions of the embrittling specie (hydrogen) with the alloy, which are not adequately understood at this time.

Comparisons of the transport controlled crack growth model have been made with experimental data on a 2219-T851 aluminum alloy tested in water vapor and with a 2-1/4 Cr-1M0 (A542, Class 2) steel tested in hydrogen sulfide [28]. Good agreement was obtained (see Figs. 4 and 5). The empirical constants β/α for these two very

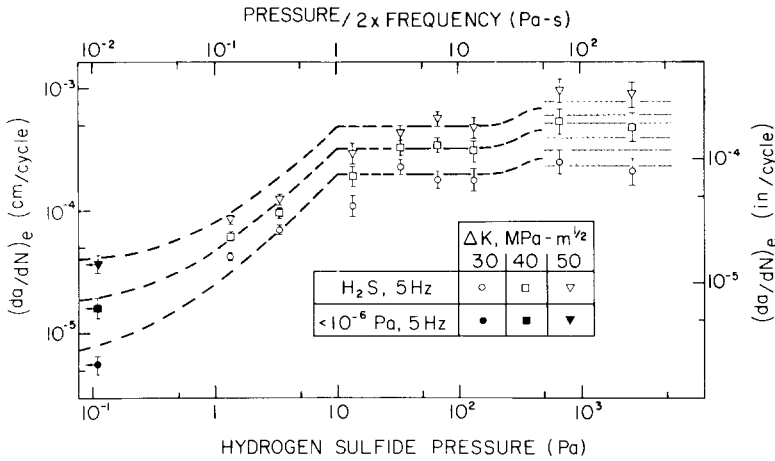


Figure 5. Influence of hydrogen sulfide pressure (or pressure/2 × frequency) on fatigue crack growth rates in 2 – 1/4Cr–1M0 (ASTM A542, Class 2) steel at room temperature. Dashed lines represent model predictions [28].

different systems appear to be equal, with $\beta/\alpha \approx 1.5$. Comparison of this model has now been made with the data of Hartman [7] and Bradshaw and Wheeler [6], Figs. 6 and 7. It appears that the same value of β/α applies to these cases as well. Further experimental work is needed to determine if β/α is indeed constant for a wide range of materials and environments. Nevertheless, the model appears adequate in predicting and explaining the pressure and frequency dependence for environment assisted fatigue crack growth.

For the surface reaction controlled case, the trend in the experimental data [11, 25] is consistent with the model prediction, in that the cycle-dependent component, $(da/dN)_{cf}$, increases with decreasing frequency and tends toward a saturation level at very low frequencies. Better agreement is obtained, however, if one uses the

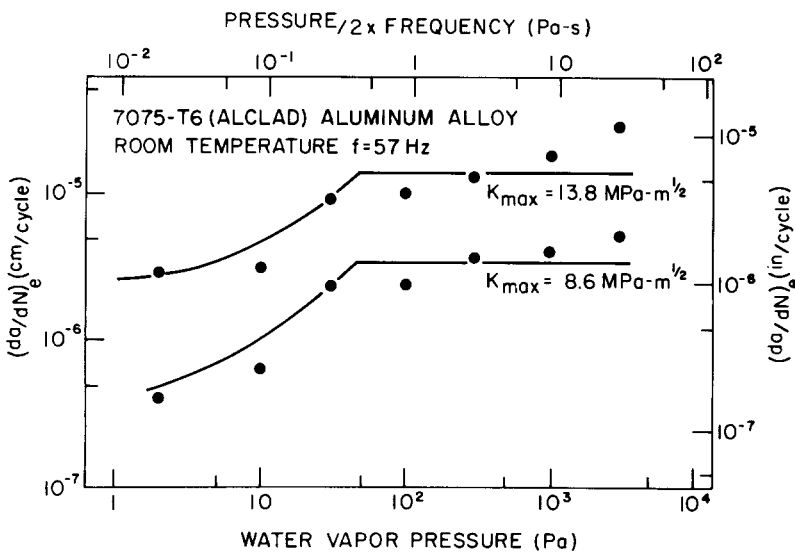


Figure 6. Influence of water vapor pressure on fatigue crack growth in 7075-T6 (Alclad) aluminum alloy at 57 Hz. Solid lines represent model predictions. (Data from Hartman *et al.* [7]).

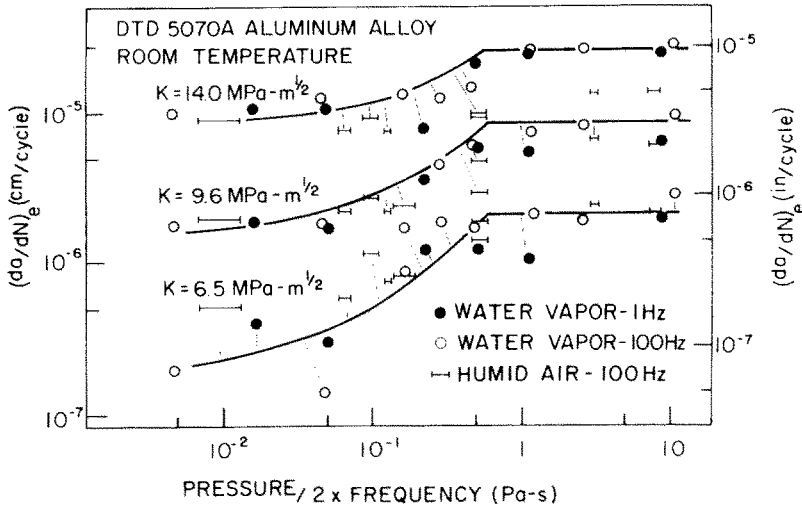


Figure 7. Influence of water vapor pressure on fatigue crack growth in DTD 5070A aluminum alloy at 1 Hz and at 100 Hz. Solid lines represent model predictions. (Data from Bradshaw and Wheeler [6]).

following relationship in place of Eqn. (11) (see Fig. 8* [25]):

$$\frac{(da/dN)_{cf}}{(da/dN)_{cf,s}} = 1 - \exp(-k_c p_0 / 2f) \tag{12}$$

Equation (12) implies that, because of the slower surface reactions associated with surface reaction control, a portion of the crack surfaces produced during the preced-

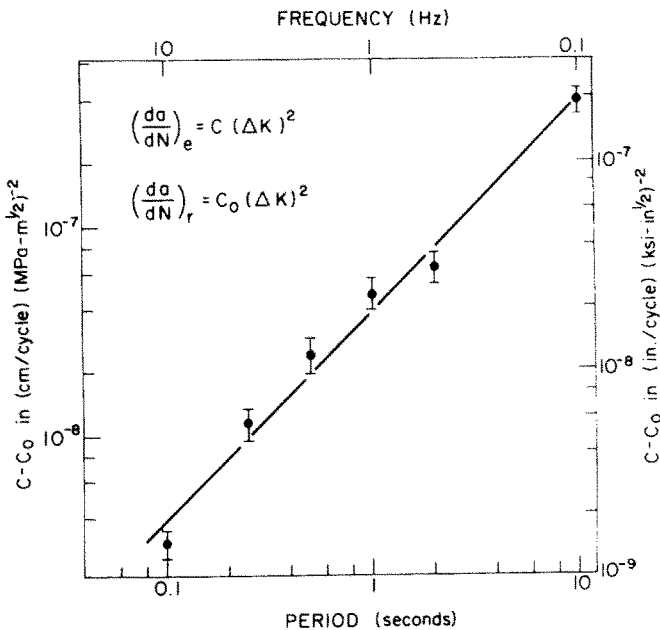


Figure 8. Environment dependent component of fatigue crack growth parameter as a function of cyclic load period for AISI 4340 steel tested in water vapor at room temperature [25].

* Here $(da/dN)_{cf}$ is expressed as difference between two constants in the relationship $da/dN = C \Delta K^2$, where C corresponds to growth rate in the environment, and C_0 , in the reference environment.

ing fatigue cycles continues to contribute hydrogen to the crack tip, in addition to the surfaces produced during the last fatigue cycle. The form of Eqn. (12) would imply that the total contribution is equivalent to treating Δa in Eqn. (4) as a constant. A more detailed study is needed to clarify the issues involved here.

5. Discussion

Recent fracture mechanics and surface chemistry studies have contributed to the phenomenological understanding of environment assisted fatigue crack growth [20, 24–28]. Correlation between the surface reaction kinetics and the dependence of fatigue crack growth response (below K_{Isc}) as a function of frequency and pressure has now been established for very different alloy-environment systems (namely, aluminum-water vapor, steel-water vapor and steel-hydrogen sulfide). Two separate regimes can now be identified, where environment enhancement of fatigue crack growth is determined by the extent of surface reaction during one loading cycle. For alloy-environment systems with “slow” reaction kinetics (e.g., steel-water vapor system), environmental effects are evident at “high” pressures and “low” frequencies, and crack growth enhancement is only a function of the surface reaction kinetics. For alloy-environment systems with “fast” reaction kinetics (e.g., aluminum-water vapor and steel-hydrogen sulfide) systems, on the other hand, environmental effects now manifest themselves at “low” pressures and “high” frequencies, and the enhancement of crack growth now also depends on the rate of transport of the external environment to the crack tip. The 8 orders of magnitude difference between the rates of water vapor reactions with aluminum alloys and with steels [20, 25, 26], and of water vapor and hydrogen sulfide reactions with steel [28] can readily account for the observed differences in environment assisted fatigue crack growth response for these alloys and environments [1–14].

On the basis of these studies, models for transport and surface reaction controlled fatigue crack growth have been developed. The models, at least for the transport controlled case, provide accurate prediction of the influences of pressure and frequency on the cycle-dependent component, $(da/dN)_{cf}$, of environment assisted fatigue crack growth. The models also describe the temperature dependence for this component in terms of the temperature dependence for surface reactions and transport. Experimental verification of temperature dependence, however, still needs to be obtained. The correlation developed in these studies, nevertheless, appears to have general applicability for the enhancement of fatigue crack growth in gaseous environments, and provides a basis for assessing environmental effects. Extension of the basic concept and approach to the considerations of cracking problems in aqueous environments should prove to be useful and is being explored.

On the practical side, reliability of service life predictions depends on a proper accounting of the environmentally induced effects. The existence of a cycle-dependent term and its frequency dependence have not been fully appreciated by most of the engineering community. This incomplete appreciation is reflected in the “indiscriminate” use of “accelerated” tests and in disregarding cyclic load frequency as a significant variable in design. The impact of this cycle-dependent term must be recognized and taken into proper account in the development of realistic design data and in fatigue life estimation. The models that have been developed on the basis of current understanding of environment assisted fatigue crack growth provide a useful starting point for the development of more meaningful and reliable testing and design procedures.

6. Summary

Recent fracture mechanics and surface chemistry based studies have contributed to further understanding of environment assisted fatigue crack growth in high-strength alloys. More specifically, these studies have led to a better understanding of the cycle-dependent contribution that required synergistic interaction of fatigue and environmental attack. The cycle-dependent contribution has been shown to arise from the reaction of the environment with fresh crack surfaces produced by fatigue, and to be a function of the extent of reaction during one loading cycle. For highly reactive alloy-environment systems, this contribution may depend also on the rate of transport of the aggressive environment to the crack tip. For gaseous environments, models for estimating pressure and frequency dependence have been developed. The framework and approach used in these fracture mechanics and surface chemistry studies are expected to be applicable to other aggressive environments (such as, aqueous environments), and should provide a basis for the development of appropriate material evaluation and life prediction procedures.

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RÉSUMÉ

La fatigue des métaux a été reconnue comme une cause importante de rupture des structures métalliques. Dans la plupart des applications, le dommage par fatigue résulte de l'action conjointe d'une contrainte appliquée de manière cyclique et d'un environnement extérieur (chimique). Dès lors, elle dépend du temps. Il est essentiel de comprendre les interactions contrainte/environnement pour la formulation de procédure de prédiction de vie résiduelle et pour le développement d'évaluation et d'essai de qualification réaliste pour l'étude des matériaux.

Les recherches entreprises au cours des 15 dernières années ont conduit à suggérer que la vitesse de propagation d'une fissure de fatigue dans un environnement agressif (da/dN) résulte de trois composants: la vitesse de propagation d'une fissure de fatigue dans un environnement inerte, qui représente la contribution de la fatigue pure, une composante dépendant de l'alternance et qui exprime l'interaction synergétique de la fatigue et de l'attaque provoquée par l'environnement, et une contribution d'une croissance de fissure sous charge constante (c.à.d. fissuration sous corrosion sous tension) à un niveau K supérieur à K_{isc} . Les études récentes de mécanique de rupture et de chimie de surface ont fourni une compréhension plus claire du terme dépendant de l'alternance et dès lors, une explication plus complète de la croissance d'une fissure de fatigue en présence d'un environnement. La composante dépendant de l'alternance résulte de la réaction de l'environnement à une surface de fissuration fraîche produite par la fatigue et est fonction de l'étendue de la réaction au cours d'un seul cycle de sollicitation. Dans le cas de systèmes alliage-environnement hautement réactifs, cette contribution dépend également de la vitesse de transport de l'environnement agressif à l'extrémité de la fissure. La base expérimentale et le développement de modèles pour le transport et la croissance d'une fissure de fatigue contrôlée sous l'effet des réactions de surface ont été passés en revue. Une interprétation des effets d'une pression partielle de l'environnement agressif ainsi que de la fréquence des cycles de sollicitation est discutée en terme de réactions de surface et de processus de transfert. Les implications que ces conclusions présentent sur la performance en service et les procédures de prédiction de vie sont discutées.

NOTE ADDED IN PROOF

It is now recognized that the data shown in Fig. 6 reflect a competition between water vapor and oxygen (which acts as an inhibitor). An appropriate model for this effect has been developed.