SUBCRITICAL CRACK GROWTH AND ITS RELATION TO PREDICTIVE ANALYSIS

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ABSTRACT

This talk will discuss the relationships between subcritical crack growth and the nature of the loading, the environment under which the loading takes place and the type of material tested, and how this data is used in predictive analysis. Loading conditions will include sustained loading as well as constant and variable amplitude cyclic loading. The environments will include vacuum as a baseline environment and both gaseous and liquid aggressive environments. The comparison between crack growth behavior in brittle and ductile materials will also be made.

The data will be discussed from the viewpoint of reproducibility and reliability for use in predictive analysis.

INTRODUCTION

The question may be asked as to why should a talk on subcritical crack growth be included in a meeting on quantitative NDE. The answer may be best answered by an experience I have just had on my trip to this meeting. I found the battery in my minimotorhome hanging out of the bottom of the vehicle. On closer inspection I found a nine-inch crack across one side of a nine-inch wide support plate and a combination of a three-inch and four-inch crack on the other side. Of course the nine-inch crack explained why the battery was hanging loose. But in regard to the topic of this talk, it was obvious that insufficient inspection, combined with the cyclically induced fatigue crack growth led to the premature failure. Even if the inspection was made initially to be able to decide when failure would occur, it requires a detailed understanding of how the crack would propagate in a specific material under the loading and environmental conditions to which it is exposed. This paper will try to give a general idea of what can be expected, including some of our recent efforts on load history effects. It is obvious that only a small segment of the topic can be discussed, so the reader is referred to some of the recent texts on the subject for details.(1-5)

SUBCRITICAL CRACK GROWTH

Subcritical crack growth can be separated into two types. The first is sustained loading where the load is applied to a material with a particular microstructure containing a flaw or crack exposed to a given environment. This is usually described as a stress corrosion crack growth phenomena. The second is where the flaw containing material of the given microstructure is exposed to an environment under a cyclic loading condition. This is usually referred to as corrosion fatigue crack growth. In general, a structure is exposed to both sustained and cyclic loading and both types of crack growth may be seen.

Stress Corrosion Crack Growth

Stress corrosion crack growth occurs for many materials under many environments. Examples are aluminum alloys in salt water, titanium alloys in salt water or methanolic solutions, and steels in aqueous solution or hydrogen on hydrogen sulfide gas. There are a great many combinations of microstructure of the material and the environment that can lead to stress corrosion cracking. An example of how the stress corrosion crack growth behavior is characterized is given in Figure 1 for a titanium alloy loaded in a methanolic solution. The experiment is to monitor crack growth as a function of the applied stress intensity, $K = \sigma \gamma \sqrt{\alpha}$, where σ is the remotely applied static stress, γ is the geometric parameter and α the crack length. What is normally observed is a value of K defined as K_{ISCC} below which no crack growth occurs, a region where crack growth is virtually K-independent, and a region of fast crack growth when K approaches a critical value which is the fracture toughness of the material. This is shown schematically in Figure 2.

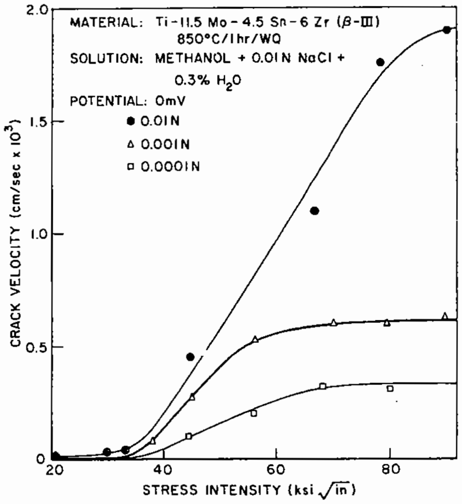

Fig. 1 Stress Corrosion Crack Velocity for Ti alloy in Methanolic Solution

To account for the stress corrosion crack growth behavior in determining the life of a structure after an initial flaw size is determined by quantitative NDE, you just integrate the crack growth rate over the time of exposure in the sustained load and environment to establish when failure is expected. For example, if a structure containing the titanium alloy was loaded at 40 Ksi $\sqrt{in}$ for two days in 0.01 N NaCl, the crack would have grown about 50 cm. This is obviously a very intense material-load-environmental condition. The obvious problem in designing to stress corrosion cracking is that a large amount of data is required to make the predictive analysis. The particular material-load-environment of interest must be evaluated.

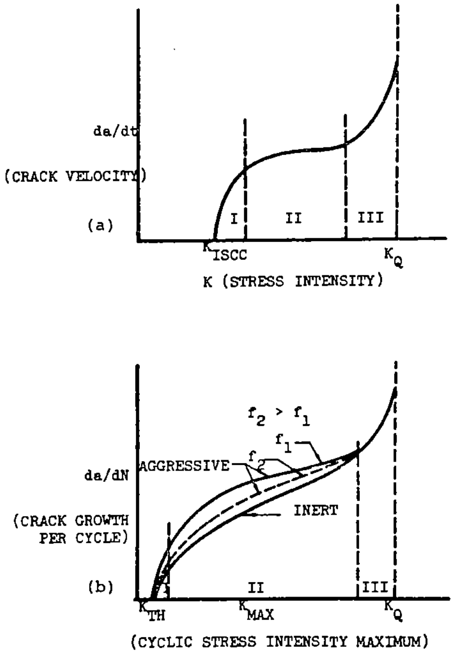

Fig. 2 (a) Schematic of stress-corrosion behavior (b) Schematic of environmental influence on fatigue-crack growth for R = 0, K_{max} = K.

Fatigue Crack Growth

The second type of loading involves the application of cyclic loads. This type of behavior is characterized experimentally in two ways. The first involves not only the crack growth under cyclic loading, but the initiation of the propagating crack. This is shown in Figure 3, where a cyclic stress, S, is plotted against a number of cycles to failure. This plot could be considered to be separated into the two regions. The first is when a crack of NDE detectable size, a_o, is established and the second, the fatigue crack growth region where the crack propagates to failure. This latter region, which is of most interest in this talk, is generally characterized by a plot of da/dN, which is the crack growth per cycle as a function of the cyclic stress intensity, ΔK, under constant amplitude loading. This is shown in Figure 2(b) for the case where $\Delta K = K_{max} - K_{min}$ and $K_{min} = 0$. Comparison of Figure 2(a) and Figure 2(b) shows some interesting effects. K_{ISCC} is at a stress intensity factor greater than the threshold stress intensity, K_{th}, the stress intensity below which no fatigue crack growth is obsered. Although no sustained load crack growth effect of environment is seen below K_{ISCC}, there is an environmental effect under cyclic loading below that value. The environmental effect is also influenced by the cyclic frequency, another loading variable, as shown schematically for two loading frequencies, f_2 greate than f_1. In general the higher the frequency the less the environmental effect after some minimum frequency. In many cases, such as in aluminum alloys, the failure mode will change such that it is intergranular in stress corrosion, with both da/dt and K_{ISCC} very microstructure-dependent and transgranular in corrosion fatigue crack growth with very limited microstructural dependence. In Figure 2(b) the inert environmental fatigue crack growth rate is determined in either vacuum or pure inert gases.

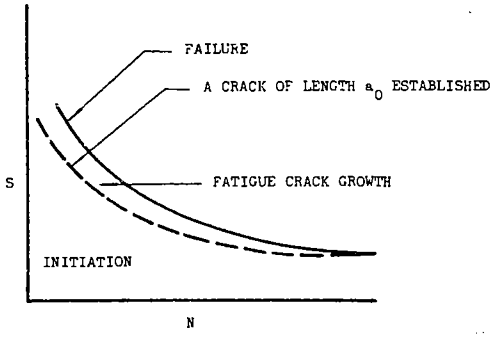

Fig. 3 S-N curve separated into crack-initiation and crack-propagation regimes.

A modification of the environment can greatly change the fatigue crack growth rate. Figure 4 shows the influence of mixing gases with hydrogen on the fatigue crack growth rate of an A514B steel for fixed microstructure and loading conditions. Pure hydrogen has a factor of about ten greater growth than vacuum, and mixed gases have varying effects on the crack growth rate observed in pure hydrogen. Similar effects have been noticed on nickel base alloys. Here again, a fracture mode change can be observed. It is very common for intergranular failure to be associated with the hydrogen embrittlement, for both sustained and cyclic loading conditions. H_2S as a gas or in aqueous solution shows a much higher growth rate than pure hydrogen.

There is a great deal of scatter associated with both types of subcritical crack growth. Figure 5 shows an example of the scatter associated with a round-robin test where the steel used was identical. The laboratory-to-laboratory scatter was about a factor of three. Which line

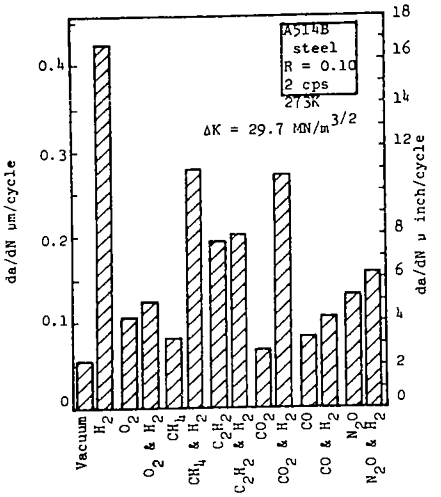

Fig. 4 The fatigue-crack propagation of ASTM A514B steel in various gaseous environments.

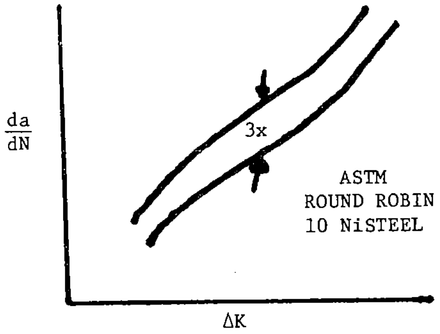

Fig. 5 Schematic of fatigue crack growth in 10 Ni steel showing scatter for round-robin testing.

to use in design is a constant problem in terms of how conservative to be.

Designing for a defined lifetime using fatigue crack growth data is similar to that discussed earlier for sustained load crack growth. The first approximation is a linear superposition of the constant amplitude da/dN data for each of the variable loads associated with a design loading spectrum. This is just the integration of the loading history combined with accounting for the continuing crack growth. The result is a crack length versus number of cycles or blocks of cycles as shown in Figure 6.

In general, the linear superposition model predicts a lifetime lower than that actually experimentally observed. This has been explained in terms of residual stresses at the tip or crack closure models. Both explanations rest on the fact that the prior non-uniform loading history must be taken into account. The crack closure model implies extra material is present on the surface of the crack which touches before the load is reduced to the minimum. This touching of the surfaces then eliminates the angularity at the crack tip and reduces the range in stress intensity, ΔK, to one that is an effective range in stress intensity, ΔK_{eff}, defined as $K_{max} - K_{closure}$. We have recently documented that at least part of the extra material on the surface is from the formation of an oxide.

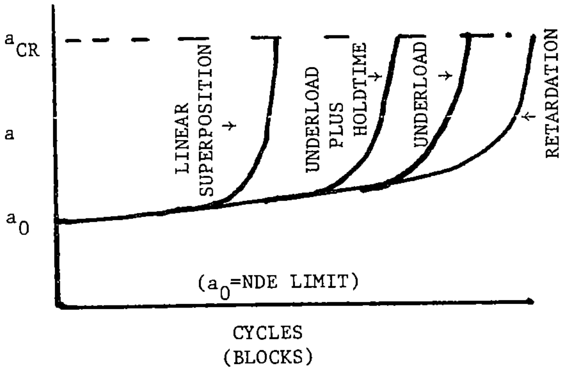

Fig. 6 Schematic of crack growth from the NDE limit a_0 to the critical value a_{cr} for several models of fatigue growth rate.

The crack growth is then modeled based on one of the models and since the ΔK is reduced to ΔK_{eff} the predicted lifetime is extended. This is also shown in Figure 6.

Another factor in load history is shown on Figure 6. This is the influence of an underload on the predictive behavior. An underload will reduce the lifetime by lowering the crack closure load on the residual stress, which increases ΔK_{eff}. Another factor we have recently studied is the influence of hold time at an underload on the subsequent growth rate. What is observed in the 2000 and 7000 series aluminum alloys is that there is relaxation process that further reduces the closure load, again increasing ΔK_{eff} and shortening the lifetime. This is also shown on Figure 6. The significant problem introduced by this result is how do you do laboratory tests in reasonable times and extrapolate them to the real time usage that a structure undergoes.

SUMMARY

In this paper I have tried to review the state of subcritical crack growth. Subcritical crack growth under either sustained or cyclic loading must be understood before the criticality of a quantitatively NDE determined flaw can be determined. It is the key link that merges the NDE crack length, a_o, and the fracture mechanic critical crack length, a_{cr}.

ACKNOWLEDGEMENT

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SUMMARY DISCUSSION
(H. Marcus)

George Gruber (Southwest Research Institute): Davidson's laboratory received a fatigue crack specimen from the Electric Power Research Institute, and they closed it. I looked at it before closing and after closing ultrasonically. I have that specimen with me today, and I will bring it in tomorrow for my talk. I have been able to measure the fracture from the crack tip even when it was as closed as I could close it. The key to it is to get off normal and come at an oblique incidence of about 30 degrees, and there you see it. You made a statement I thought I should reply to that we can at times determine the crack tip, the length of the crack even if it has been already closed.

Harris Marcus: I'm sure there isn't a hundred percent transmission through the totally closed crack, and as you get better and better into the signal-to-noise, as you are doing, you will be able to bring it out.

George Gruber: You can monitor either growth or shrinkage of the crack, so to speak, even if it's very closed. You will get an ultrasonic signal if you get off the normal to the crack.

Harris Marcus: I'm not sure what you mean by shrinkage.

George Gruber: Closing.

Harris Marcus: You are monitoring the section that is closed.

Gordon Kino (Stanford University): Perhaps what we are saying is if you come at an angle to a crack, you can see the crack tip from time delay, but amplitude measurements are unreliable.

Harris Marcus: Good. That is what I think the whole name of the game is within this group, how to get at them when they are simple transmissional type of work that I have been using. The thing you have to recognize is that little signal is really the one you want if you want to measure the true crack, not the big one.

George Gruber: If you come on normal, the little signal gets swamped by reflective waves.

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