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A STUDY OF STRESS-CORROSION CRACKING BY WEDGE-FORCE LOADING

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A Study of Stress-Corrosion Cracking

by Wedge-Force Loading

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Abstract

Wedge-force loading a center-cracked sheet specimen provides a unique resolution of whether stress-corrosion cracking (SCC) depends on an applied crack-tip stress-intensity factor or on net-section stresses. With this loading, crack extension causes a decreasing stress-intensity factor at the crack tip, while the net-section stresses increase. Therefore, when stress-corrosion crack growth is arrested in this specimen, the dependency on stress intensity is proved. The stress intensity at arrest agrees remarkably well with K_{SCC} values determined by more conventional techniques that establish crack initiation thresholds through multiple tests. Crack growth rate data important to the establishment of inspection intervals in structure can also be obtained. Finally, the technique affords considerable economy of test time and material costs in stress-corrosion studies.

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Introduction

Recent studies have associated the initiation of stress-corrosion cracking (SCC) with stress concentrations due to localized fretting attack or other surface imperfections [1,2]. Previously, a measure of susceptibility to SCC was sought by testing smooth specimens in corrosive environments and recording the time to failure at different stress levels. This procedure resulted in the rate of pit growth being interpreted as the rate of stress-corrosion crack growth. Furthermore, some titanium alloys that were highly susceptible to SCC were immune to pitting in the same environment, so that tests conducted on specimens without stress raisers resulted in the erroneous conclusion that these alloys were immune to SCC. For these alloys, it was obvious that artificial stress raisers must be provided. Several arguments can be offered in favor of providing artificial stress raisers for SCC testing of all materials:[1]

- Testing time can be shortened by eliminating the need for pit growth.
- Testing for SCC can be accomplished in alloys that do not pit.
- A stress raiser can easily be provided in the form of a machined notch of controlled geometry that is sharpened to crack acuity by fatigue loading. This facilitates a fracture mechanics approach to the analysis of the stress field near the tip of a stress-corrosion crack, which would be difficult if the stress raiser were in the form of an irregularly shaped pit.

The fracture mechanics approach to stress analysis of cracks, first introduced by Irwin [3], is now well established. In this analysis, it was shown that the stress-intensity factor K characterized the stress field in the vicinity of a crack tip. This analysis was extended by Paris, Gomez, and Anderson [4] to describe the mechanics of subcritical crack growth observed in fatigue tests. A uniform stress applied normally to the plane of a crack is intensified in the region of the crack tip by an amount proportional to K. As the load producing the stress increases, K increases; when K reaches a value critical to the material, fracture occurs. This value is termed the critical stress-intensity factor or "fracture toughness" of the material.

Several investigators [1,2,5] have shown that there is a threshold K value below which SCC does not initiate. However, the microprocesses of stress-corrosion crack growth are controlled in part by the state of stress at the crack tip. Several titanium alloys have been tested in different sheet and plate thicknesses [5,6] and the data show that, whereas stress-corrosion cracks extend readily under plane-strain conditions, they often do not propagate in somewhat thinner sections. This leads to the conclusion that the K threshold for the initiation of SCC is strongly influenced by the state of stress. Unfortunately, little has been done to classify thresholds as to plane stress or plane strain. Thus, at present, the K threshold in sheet material is simply termed K_{SCC} and in plate material, K_{ISCC}.

Although the opinion is widely held that SCC is K controlled, it can be argued that a threshold can be described in terms of net-section stresses. For example, Brown and Beachem [6] demonstrated that K_{ISCC} is an intrinsic material property when they obtained the same K_{ISCC} values on three different specimen configurations of a 4340 steel (center-cracked and surface-flawed tension specimens and cantilever bend specimens). The graph of K as a function of time to failure is shown in Fig. 1; it can be seen that the curves delineate similar K_{ISCC} values of approximately 14 ksi $\sqrt{in}$. When net-section stresses calculated from Brown and Beachem's data were plotted against time to failure, a similar threshold σ_{nSCC} was indicated (Fig. 2). However, Brown and Beachem noted that identical values of K_{ISCC} were obtained from observing the initiation of crack growth in a center-cracked and in a surface-flawed tension specimen. At the same time, they noted that the net-section stress of the center-cracked panel at failure was approximately 20,000 psi less than that of the surface-flawed specimen. From this they concluded that net-section stresses were too strongly influenced by geometry to act as criteria for initiation of SCC.

The K dependency of SCC can be demonstrated more convincingly by means of the wedge-force-loaded, center-cracked tension specimen shown in Fig. 3. The stress-intensity factor at the tip of a crack subjected to wedge forces is given by: [7]

$$K = \frac{P}{2t}\left(\frac{a}{\pi}\right)^{1/2} \left[\frac{(3+\nu)\, S^2 + 2a^2}{(a^2 + S^2)^{3/2}} \right] \left[\frac{W}{2\pi a} \sin \frac{2\pi a}{W} \right]^{-1/2} \tag{1}$$

where

- P = load
- t = thickness
- ν = Poisson's ratio
- a = half crack length
- W = width
- S = distance between the point of load application and the crackline

When S is sufficiently small compared with a and a is small compared with W, K varies inversely as $\sqrt{a}$. Equation (1) is plotted in terms of $\frac{Kt}{P}\sqrt{\frac{W}{2}}$ versus $\frac{2a}{W}$ in Fig. 4. A minimum on the curve appears when $\frac{2a}{W}$ equals approximately 0.5 because of the influence of the sine function. Figure 4 also includes a graph of $\frac{\sigma_n Wt}{P}$ versus $\frac{2a}{W}$. For a specimen

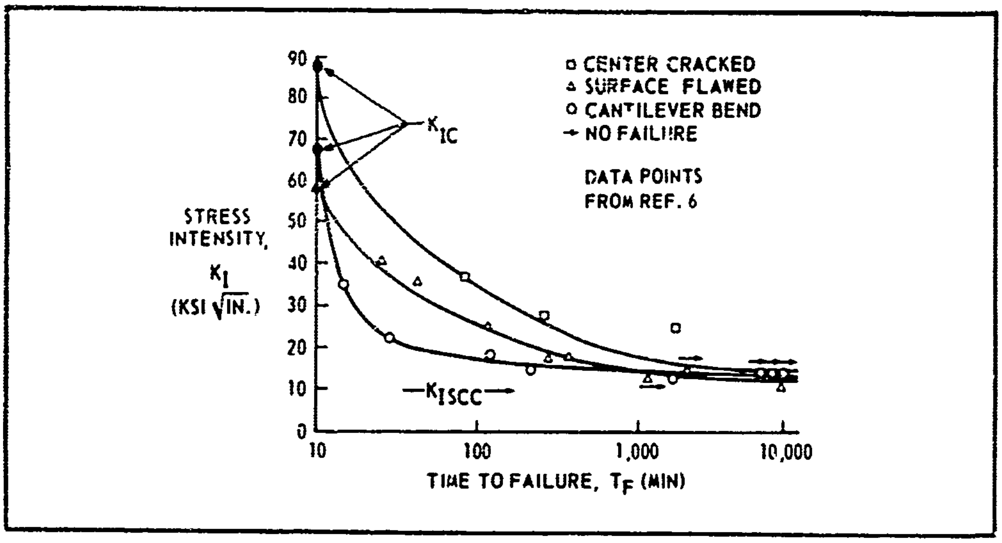

FIG. 1 K_{ISCC} FOR 4340 STEEL TESTED IN THREE DIFFERENT SPECIMEN CONFIGURATIONS

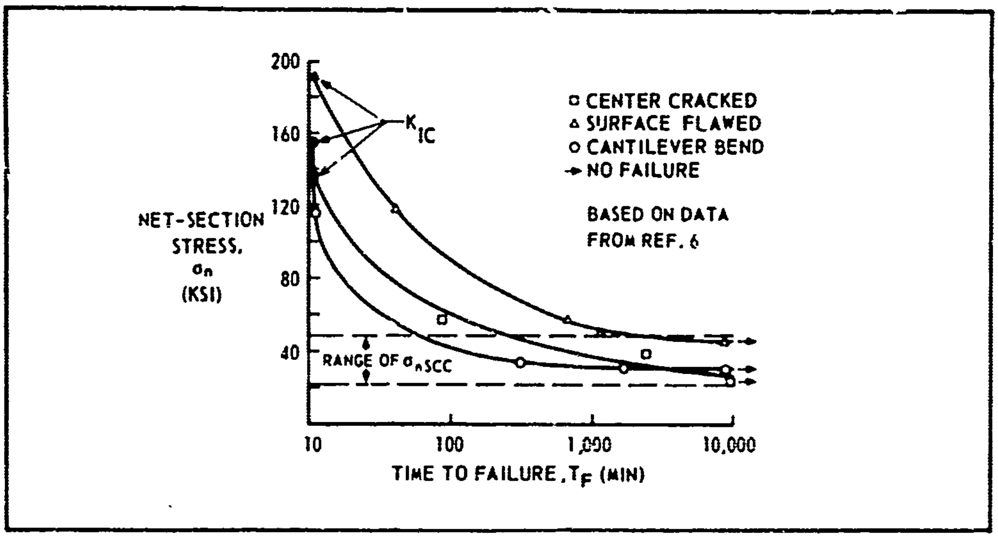

FIG. 2 σ_{nSCC} FOR 4340 STEEL TESTED IN THREE DIFFERENT SPECIMEN CONFIGURATIONS

of given dimensions subjected to a constant load, the only variables are K and 2a. Therefore, from Fig. 4 it can be seen that if SCC is K dependent, crack growth should be arrested if K decreases to K_{SCC} before the crack grows to a value of $\frac{2a}{W}$ equals 0.5. On the other hand, if SCC is σ_n dependent, crack growth should continue until the specimen fails, and no arrest should occur.

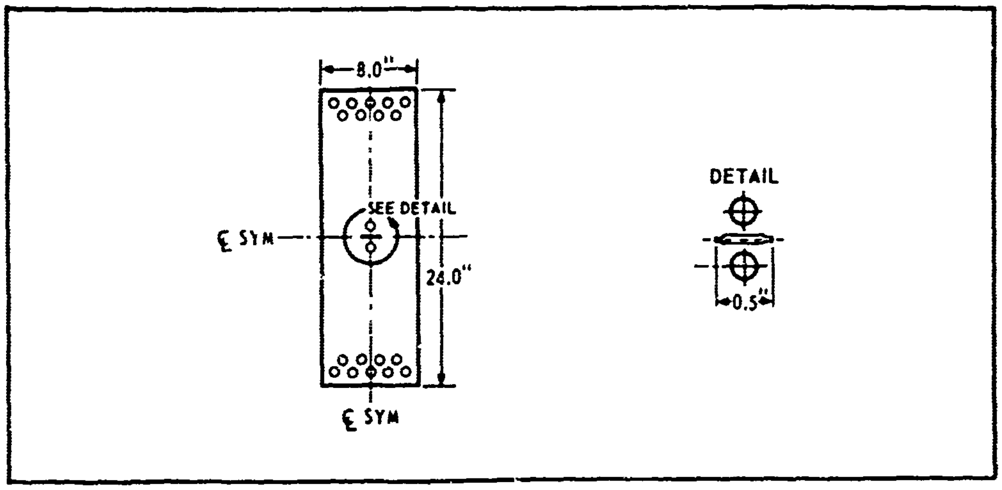

FIG. 3 CENTER-CRACKED WEDGE-FORCE-LOADED PANEL

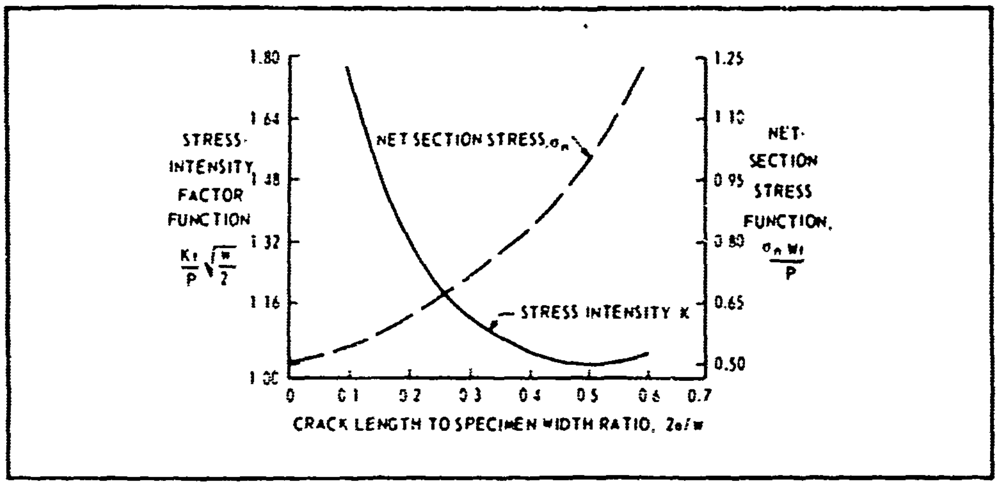

FIG. 4 K AND σ_n VERSUS 2a/W FOR A WEDGE-FORCE-LOADED CENTER-CRACKED PANEL

Results and Discussion

The wedge-force test setup is shown in Fig. 5. Specimens were fabricated from mill-annealed, 0.160-in.-thick Ti 8Al-1Mo-1V sheet. The yield strength of the material was approximately 145 ksi and its indicated K_{SCC} was 24 ksi $\sqrt{in.}$[5]. Each specimen was fitted with a container surrounding the notch area and was fatigue precracked by sinusoidal wedge-force loading where P_{max} was 6.35 kips and the ratio of minimum to maximum loads R was 0.05. It was necessary to have the fatigue precrack at least 0.8 in. long to avoid errors in the crack-tip stress-intensity factor caused by the pinhole stress concentration that exists for a distance of 2S along the crackline. The final cycle of fatigue loading was interrupted to cause a static load of 6.35 kips to be maintained over the crack length of 0.8 in. Under these conditions, the K value was 35 ksi $\sqrt{in.}$ Salt solution (3.5 percent NaCl) was added to the container to begin the SCC study.

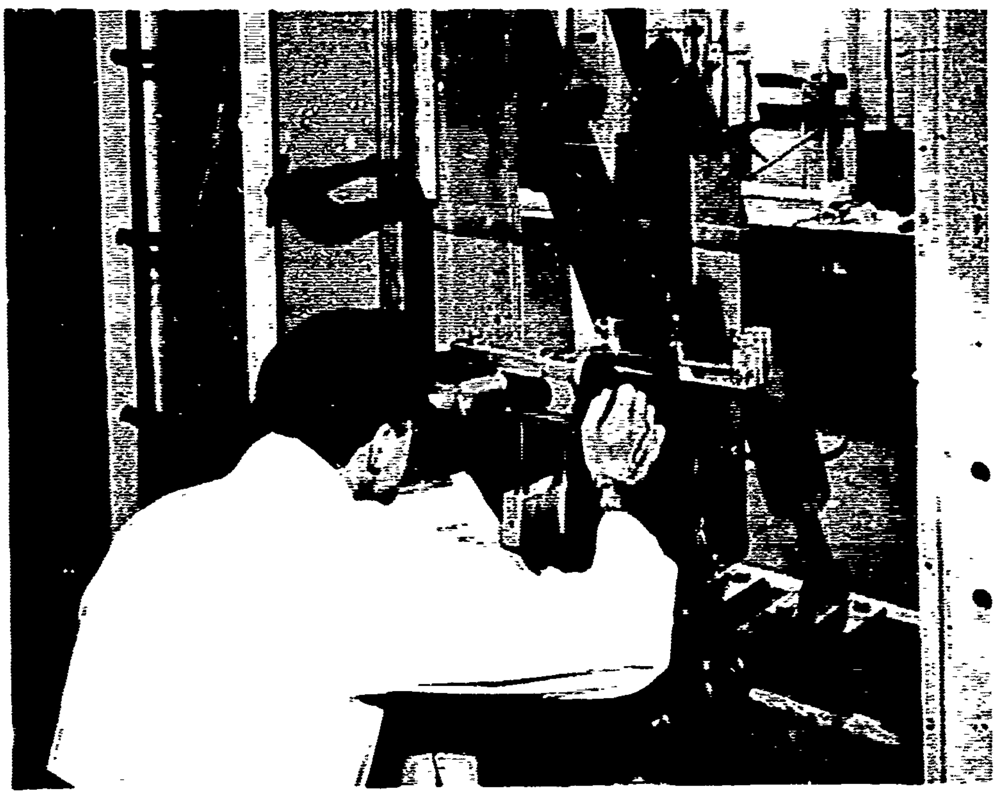

FIG. 5 WEDGE-FORCE TEST JIG

The fatigue precrack grew immediately under the influence of the static load and aqueous environment. Crack growth was monitored by means of a telescope mounted beside the specimen, as shown in Fig. 5. Crack growth rate was rapid in the beginning, decreased as the crack extended, and finally appeared to be arrested. After the crack was first judged to be arrested, an additional hour at stress was allowed to insure that no further crack growth occurred. It was found that the process could be repeated on the same specimen by increasing the load, provided that the $\frac{2a}{W}$ ratio did not exceed 0.5 at arrest. Three specimens were tested in this manner, and each time the crack growth was arrested the calculated value of K was between 2. and 22 ksi $\sqrt{in}$. These values were in excellent agreement with the K_{SCC} value of between 20 and 25 ksi $\sqrt{in}$. determined for mill-annealed Ti 8Al-1Mo-1V sheet by Piper and associates [5]. It was concluded, therefore, that SCC arrest occurs in the wedge-force-loaded specimen at K_{SCC}. A test was also performed whereby a load was selected that resulted in a K value greater than K_{SCC} at $\frac{2a}{W}$ equals 0.5. In this test the crack continued to grow until the specimen failed.

In Fig. 6, the crack growth rate from a typical test is plotted against both K and σ_n. The relationship with K is direct, whereas with σ_n it is inverse, which again suggests that SCC is K dependent. A compilation of the crack growth rate data obtained from multiple tests on three specimens is shown in Fig. 7. The fact that the crack growth rate appears to have less acceleration at the higher K levels indicates that the SCC process is time dependent and cannot keep pace with the rate of increase of K.

For one of the tests the wedge-force assembly was removed to the ends of the specimen after the first arrest was obtained. The

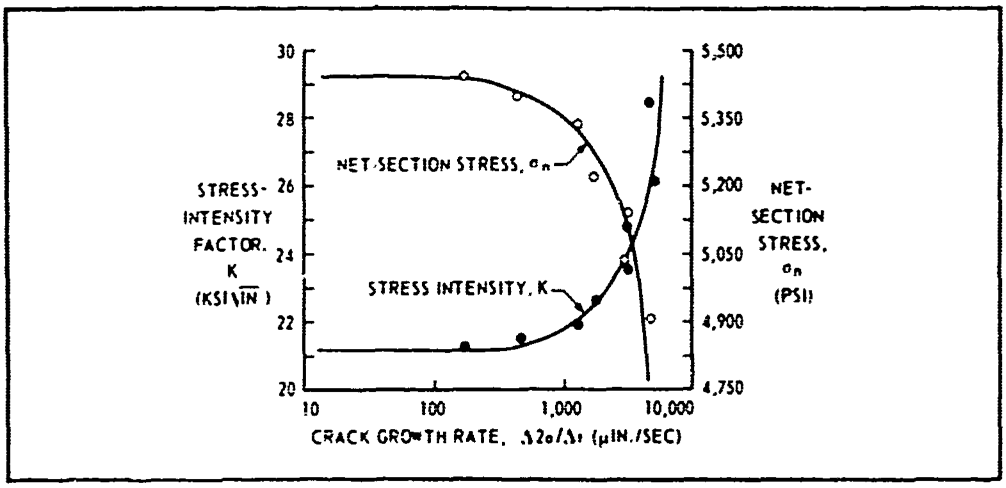

FIG. 6 STRESS-INTENSITY FACTOR AND NET-SECTION STRESS VERSUS CRACK GROWTH RATE FOR A WEDGE-FORCE-LOADED SPECIMEN

stress-corrosion crack was then extended by fatigue loading in air to a $\frac{2a}{W}$ value of 0.45. The specimen was failed in tension to obtain the expected [5] K_C value of 72 ksi $\sqrt{in}$.

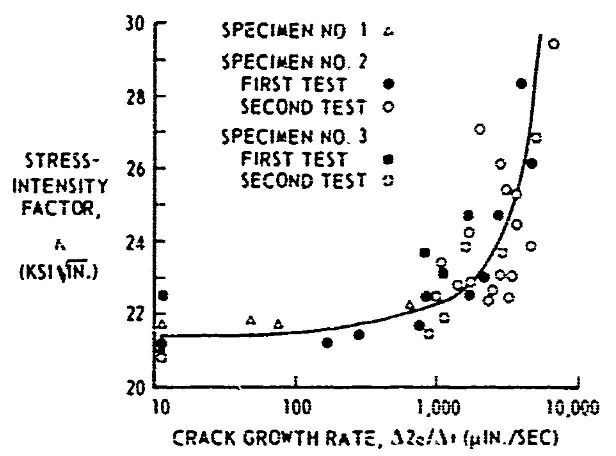

FIG. 7 CRACK GROWTH RATE DATA FOR MILL-ANNEALED Ti 8Al-1Mo-1V ALLOY SHEET

The pinhole diameter for wedge-force loading shown in the specimen in Fig. 3 is suitable for tests involving a maximum K value of 45 ksi $\sqrt{in}$. in titanium alloys. Above this limit, higher loads are required and bearing failures at the pinholes become a problem, which necessitates larger pinhole diameters. Care must be taken not to calculate critical K values for crack lengths less than 2S, the crackline length over which a stress concentration due to the pinhole diameter influences the crack-tip stress intensity. Specific dimensions for pinhole diameters can be calculated by using the familiar relationships between sheet dimensions, bearing strength, and applied loads.

In view of these results, it seems reasonable that stress-corrosion testing of one or two center-cracked specimens, using wedge-force and end loading, should yield both K_{SCC} and K_C, as well as crack growth rate data. The advantage of the wedge-force loading technique is obvious when it is compared with the techniques that involve 4 or 5 specimens exposed for extended periods of time to develop the K versus time-to-failure relationship. At the same time, it is inherently reassuring to observe from the wedge-force test that a structural design exists in which crack growth can be arrested in corrosive environments.

References

1. B. F. Brown and C. D. Beachem, "A Study of the Stress Factor in Corrosion Cracking by Use of the Pre-Cracked Cantilever Beam Specimen," Corrosion Science, Vol. 5, 1965, pp. 745-750.

2. H. H. Johnson and A. M. Willner, "Moisture and Stable Crack Growth in a High Strength Steel," Applied Materials Research, Vol. 4, 1965, p. 34.

3. G. R. Irwin, "Fracture," Handbuch Der Physik, Vol. VI, Springer, Berlin, 1958, pp. 551-590.

4. P. C. Paris, M. P. Gomez, and W. E. Anderson, "A Rational Analytic Theory of Fatigue," The Trend in Engineering, Vol. 13, No. 1, January 1961, p. 9.

5. D. E. Piper, S. H. Smith, and R. V. Carter, "Corrosion Fatigue and Stress-Corrosion Cracking in Aqueous Environments," presented at Materials for Oceanspace Symposium, National Metal Congress, American Society for Metals, Chicago, Illinois, Oct. 31-Nov. 3, 1966.

6. B. F. Brown and C. D. Beachem, "A Comparison of Three Specimens for Evaluating the Susceptibility of High Strength Steel to Stress Corrosion Cracking," internal report, Naval Research Laboratories, 1966.

7. P. C. Paris and G. C. Sih, "Stress Analysis of Cracks," Fracture Toughness Testing and Its Applications, ASTM Special Technical Publication No. 381, presented at the Sixth-seventh Annual Meeting, American Society for Testing and Materials, Chicago, Illinois, June 21-26, 1964.

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13. ABSTRACT

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Wedge-Force Loading						
Stress-Corrosion Cracking						
Crack Growth Rate						
Titanium Alloy						

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