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Stress History Effect on Incubation Time for Stress Corrosion Crack Growth in E-4340 HR Steel

Prepared by D. L. DULL and L. RAYMOND
Material Sciences Laboratory

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FOREWORD

This report is published by The Aerospace Corporation, El Segundo, California, under Air Force Contract No. F04701-71-C-0172.

This report, which documents research carried out from June to December 1971, was submitted 10 May 1972 to Captain Gary R. Edwards, SYAE, for review and approval.

Approved

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Material Sciences Laboratory

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Gary R. Edwards
Capt., United States Air Force
Project Officer

ABSTRACT

The effect of stress history on stress corrosion cracking of E-4340 HR steel in an aqueous environment has been studied with the use of double-cantilever beam specimens. The stress history effect was found to influence the incubation time period with changes in the stress intensity. When the stress intensity was decreased, the incubation time period was dependent on the ΔK and final K_f during stress corrosion testing. When the stress intensity was increased, the incubation time period was independent of the applied stress intensity. However, the stress history effect did not influence the steady-state crack growth rates. In this report, the stress history effect is explained by using the hydrogen embrittlement mechanism.

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I. INTRODUCTION

The total time for a structural failure to occur because of stress corrosion cracking (SCC) includes the time for crack nucleation and the time for subcritical crack growth prior to rapid fracture. The transition is continuous and extremely difficult to detect. For high-strength steels, crack nucleation appears to occur in two steps. The first step is dependent only on the surface phenomena and falls under the category of general corrosion studies on pit and crevice formation. For example, Tiner and Gilpin[1] found that pits on AISI 4340 steel in 3% NaCl solution formed at inclusion sites. This then led to a slow chemical attack of the prior austenitic grain boundaries before subcritical crack growth occurred.

The second step is a stress-dependent step that requires time for diffusion of the interstitial hydrogen element to reach a critical concentration at the point of maximum triaxial stress inside the metal. Troiano,[2] using a notched round bar, Steigerwald,[3] using a precracked notched tension specimen, and Slaughter, et al.,[4] have demonstrated the importance of stress in the continual subcritical growth of a crack in a material. The various stress corrosion mechanisms for hydrogen embrittlement in steels have been discussed by Tetelman[5] and Elsea and Fletcher.[6]

Incubation time periods have been reported by Troiano and coworkers.[2,7-9] By using electrical resistance techniques on hydrogen-charged notched round bars, they found that a period of time existed where no apparent crack growth was observed. This incubation period was required for hydrogen to diffuse to the region of maximum triaxial state of stress. They also found that if the hydrogen were baked out before this time period elapsed, then hydrogen embrittlement would not occur. In other words, the mechanism was reversible. Loomba[10] has defined his incubation time to include both the stress-independent pit formation step and the stress-dependent step, which involves the transformation of a pit to a crack.

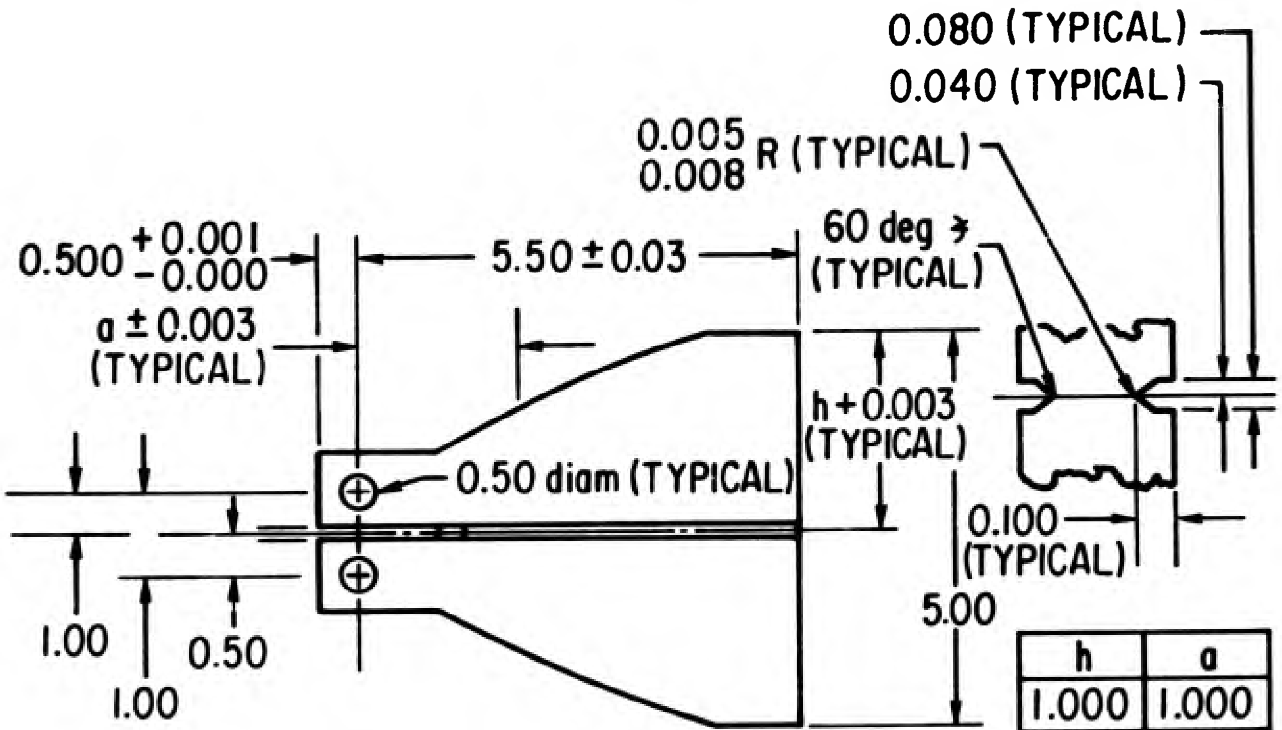
The purpose of our investigation was to study the incubation time in the stress-dependent step of crack nucleation. Our specimens were fatigue precracked before exposure to the environment. Two incubation time periods were measured: first, the time required for the fatigue precrack to start growing at a steady-state rate at an initial applied stress intensity, and second, the time required for a crack to grow at a steady-state rate after a change from a previous stress intensity where the crack growth rate was steady state under SCC conditions. The characterization of this latter incubation time period is the primary subject of this report.

II. EXPERIMENTAL PROCEDURE

We selected E-4340 HR steel for this investigation because its stress corrosion behavior is well characterized. Four contoured double-cantilever beam (DCB) specimens heat treated to R_c-52 were used. The detailed dimensions are shown in Fig. 1. The procedure for calibration of this specimen configuration when using arm extensions has been published elsewhere.[11] A solution of 0.05% sodium dichromate was selected as the environment because it has been shown to inhibit general corrosion without affecting the subcritical crack growth in distilled water.[12] The incubation time was continuously monitored by measuring the crack opening displacement (COD) with a linear variable differential transformer (LVDT) excited by a Dentronics Model 201C transducer exciter demodulator. The output was recorded on a strip chart recorder with a time base. A typical experimental setup is shown in Fig. 2.

A flow diagram of the stress intensity* loading sequence is shown in Fig. 3. Essentially, it involves fatigue precracking the specimen in air over a range of K_{max} to 0.1 K_{max}, i.e., R = 0.1. The specimen was moved to a creep frame, immersed in the aqueous environment, and then loaded to an initial stress intensity K_i, which was not necessarily equal to K_{max} during fatigue. The incubation time and steady-state crack growth rates were then monitored. Crack growth rates were determined in the same manner as reported by Van der Sluys.[13] The incubation time was defined as that time required for the crack to propagate at a steady-state crack growth rate. The stress intensity was then decreased to another value K_{ii} until steady state was achieved, and then again increased to K_i. The details of the loading sequence are given in Table 1 together with the measured incubation time and steady-state crack growth rates.

*Stress intensity K at the crack tip is given as $K = P\left\{[E(\partial C/\partial a)]/[2b_n(1-\nu^2)]\right\}^{1/2}$ for the contoured DCB specimen.



h	a
1.000	1.000
1.250	1.443
1.500	1.936
1.750	2.475
2.000	3.055
2.250	3.674
2.500	4.330

Fig. 1. Dimensions and Configuration for the Double-Cantilever Beam Specimen

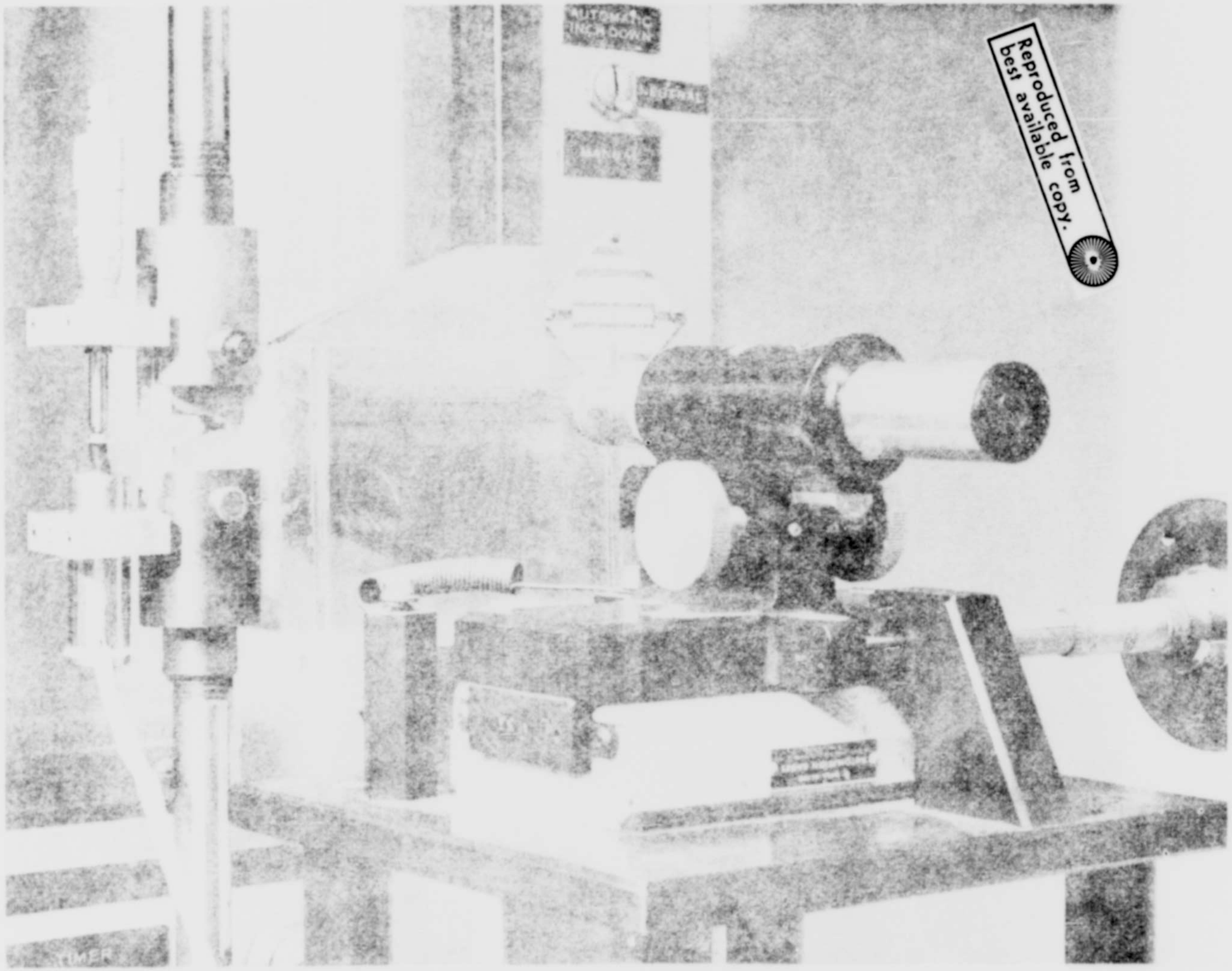


Fig. 2. Typical Experimental Test Setup Showing LVDT Measuring Changes in COD and Optical Traveling Microscope for Measuring Crack Length

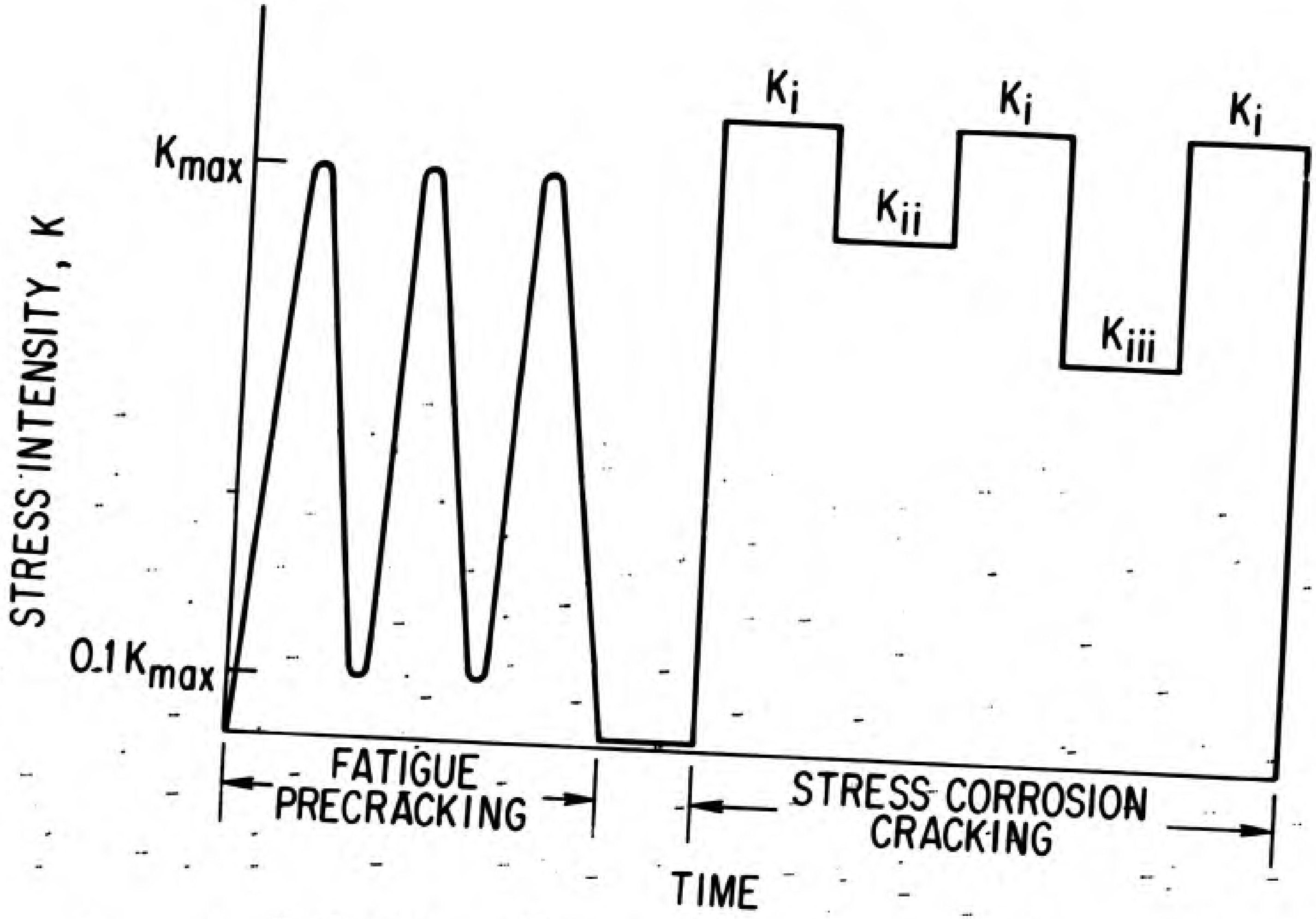


Fig. 3. Flow Diagram of Loading Sequence

Table 1. Sequential Steps Used to Determine the Effects of Stress History on Incubation Time

Step	Stress Intensity, ksi$\sqrt{in.}$	Incubation Time, min	Steady-State Crack Growth Rate, mil/min
a-0*	K_{max} = 40.6	—	—
a-1	K_i = 65.0	11	17.6
a-2	K_{ii} = 43.4	2	12.8
a-3	K_i = 65.0	0	16.5
a-4	K_{iii} = 27.1	220	7.5
a-5	K_i = 65.0	0	17.2
a-6	K_{iv} = 19.0	2500	5.8
a-7	K_i = 65.0	0	21.1
b-0*	K_{max} = 16.3	—	—
b-1	K_i = 43.4	37	14.0
b-2	K_{ii} = 27.1	10	8.0
b-3	K_i = 43.4	0	13.2
b-4	K_{iii} = 19.0	28	6.5
b-5	K_i = 43.4	0	15.4
c-0*	K_{max} = 16.3	—	—
c-1	K_i = 27.1	440	9.2
c-2	K_{ii} = 19.0	6	5.7
c-3	K_i = 27.1	0	8.7
d-0*	K_{max} = 16.3	—	—
d-1	K_i = 19.0	3000	9.7
e-0*	K_{max} = 61.1	—	—
e-1	K_i = 43.4	25	16.6
f-0*	K_{max} = 61.1	—	—
f-1	K_i = 27.1	>20400	—

*Zero designation indicates that the crack was extended at least 50 mil by fatigue at R = 0.1. This crack distance is beyond the plastic zone size, which is estimated as $(1/6\pi)(K_{Ic}/YS)^2$, or about 10 mil maximum.

The fracture toughness or critical stress intensity for this material was found to average 79 ±3 ksi $\sqrt{in.}$ for three specimens. This was a valid K_{Ic} measurement in accordance with the ASTM E-24 criterion that $B \geq 2.5 (K_{Ic}/YS)^2$ if the yield strength YS is assumed to be 240 ksi, which is a reasonable assumption for E-4340 HR steel heat treated to R_c-52. This fracture toughness value is higher than the service value of 58 ksi $\sqrt{in.}$ suggested by Beachem and Brown,[14] who heat treated AISI 4340 material to a R_c 51. However, it is within the range of fracture toughness values (57.0 to 88.5 ksi $\sqrt{in.}$) obtained with the various specimen configurations used in their determinations.

III. RESULTS

The results summarized in Table 1 can be analyzed to demonstrate three different effects as discussed below.

A. EFFECT OF SCC HISTORY ON INCUBATION TIME

The data of Table 1 show that the incubation time for steady-state crack growth is significantly affected by a previously applied stress intensity during SCC. For example, the incubation time for a change in stress intensity from 65 to 19 ksi $\sqrt{\text{in.}}$ is 2500 min (step a-6). However, if the stress intensity is "walked-down" in small increments, the incubation time can be reduced to 18 min. This effect is demonstrated by combining steps a-2 (65 to 43.4 ksi $\sqrt{\text{in.}}$), b-2 (43.4 to 27.1 ksi $\sqrt{\text{in.}}$), and c-2 (27.1 to 19 ksi $\sqrt{\text{in.}}$). The incubation times for these steps are 2, 10, and 6 min, respectively. In order to demonstrate the significance of this effect, these results are plotted in Fig. 4.

In Fig. 5, we attempt to derive an empirical relationship between $\Delta K/K_f$ and the incubation time. The change in stress intensity ΔK is the difference between the previous higher stress intensity and the final stress intensity K_f. When the stress intensity is increased, i.e., ΔK is a negative number, then the incubation time is reduced to zero as noted in Table 1. An incubation time is observed only when the stress intensity is decreased.

B. EFFECT OF FATIGUE PRECRACKING HISTORY ON INCUBATION TIME

If K_{max} during crack extension by fatigue in air is below the initial applied stress intensity K_i in an aqueous environment, an incubation time is still observed (steps a-1, b-1, c-1, and d-1). However, if K_{max} is significantly larger than K_i, then the incubation time can be prolonged extensively (step f-1). Carter[15] has shown that prestressing, which in this case is considered comparable to fatigue precracking, can cause an increase in the overall time to failure in 4340 preflawed steel specimens. In general,

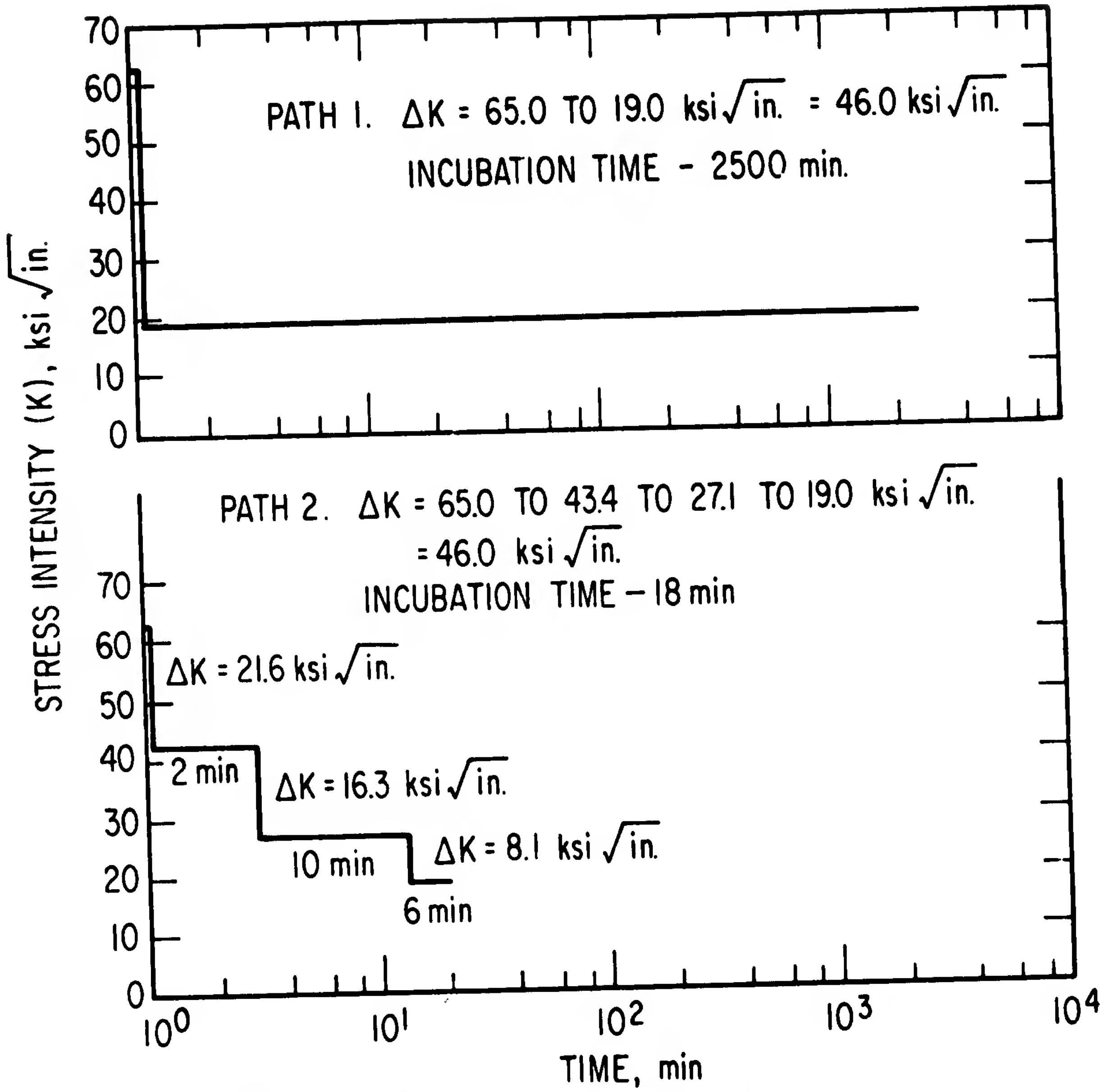


Fig. 4. Incubation Time by Two Different Paths for E-4340 HR Steel

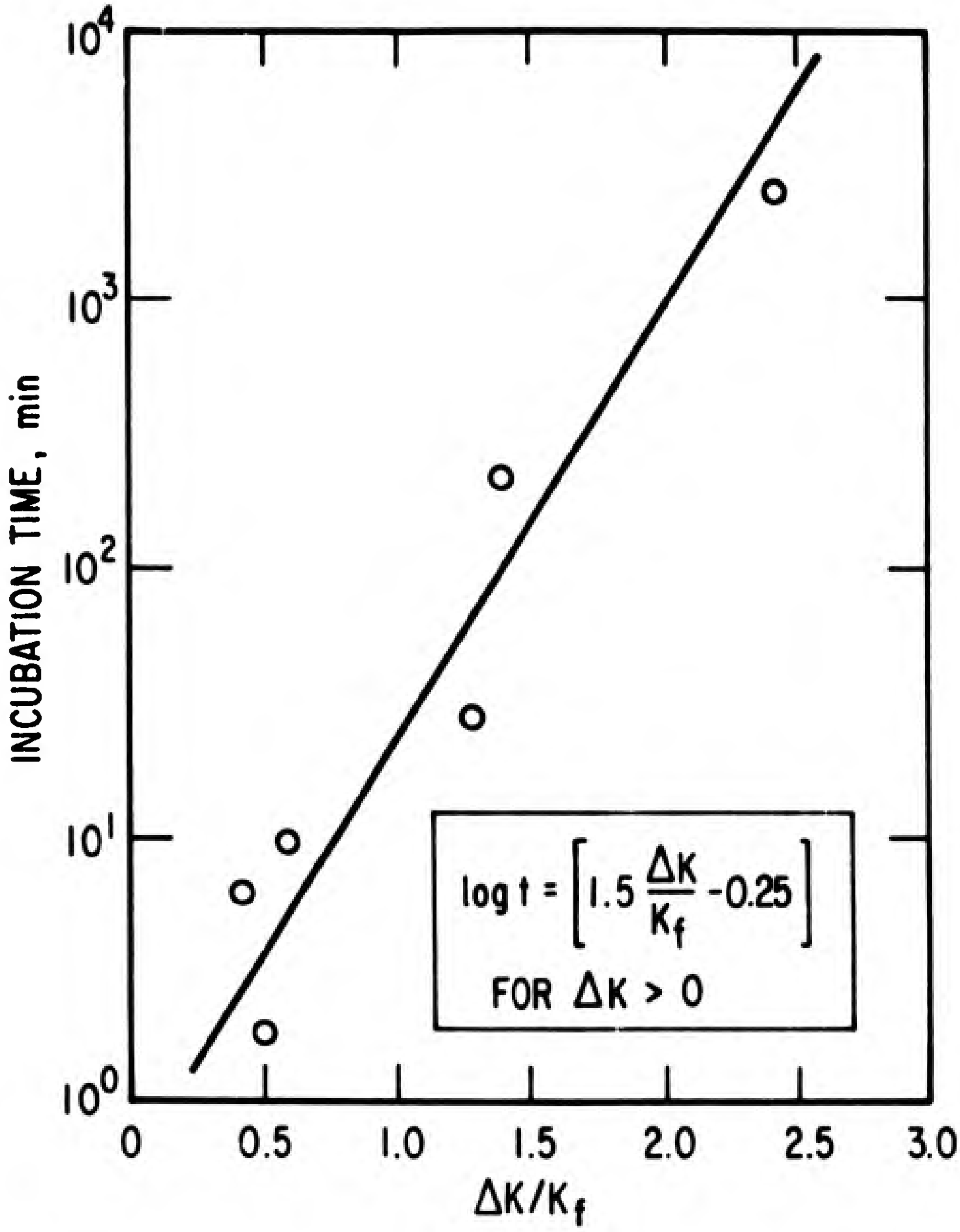


Fig. 5. **Effect of Stress Corrosion Cracking History on Incubation Time for E-4340 HR Steel**

the data indicate that in order to minimize the incubation time for testing purposes, K_{max} in fatigue precracking should not exceed K_i.

C. EFFECT OF STRESS HISTORY ON STEADY-STATE CRACK GROWTH RATE

The results of this study clearly demonstrate that neither SCC history nor fatigue precrack history affects the final steady-state crack growth rate. They are strictly functions of the applied stress intensity. The data are in fair agreement with those of Van der Sluys,[13] whose crack growth rates were approximately twice as fast. This is attributed to the difference in metallurgical processing of the specimens. We report K_{Ic} of 79 ksi $\sqrt{in.}$ in contrast to his 51 ksi $\sqrt{in.}$ The accuracy of our data is demonstrated in Table 2, which was compiled from data extracted from Table 1. It should be noted that the crack growth rate data were obtained from four separate specimens at various crack length positions.

Table 2. Steady-State Crack Growth Rate vs Stress Intensity

Stress Intensity, ksi$\sqrt{\text{in.}}$	Steady-State Crack Growth Rate, mil/min
65.0	18.1 ± 1.8
43.4	14.4 ± 1.4
27.1	8.4 ± 0.6
19.0	6.9 ± 1.6

IV. ANALYSIS OF THE DATA

The mechanism for SCC of E-4340 HR steel in 0.05% sodium dichromate solution appears to be hydrogen embrittlement. Figure 6 is a scanning electron micrograph of the surface of a specimen grown under SCC conditions at a stress intensity of 27.1 ksi $\sqrt{in.}$ Note that the failure mode is intergranular, which is typical of hydrogen embrittlement in this material.[16,17]

This SCC mechanism implies that a critical hydrogen concentration at the crack tip must be present at each stress intensity level for subcritical crack growth. If it is assumed that the critical hydrogen concentration for crack propagation is inversely proportional to the applied stress intensity, then the stress history dependence on incubation time for SCC can be explained. This assumption is not unreasonable when one considers the work of Johnson, Morlet, and Troiano,[7] who have shown that the "static fatigue limit" decreases with higher hydrogen concentrations. Thus, a decrease in the stress intensity must be accompanied by an incubation time for the critical hydrogen concentration required for continued crack growth to be reached. This is illustrated in Fig. 7, where two paths (paths 1 and 2) are proposed for decreasing the stress intensity. At the right side of the curve, the hydrogen concentration is sufficient for crack propagation; at the left side, it is insufficient for crack propagation. Path 1 assumes a single ΔK decrease from point A to point B. In this region, the hydrogen concentration is too low for crack growth and, thus, the crack growth is arrested until the hydrogen concentration is sufficiently increased because of surface chemical reactions. Once the hydrogen concentration reaches critical again, at point C, the crack will continue to grow.

Path 2 assumes a series of small incremental ΔK decreases where only small changes in hydrogen concentration are required for continued crack propagation. Hence, a shorter incubation time occurs at each ΔK decrease. The experimental data show that the total incubation time of

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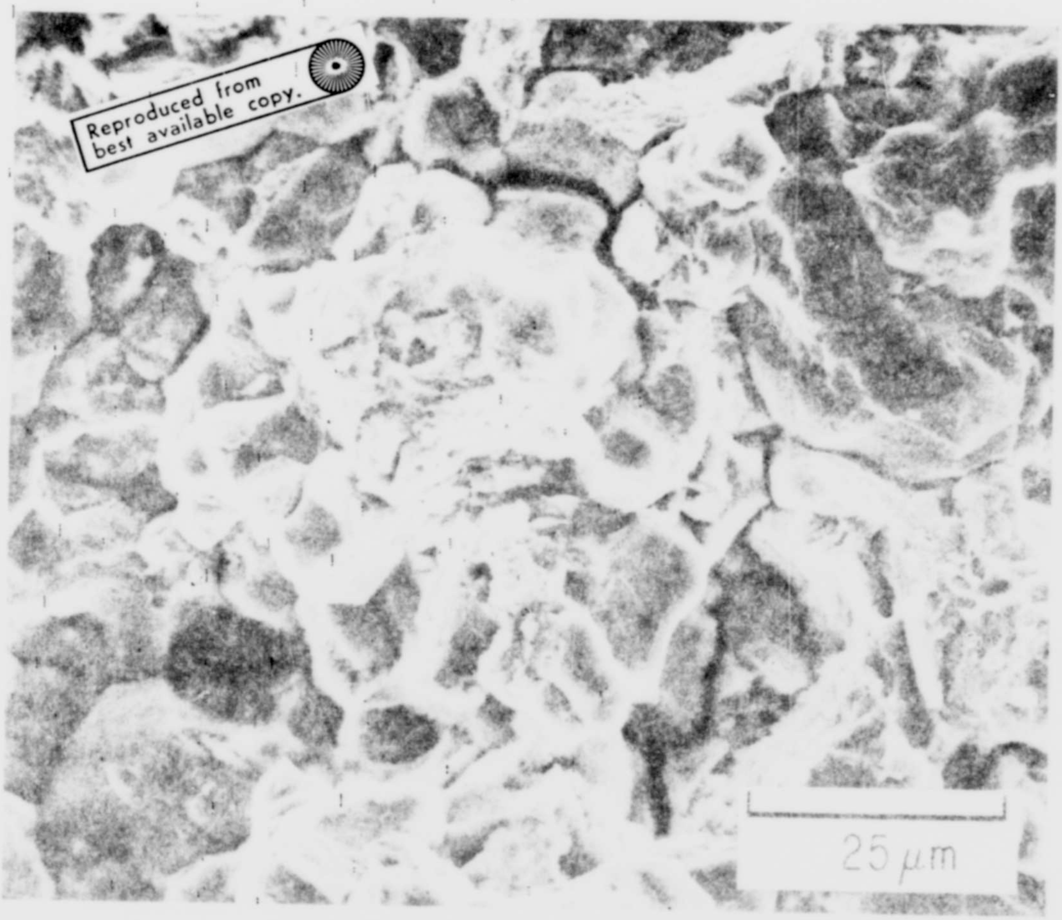

Fig. 16. Scanning Electron Micrograph of the Surface of E-4340 HR Steel Grown Under Stress Corrosion Cracking Conditions at a Stress Intensity of 27.1 ksi $\sqrt{in}$.

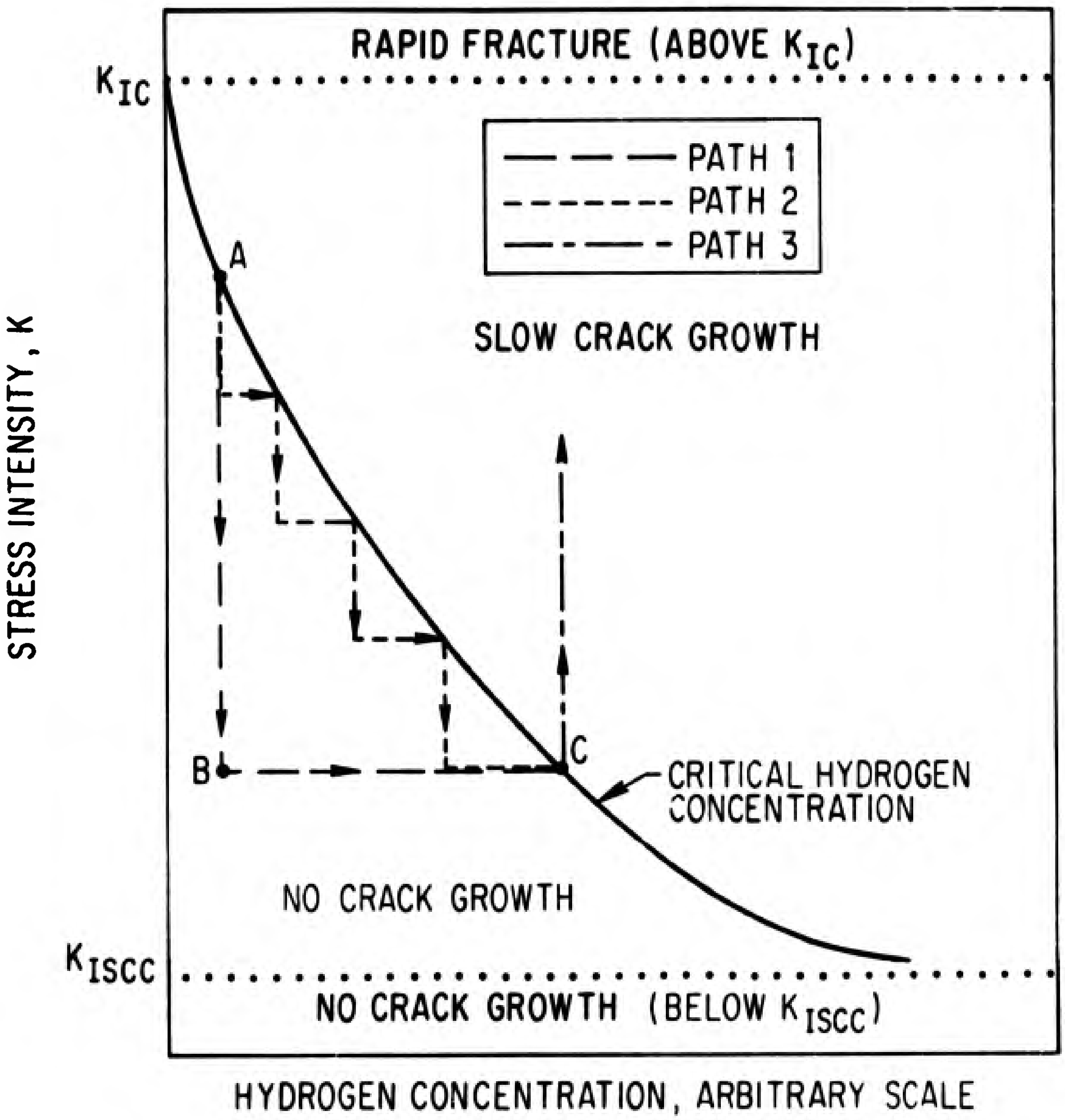

Fig. 7. Proposed Inverse Relationship Between Stress Intensity and Critical Hydrogen Concentration Required for Crack Growth

path 1 is considerably longer than that of path 2. This is believed to be due to a "stress-assisted diffusion" of the hydrogen through the lattice as demonstrated by Steigerwald, Schaller, and Troiano.[8]

The zero incubation time when increasing the ΔK is shown by path 3 (Fig. 7). The critical hydrogen concentration never falls below that required for crack growth. Thus, the incubation time is independent of the ΔK increase.

V. CONCLUSIONS

This study has shown experimentally that a stress history effect influences the incubation time for steady-state crack growth rates in stress corrosion testing of E-4340 HR steel. The following conclusions are reached:

1. When the stress intensity is decreased, the incubation time is dependent on the magnitude of the stress intensity decrease and the magnitude of the final stress intensity.
2. When the stress intensity is increased, the incubation time is zero and is independent of the stress intensity increase.
3. The stress history effect either from previous fatigue precracking or from stress corrosion testing does not affect the steady-state crack rate.
4. The stress history effect can be explained by the hydrogen embrittlement mechanism with the additional assumption that the critical hydrogen concentration required for crack propagation is inversely proportional to the applied stress intensity.

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