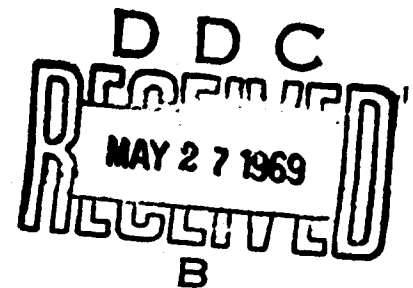D6-23871
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Stress Corrosion Crack Branching in High-Strength Steels

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STRESS CORROSION CRACK BRANCHING
IN HIGH-STRENGTH STEELS*

By

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ABSTRACT

The criteria for stress corrosion crack branching in high-strength steels are shown to be (1) a constant crack velocity and (2) attainment of a critical stress intensity K_{Ib}. For the steels investigated, values of K_{Ib}/K_{Iscc} range from 2 to 4. This indicates that when K_{Iscc}/K_{Ic} exceeds 0.5, rapid brittle fracture will occur before K_{Ib} can be reached.

SYMBOLS

K_I Plane-strain stress intensity factor $(ksi\sqrt{in.})$

K_{Ib} Critical stress intensity factor for crack branching $(ksi\sqrt{in.})$

K_{Ic} Plane-strain fracture toughness $(ksi\sqrt{in.})$

K_{Id} Stress intensity factor at which crack growth rate deviates from constant velocity $(ksi\sqrt{in.})$

K_{Ii} Initial stress intensity $(ksi\sqrt{in.})$

K_{Iscc} Plane-strain threshold stress intensity factor below which stress corrosion cracking does not occur $(ksi\sqrt{in.})$

$K_{I\delta}$ Critical stress intensity factor for terminal fracture $(ksi\sqrt{in.})$

n Ratio of K_{Ib}/K_{Ic} or K_{Ib}/K_{Iscc}

Y Yield strength (ksi)

INTRODUCTION

Crack branching has been observed during the rapid unstable fracture of various brittle materials, for example glass and alumina (1,2). A recent study (3) has revealed that an identical phenomenon can occur during the stress corrosion cracking of high-strength steels (Fig. 1).
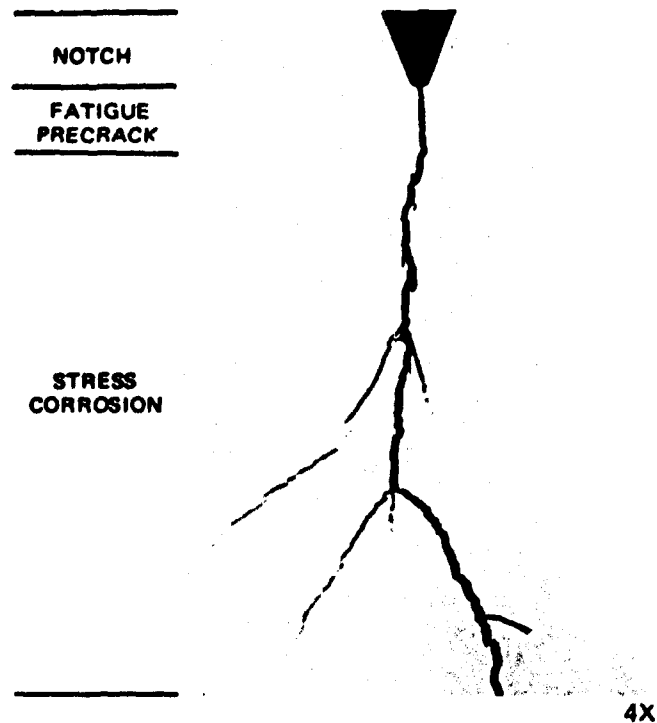

Fig. 1. Stress corrosion crack branching in 9Ni-4Co-0.45C (martensitic) steel.

A theoretical analysis by Yoffe (4) showed that when the crack velocity exceeded approximately 60% of the elastic shear wave velocity, the normal stress on two symmetrically inclined planes through the crack tip became greater than on the crack plane. Experimental data indicated that the crack accelerated to a limiting velocity and that branching could often be associated with this region of constant crack speed. Therefore, crack branching was usually attributed to the velocity-induced modification of the stress pattern as proposed by Yoffe.

Clark and Irwin, however, showed that the crack speed is essentially constant prior to crack division (5). They pointed out that the stress distribution around the tip of a static crack is such that the maximum normal stress along the crack plane is significantly less than along planes inclined 60° to the crack tip. This was said to encourage development of "advance" cracks away from the plane of the main crack. During initial extension of the main crack, the opportunity for the advance cracks to extend by growth of the stress field is at first counteracted by the rapid acceleration of the main crack. When the limiting crack speed is reached, the increase of the stress field is no longer counteracted in this way, and branching occurs. Mostovoy et al. (6) have associated stress corrosion crack branching in high-strength steels with constant crack velocity and concluded that this was a necessary but perhaps not a sufficient criterion for branching.

Clark and Irwin (5) considered that, in addition to constant velocity, a critical stress intensity level must be attained for crack branching to occur. Congleton and Petch (7) analyzed the conditions required to extend an advance crack and also concluded that a critical stress intensity was required for branching. This was experimentally confirmed by rapid fracture tests on glass and other brittle materials. However, the data obtained from glass samples indicated that branching occurred over a wide range of crack velocities, and Congleton and Petch suggested that velocity need not be constant.

Recently, Anthony and Congleton (8) re-examined the criteria for branching of a propagating brittle crack and proposed that the critical stress intensity for branching K_{Ib} can be expressed by:

$$K_{Ib} = nK_{Ic}$$

where K_{Ic} is the plane-strain fracture toughness and n depends on the distance ahead of the main crack that the advance crack must be generated. They considered that n should be equal to 2 or greater but should not increase to a very large value. Johnson and Holloway (2) suggested that branching occurred when the strain energy release rate was sufficient to create four, rather than two, new surfaces; in this case, n would equal $\sqrt{2}$.

Crack branching was observed during studies of the stress corrosion cracking characteristics of various high-strength steels (3,9,10), and the conditions for branching were determined. This paper summarizes these data, which indicate that the criteria for stress corrosion crack branching are constant velocity and a critical stress intensity.

MATERIALS AND TESTING

The following materials were used: 4330V, 1111, 9Ni-4Cr-0.45C (bainitic and martensitic), 4340 with various silicon contents, and 250, 300, 350 grades of maraging steel. Details of chemical composition, heat treatment, and mechanical properties have been given elsewhere (3,9,10).

The stress corrosion susceptibility was determined by deadweight loading fatigue-precracked, single-edge-notched specimens in either four-point or cantilever bending using the technique described by Brown (11). The corrosive environment was 3.5% aqueous sodium chloride solution. All the studies, except on 350 grade maraging steel, used a specimen 0.5 in. thick, 1.5 in. wide, and 7.5 in. long containing a combined notch and fatigue precrack approximately 0.3 in. deep. Standard 0.394-in.-square Charpy specimens were used to evaluate the 350 grade maraging steel.

The stress intensity was calculated from the relationships given by Srawley and Brown (12); in the case of cantilever loading, it was assumed that the conditions corresponded to three-point loading with a span-to-width ratio of 8. The results of the tests were plotted as the initial applied stress intensity level K_{Ii} versus time to failure, and the plane-strain* threshold stress intensity level K_{Iscc}, below which stress corrosion cracking did not occur, was determined.

In a number of these tests, the crack growth was monitored optically, using low-power magnification. From these observations, a curve of crack length versus time was constructed. (See example, Fig. 2.) The slope of the curve, which represents the instantaneous crack growth rate, was graphically determined for various crack length values; from this, the relation between stress intensity and crack velocity was determined. After failure, all specimens were macroscopically examined to determine the branching characteristics. The crack length at the onset of branching was measured and the corresponding stress intensity level determined as discussed above. The critical stress intensity $K_{I\delta}$ for the onset of rapid brittle fracture was determined by a similar procedure.

CRACK VELOCITY CHARACTERISTICS

Earlier studies on the kinetics of stress-corrosion cracking of two high-strength steels (H11 and 4340) indicated that the crack velocity was directly proportional to the applied stress intensity (13,14). This was also observed in studies on 350 grade maraging and on 4340 steels in certain heat-treatment conditions (Figs. 3a and 4a). However, in most of the steels studied, it was observed that the crack velocity was constant over a wide range of stress intensity (Figs. 5a and 6a); similar behavior has been reported by Mostovoy et al. (6). Our crack growth measurements and other evidence discussed later indicated that the range of constant velocity usually extended from $\sim K_{Iscc}$ to $\sim K_{Ic}$.
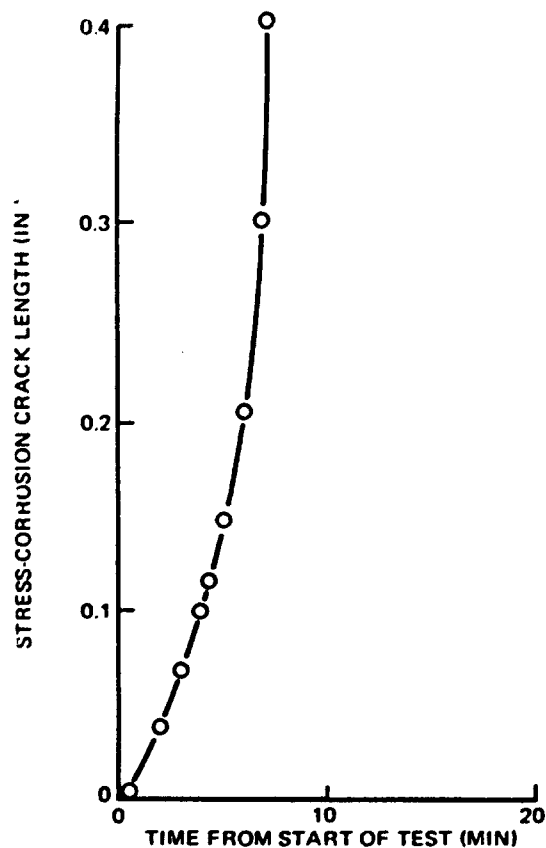

a. 4340 (0.09% Si) Q&T 400° F
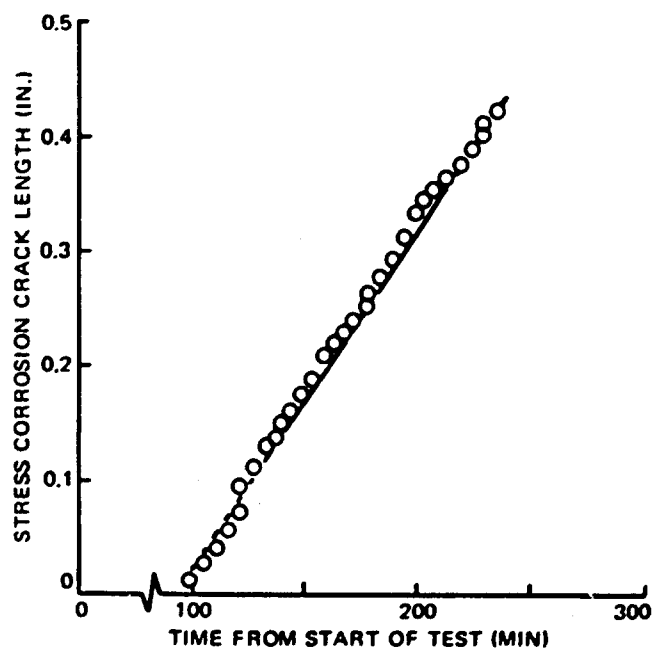
b. 4340 (0.54% Si) Q&T 750° F

Fig. 2.   Crack growth characteristics for two steels

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* The specimens were sufficiently thick that plane-strain conditions existed (12)

3

Stress corrosion curves of K_{Ii} versus time to failure also appear to reflect the crack growth kinetics. When crack velocity is proportional to stress intensity (Figs. 3a and 4a), time to failure shows a pronounced dependence on initial stress intensity K_{Ii} (Figs. 3b and 4b). On the other hand, the time to failure is only slightly dependent on K_{Ii} when the crack velocity is constant (Figs. 5 and 6); some dependence is to be expected because the critical crack length to cause terminal mechanical fracture depends on the applied bending moment and, hence, K_{Ii}. This correspondence has been observed in a number of steels despite the fact that stress corrosion crack initiation is often preceded by an incubation period, which might be expected to have a masking effect. Therefore, in the absence of crack velocity data for an alloy, it appears possible to qualitatively predict the kinetics from the form of the curve of K_{Ii} versus time to failure.
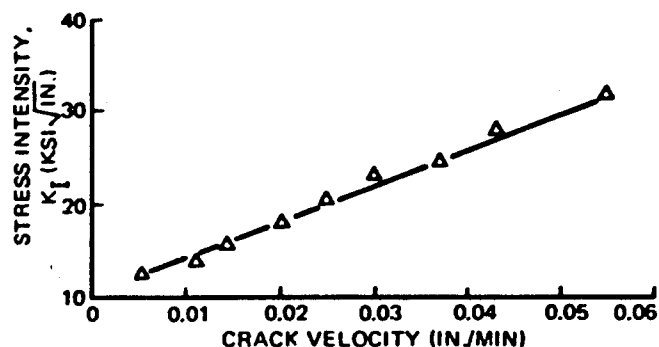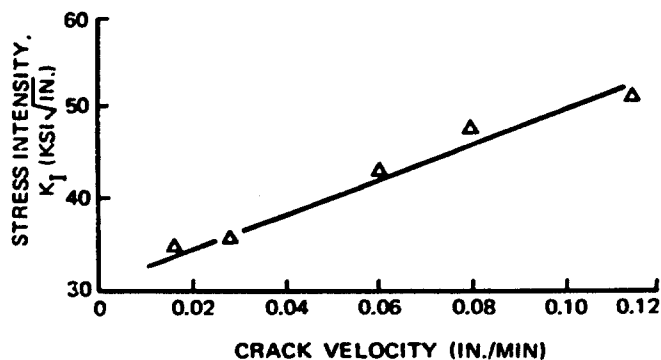

a. Velocity curve
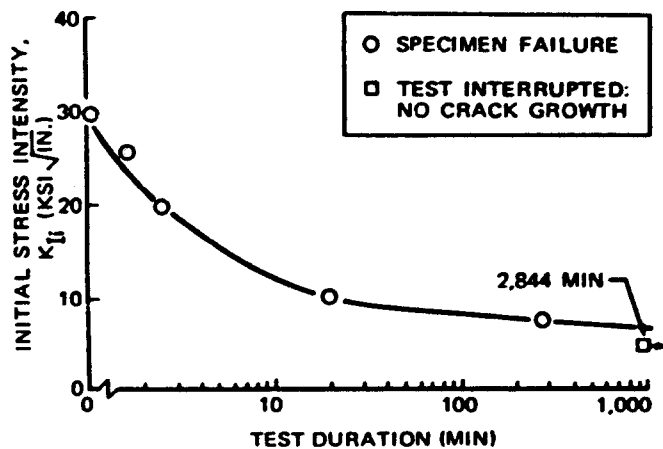
b. Stress corrosion curve

Fig. 3. Comparison of stress corrosion and crack velocity curves for 350 grade maraging steel aged 8 hr at 800°F.

a. Velocity curve

b. Stress corrosion curve

Fig. 4. Comparison of stress corrosion and crack velocity curves for 4340 steel (1.08% Si), Q&T 500°F.

CRACK BRANCHING

Crack morphology in the alloys 300 grade maraging, 9Ni-4Co-0.45C (bainitic), 9Ni-4Co-0.30C, and 4330V was observed to be dependent on the value of K_{Ii} (Fig. 7). Branch cracks, when they occurred, extended from the tip of the fatigue precrack. Otherwise the stress corrosion crack extended to critical length along the fatigue crack plane with little evidence of branching (3). From the data in Fig. 7, it was possible to "bracket" the stress intensity level required to cause branching (Table I).

a. Velocity curve

b. Stress corrosion curve

Fig. 5. Comparison of stress corrosion and crack velocity curves for 4340 steel (1.08% Si), Q&T 800°F.
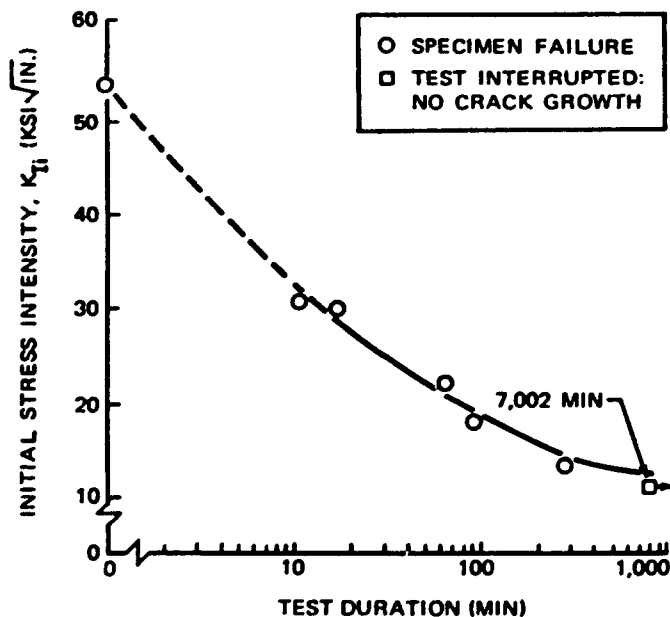

a. Velocity curve

b. Stress corrosion curve

Fig. 6. Comparison of stress corrosion and crack velocity curves for 300 grade maraging steel aged 6 hr at 900°F.
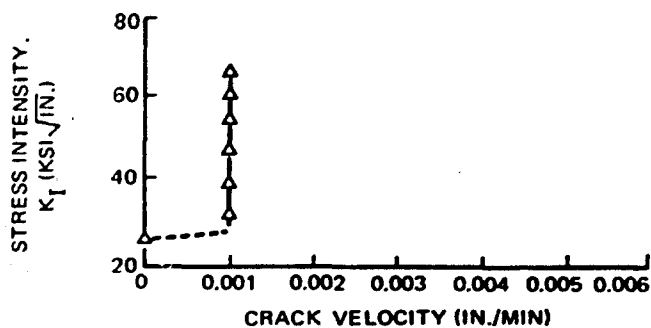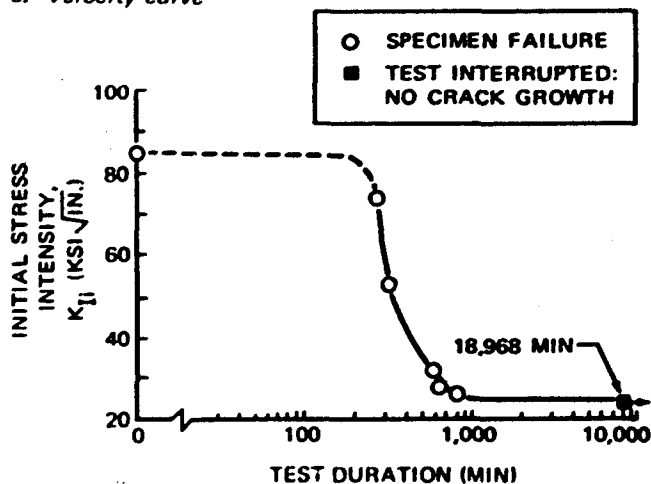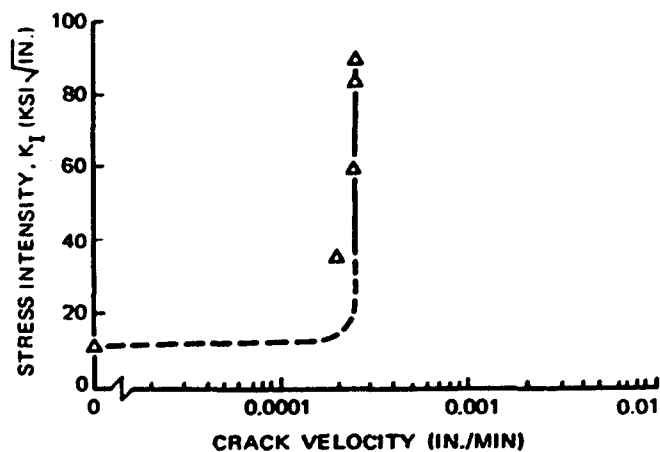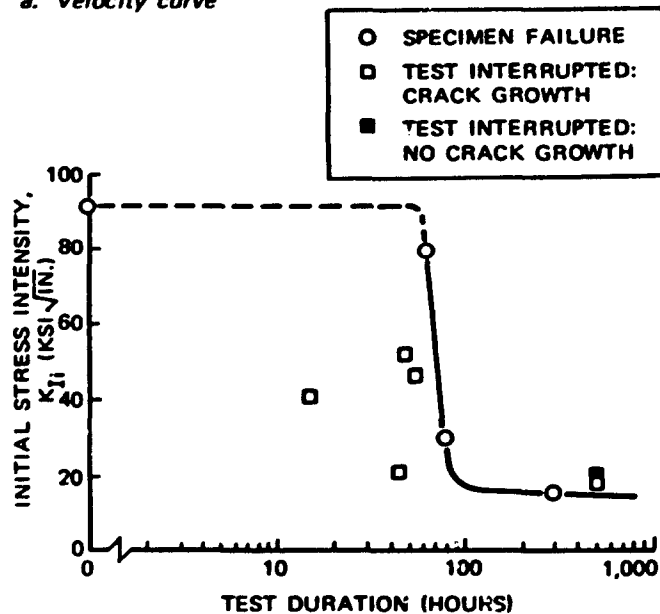
Somewhat different behavior was noted in 9Ni-4Co-0.45C (martensitic), 350 grade maraging, and 4340 with various levels of silicon. Either branching occurred from the tip of the fatigue precrack or, depending on K_{Ii}, the stress corrosion crack extended along the fatigue crack plane and subsequently branched. The crack length at which branching first occurred could be measured, and hence a direct estimate obtained of the stress intensity required for branching. These values, obtained from specimens loaded to various stress intensity levels (Table II), are essentially constant for a given alloy and heat treatment, indicating that a critical stress intensity K_{Ib} is required for branching. Tables I and II clearly show that branching is invariably associated with constant velocity. Moreover, K_{Ib} is much higher than the stress intensity level (approximately K_{Iscc}) required to establish a constant velocity.

The analysis of Anthony and Congleton (8) can be extended to stress corrosion cracking by determining the conditions required to propagate an advance crack by stress corrosion instead of mechanical fracture. This leads to:

$$K_{Ib} = nK_{Iscc}$$

where n is limited to the values discussed earlier and has a value of approximately 2 for small plastic zones. Tables I and II show that K_{Ib}/K_{Iscc} ratios range from 2 to 4 for all the steels

examined. Furthermore, the plastic zone size can be estimated (16) as $1/3\,\pi(K_I/Y)^2$; the yield strength Y and K_{Iscc} levels of these steels are such that this zone is small when branching occurs. Therefore, the results are in excellent agreement with the criteria suggested by Anthony and Congleton (8).
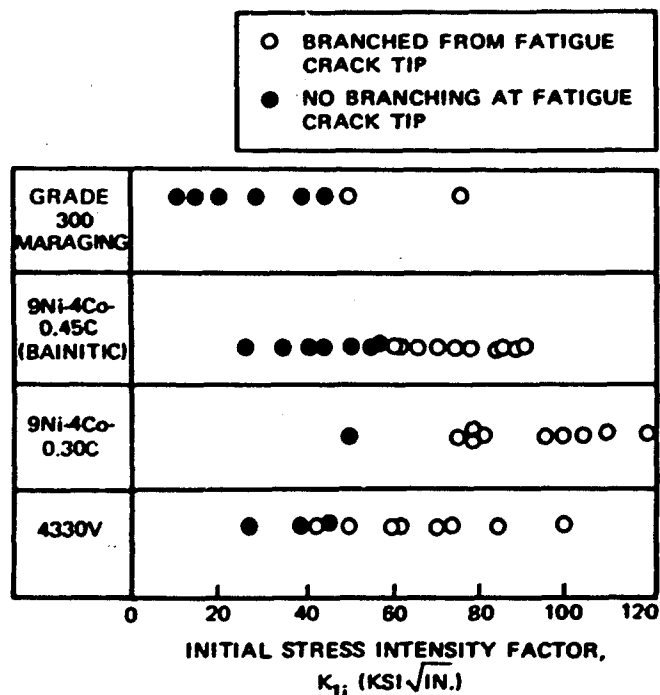
O	BRANCHED FROM FATIGUE CRACK TIP	
●	NO BRANCHING AT FATIGUE CRACK TIP	

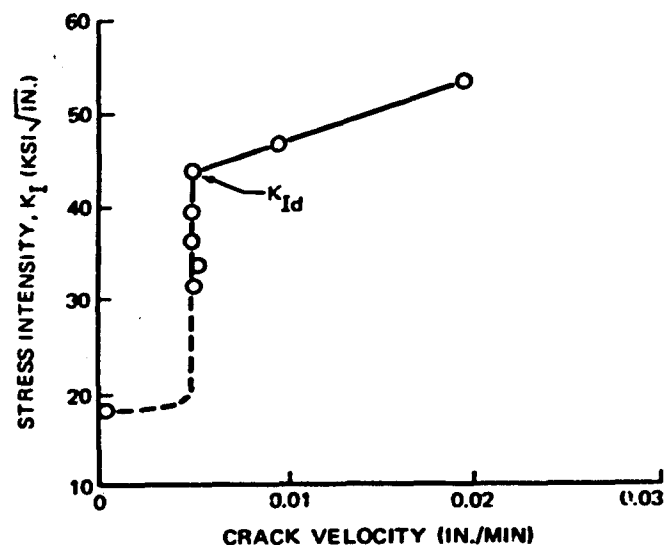Fig. 7. Influence of K_{Ii} on crack morphology.

Fig. 8. Crack velocity curve for 4340 steel (2.15% Si), Q&T 925°F.

This model necessarily assumes that the aggressive environment responsible for stress corrosion crack extension has access to the advance crack. The mechanism of environmental cracking in high-strength steels can be attributed either to stress corrosion along active paths or to hydrogen embrittlement. If this model is correct, hydrogen embrittlement (by diffusion of hydrogen to the advance crack sites) must be the explanation. Also, these cracks would be expected to initiate in regions of dislocation movement, i.e. the crack-tip plastic zone; that branching is in fact associated with these regions was suggested by an earlier study of crack morphology (3).

An additional observation made in these studies was that specimens loaded to K_{Ii} levels approaching K_{Ic} exhibited branching from the fatigue precrack: for example, 9Ni-4Co-0.45C (bainitic), 9Ni-4Co-0.30C, 300 grade maraging, and 4330V steels loaded to K_{Ii}/K_{Ic} ratios of 0.98, 0.94, 0.88, and 0.80, respectively. This confirms that crack velocity in these particular steels was constant at stress intensity levels approaching K_{Ic}.

ABSENCE OF CRACK BRANCHING

In certain heat-treatment conditions, some of the steels examined did not show crack branching. Table III shows that branching did not occur when the crack growth rate was directly proportional to stress intensity. This further substantiates that a constant velocity is a requirement for branching.

Note in Table III that two steels, 250 grade maraging and 4340 (2.15% silicon) did not exhibit branching despite the fact that the crack velocity was constant. This can be explained as follows: The K_{Iscc} and K_{Ic} for the maraging steel were 45 $ksi\sqrt{in.}$ and 92 $ksi\sqrt{in.}$, respectively; therefore, it was not possible for the stress intensity at the tip of the extending stress corrosion crack to reach the critical level for branching (> 2 K_{Iscc}) before the onset of rapid brittle fracture at K_{Ic}. The stress corrosion characteristics of a number of steels in the yield strength range from 150 to 200 ksi have been

recently reported (17,18). These steels have much higher K_{Iscc}/K_{Ic} ratios than those discussed in this paper, with some ratios almost equal to unity. Branching would not be anticipated in these steels and, indeed, none has been observed. In some materials, it is possible for the crack velocity to change from a constant rate to a K dependency with increasing stress intensity (Fig. 8). If the stress intensity where this change occurs is denoted as K_{Id}, branching will not occur when $2K_{Iscc} > K_{Id}$ because the stress intensity and constant velocity requirements are not simultaneously fulfilled. It is considered that the 4340 (2.15% silicon) did not branch for this reason because as shown in Fig. 8, $2K_{Iscc} \approx K_{Id}$.

TERMINAL FRACTURE

The conditions required for terminal fracture of the specimen by the onset of rapid brittle fracture were discussed previously (3). However, they are briefly reconsidered here to illustrate the effect of crack branching. The values of critical stress intensity $K_{I\delta}$ required to cause terminal fracture of branched specimens are shown in Table IV. These indicate that $K_{I\delta}$ is approximately equal to twice K_{Ic}. This can be attributed to a significant reduction (~ 2) in the stress intensity at each branch crack tip as compared to a single crack under similar loading conditions.

INFLUENCE OF EXPERIMENTAL VARIABLES IN CRACK MORPHOLOGY

Relatively minor changes in the heat treatment of certain steels can significantly influence stress corrosion crack growth kinetics and hence crack morphology. For example, increasing the aging temperature of 350 grade maraging steel from 800° to 900°F changed the crack velocity from a K dependency to a constant rate. The mechanisms responsible for these changes are not apparent, but it does appear that the crack velocity is directly proportional to stress intensity when the alloy is in the most stress corrosion susceptible condition. Similarly, it is conceivable that the morphology may be significantly influenced by changes in the pH, temperature, or composition of the environment or by impressed potentials.

CONCLUSIONS

1. There are two requirements for stress corrosion crack branching: a constant crack velocity and a critical stress intensity K_{Ib}.

2. K_{Ib} equals two to four times K_{Iscc} for several high-strength steels; this is in excellent agreement with the branching criteria proposed by Anthony and Congleton. An implication of this observation is that, when the K_{Iscc}/K_{Ic} ratio exceeds 0.5, rapid brittle fracture will occur before K_{Ib} can be reached. This may explain the absence of stress corrosion crack branching in steels with high K_{Iscc}/K_{Ic} values.

Table I. Conditions for branching at tip of fatigue precrack.

Alloy	Heat treatment	Yield strength (ksi)	K_{Ic} (ksi $\sqrt{in.}$)	K_{Iscc} (ksi $\sqrt{in.}$)	Bracketed transition (from Fig. 7), K_{Ib} (ksi $\sqrt{in.}$)	K_{Ib}/K_{Iscc}	Crack velocity characteristics[a]
300 grade maraging	Aged 6 hr at 900°F	289	89	12	45.0-50.8	3.8-4.2	Constant[b] (Fig. 5)
9Ni-4Co-0.45C	475° F baintic treatment	220	89	20	58.0-62.4	2.9-3.1	Constant (refs.3, 15)
9Ni-4Co-0.30C	Q&T 950°F	200	116	35[c]	50.6-75.4	1.5-2.1	Constant (ref. 3)
4330V	Q&T 500°F	196	103	25	43.9-49.9	1.8-2.0	Constant (ref. 3)

a   Assumed from shape of K_{Ii} vs. time-to-failure curve, except where noted.
b   Determined by measurement.
c   Uncertain value.

Table II. Conditions for branching of stress corrosion crack.

Alloy	Heat treatment	Yield strength (ksi)	K_{Ic} (ksi $\sqrt{in.}$)	K_{Iscc} (ksi $\sqrt{in.}$)	K_{Ii} (ksi $\sqrt{in.}$)	K_{Ib} (ksi $\sqrt{in.}$)	K_{Ib}/K_{Iscc} (mean)	Crack velocity characteristics[a]
4340 (0.54% or 1.08% Si)	Q&T 750°/800°F	230	83	24	24.7 26.1 31.5	52.8 58.2 58.2 ‾‾‾‾ 56.4 (mean)	2.4	Constant (ref.9)
9Ni-4Co-0.45C (martensitic)	Q&T 500°F	236	69	15	33.8 45.0 47.0 51.5	49.0 53.0 47.0 67.0 ‾‾‾‾ 55.4 (mean)	3.6	Constant[b] (ref. 3)
350 grade maraging	Aged 8 hr at 900°F	335	36	10	12.5 15.3 20.5	25.6 22.7 31.2 ‾‾‾‾ 26.6 (mean)	2.7	Constant (ref. 10)
350 grade maraging	Aged 3 hr at 950°F	330	42	10	10.3 12.5 15.5 20.0	22.1 19.7 33.5 21.0 ‾‾‾‾ 24.1 (mean)	2.4	Constant (ref. 10)

a   Determined by measurement except where noted.
b   Assumed from shape of K_{Ii} vs. time-to-failure curve.

Table III. Summary of steels that did not exhibit branching.

Alloy	Heat treatment	Yield strength (ksi)	K_{Ic} (ksi $\sqrt{in}$.)	K_{Iscc} (ksi $\sqrt{in}$.)	Crack velocity characteristics[a]
4340 (0.05% Si)	Q&T 400°F	201.8	74.2	14	Directly proportional to K (ref. 9)
4340 (0.54% Si)	Q&T 400°F	216.5	55.0	13	Directly proportional to K (ref. 9)
4340 (1.08% Si)	Q&T 500°F	240.0	53.8	13	Directly proportional to K (Fig. 4)
4340 (1.58% Si)	Q&T 500°F	236.7	55.2	16	Directly proportional to K (ref. 9)
4340 (2.15% Si)	Q&T 500°F	240.7	51.9	16	Directly proportional to K (ref. 9)
H11	Q&T 1100°F	188.0	54	30	Directly proportional to K[b] (ref. 3)
350 grade maraging	Aged 8 hr at 800°F	299.0	30	5	Directly proportional to K (Fig. 3)
250 grade maraging	Aged 3 hr at 900°F	249.0	92	45	Constant[b] (ref. 3)
4340 (2.15% Si)	Q&T 925°F	215.8	51.9	18	Constant[c] (Fig. 8)

[a] Determined by measurement except where noted.

[b] Assumed from shape of K_{Ii} vs. time-to-failure curve.

[c] Crack velocity directly proportional to K when stress intensity exceeded 44 ksi $\sqrt{in}$.

Table IV. Comparative $K_{I\delta}$ and K_{Ic} values.

Alloy	Heat	Yield strength (ksi)	K_{Ic} (ksi $\sqrt{in}$.)	K_{Ii} (ksi $\sqrt{in}$.)	$K_{I\delta}$ (ksi $\sqrt{in}$.)	$K_{I\delta}/K_{Ic}$
9Ni-4Co-0.45C (martensitic)	A	237	76.4	62.1	144	1.89
				61.1	134	1.76
				57.3	173	2.26
				45.0	113	1.48
	B	233	66.0	55.7	91	1.37
				51.5	152	2.30
				45.0	128	1.94
	C	237	58.8	47.0	109	1.64
				40.4	92	1.38
300 grade maraging		289	89.3	78.3	170	1.91

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13. ABSTRACT

The criteria for stress corrosion crack branching in high-strength steels are shown to be (1) a constant crack velocity and (2) attainment of a critical stress intensity K_{Ib}. For the steels investigated, values of K_{Ib}/K_{Iscc} range from 2 to 4. This indicates that when K_{Iscc}/K_{Ic} exceeds 0.5, rapid brittle fracture will occur before K_{Ib} can be reached.

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Crack morphology						
Fracture mechanics						
Crack velocity						