Lecture 7

Environmentally-assisted Cracking & Corrosion Fatigue

Environmentally-assisted Cracking (Stress corrosion cracking)

1. The application of stress and an aggressive environment may cause stable crack growth

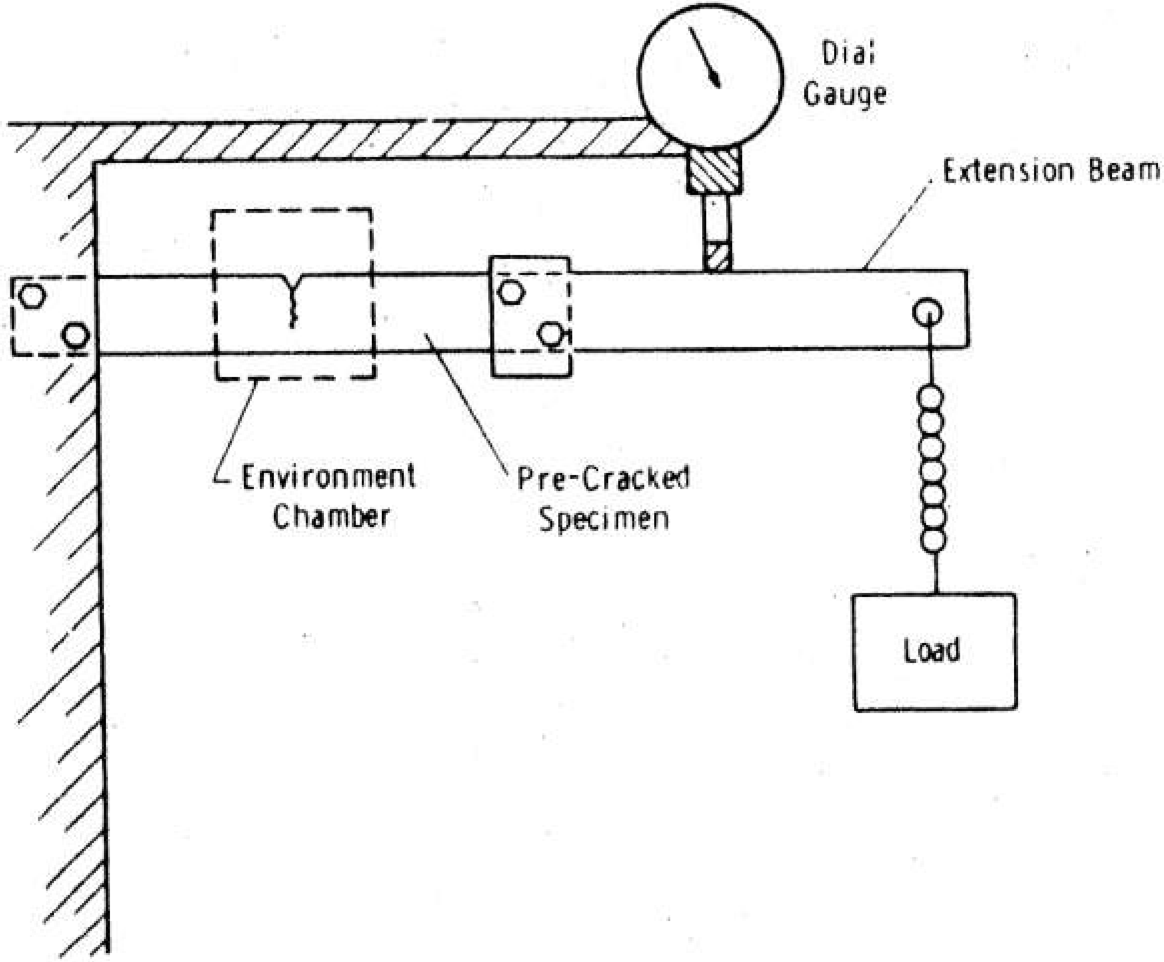
2. The usual approach is to look for a threshold value of K below which the crack does not grow, K_{Iscc} (or K_{IEAC})

3. The aggressive environment also influences the da/dN vs ΔK fatigue crack growth

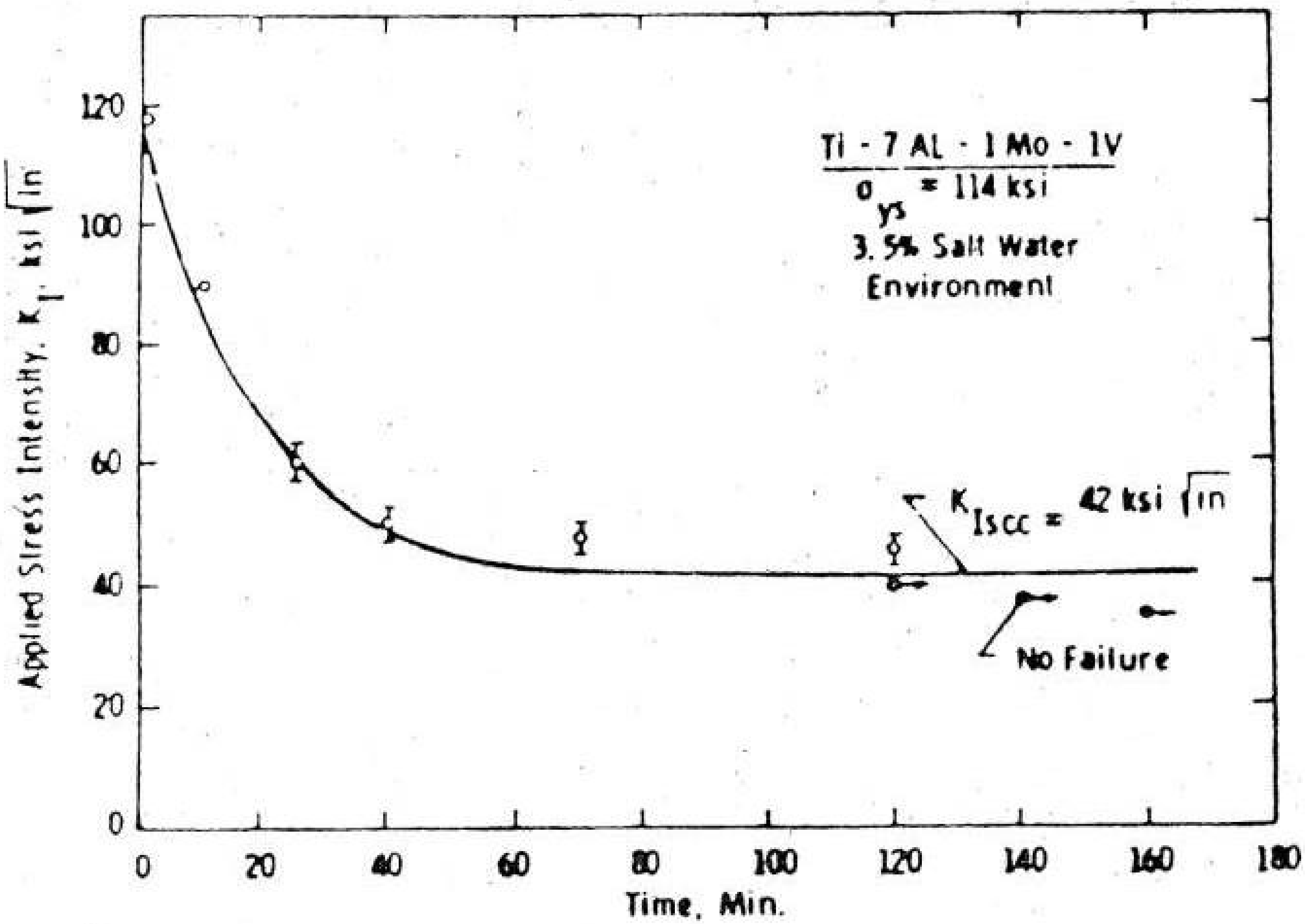
Influence on Environment on Time To Failure of 300 M* Steel

ENVIRONMENT	TIME TO FAILURE, MIN.
Recording Ink.	0.5
Distilled Water	6.5
Butyl Acetate	18.0
Butyl Alcohol	28.0
Amyl Alcohol	35.8
Acetone	120
Lubricating Oil	150
Benzene	2247
Carbon Tetrachloride	No failure in 1280
Air	No failure in 6000

*245 ksi yield strength low-alloy martensitic steel. M(T), CCT specimen with 75 ksi nominal stress applied.



Cantilever beam corrosion apparatus



- *Stress corrosion cracking behavior of Ti - 7 - 1 - 1 in salt water.*

Designation: E 1681 – 95[ε1]

Standard Test Method for Determining a Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials Under Constant Load[1]

This standard is issued under the fixed designation E 1681; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ϵ^1 Note—Section 9.1.1 was editorially corrected in May 1999.

1. Scope

1.1 This test method covers the determination of the environment-assisted cracking threshold stress intensity factor parameters, K_{IEAC} and K_{EAC}, for metallic materials from constant-load testing of fatigue precracked beam or compact fracture specimens.

1.2 This test method is applicable to environment-assisted cracking in aqueous or other aggressive environments.

1.3 Materials that can be tested by this test method are not limited by thickness or by strength as long as specimens are of sufficient thickness and planar size to meet the size requirements of this test method.

1.4 A range of specimen sizes with proportional planar dimensions is provided, but size may be variable and adjusted for yield strength and applied load. Specimen thickness is a variable independent of planar size.

1.5 Specimen configurations other than those contained in this test method may be used, provided that well-established stress intensity calibrations are available and that specimen dimensions are of sufficient size to meet the size requirements of this test method during testing.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 1141 Specifications for Substitute Ocean Water[2]
E 4 Practices for Force Verification of Testing Machines[3]
E 8 Test Methods of Tension Testing of Metallic Materials[3]
E 399 Test Method for Plane-Strain Fracture Toughness of Metallic Materials[3]
E 616 Terminology Relating to Fracture Testing[3]
E 647 Test Method for Measurement of Fatigue Crack Growth Rates[3]
G 1 Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens[4]
G 3 Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing[4]
G 5 Reference Test Method for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements[4]
G 15 Terminology Relating to Corrosion and Corrosion Testing[4]

3. Terminology

3.1 Terminology related to fracture testing given in Terminology E 616 and terms related to corrosion testing given in Terminology G 15 are applicable to this test method.

3.2 *Definitions:*

3.2.1 *crack-mouth-opening displacement (CMOD), $2v_m$[L]*—the Mode I (also called opening mode) component of crack displacement due to elastic and plastic deformation, measured at the location on a crack surface that has the greatest elastic displacement per unit load.

3.2.2 *original crack size, a_0[L]*—the physical crack size at the start of testing.

3.2.3 *original uncracked ligament, b_0[L]*—distance from the original crack front to the back edge of the specimen ($b_0 = W - a_0$).

3.2.4 *physical crack size, a_p[L]*—the distance from a reference plane to the observed crack front. This distance may represent an average of several measurements along the crack front. The reference plane depends on the specimen form, and it is normally taken to be either the boundary, or a plane containing either the loadline or the centerline of a specimen or plate. The reference plane is defined prior to specimen deformation.

3.2.5 *specimen thickness, B[L]*—the side-to-side dimension of the specimen being tested.

3.2.6 *stress-corrosion cracking, SCC*—a cracking process that requires the simultaneous action of a corrodent and sustained tensile stress.

[1] This test method is under the jurisdiction of ASTM Committee E-8 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.06 Crack Growth Behavior.

Current edition approved Feb. 15, 1995. Published April 1995.

[2] *Annual Book of ASTM Standards*, Vol. 11.02.

[3] *Annual Book of ASTM Standards*, Vol 03.01.

[4] *Annual Book of ASTM Standards*, Vol 03.02.

Latest EAC Standard

- **ASTM E1681 - 03(2008) Standard Test Method for Determining a Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials**

Standard E 1681 on Threshold Stress Intensity Factor for Environmentally Assisted Cracking, K_{EAC}

1. Measures K_{EAC} or K_{IEAC}, K_{Iscc}

2. Cantilevered bend or C(T) specimens, precracked

3. Constant load or step load, or other

4. Test times:

Steel, $\sigma_{ys} < 1200$ MPa	10,000 hr
Steel, $\sigma_{ys} > 1200$ MPa	5000 hr
Al alloys	10,000 hr
Ti alloys	1000 hr

5. If E 399 requirements are met, then K_{IEAC}

Bolt load Test

1. Load a specimen with a bolt turned against a split pin, see Fig.

2. Measure the initial displacement, v_o

3. Put self loaded specimen in environment, test as long as desired (no test machine is needed)

4. At end of test, measure

   - unloading v
   - Final crack length

5. Use the calibrations, $\lambda = BEv/P$, $K = Pf/B\sqrt{W}$ to get K_o and $K_f = K_{Iscc}$

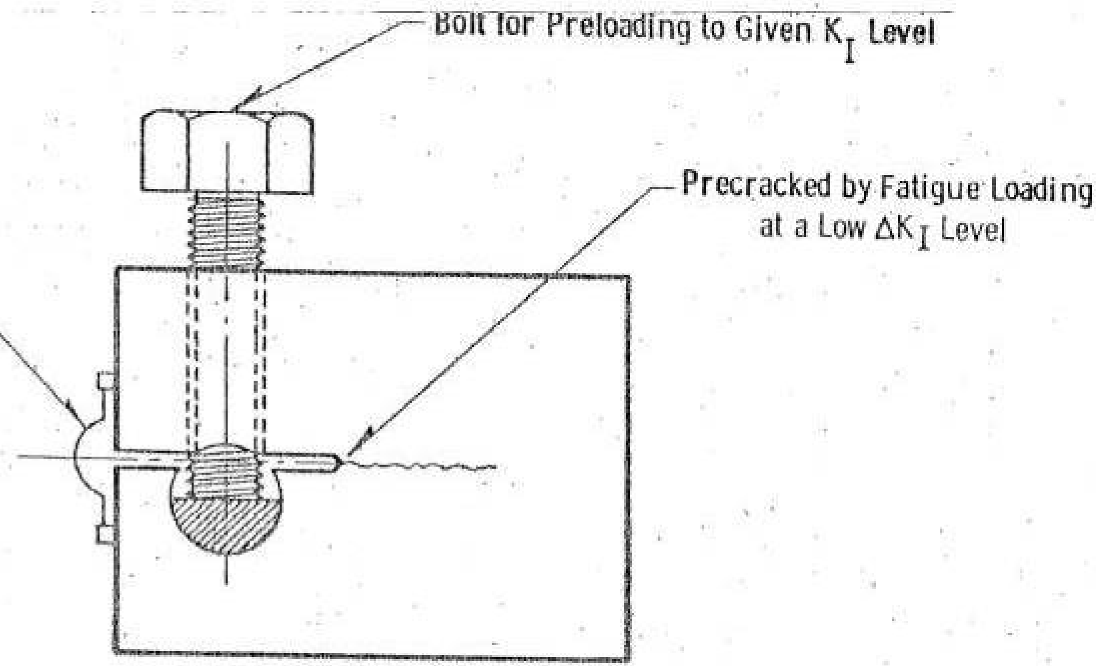


Fig. 10--WOL specimen modified for use as a stress corrosion susceptibility test specimen

Bolt load Calculation - N

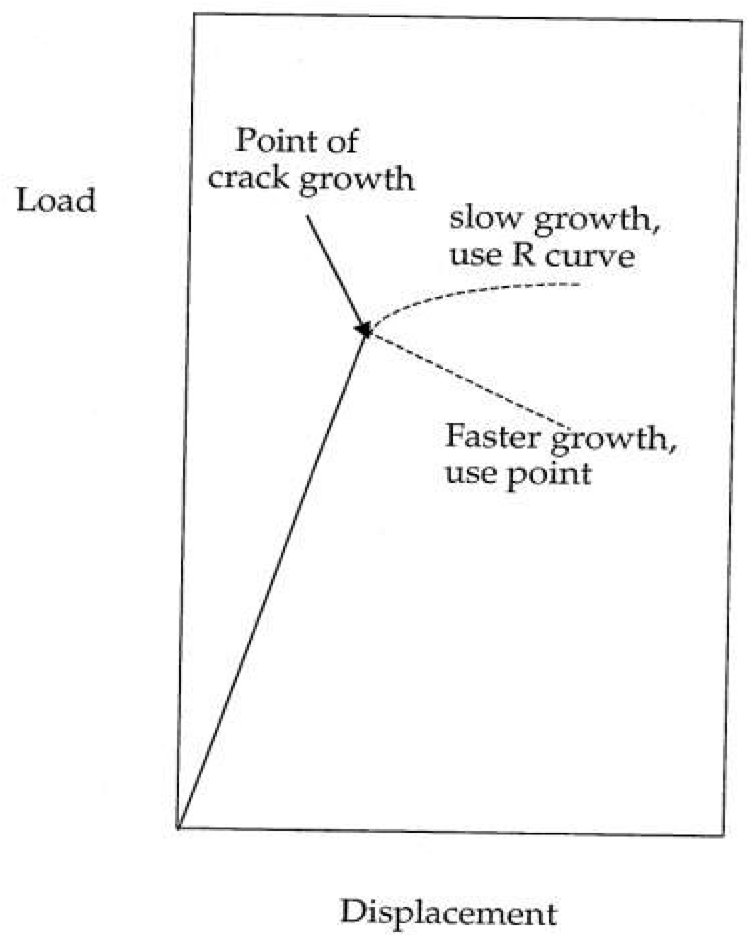
- Given: CT loaded to disp. = 0.010 in. with W = 2 in, B = 1 and a_o = 0.8, E = 30,000 ksi
- a/W = 0.4, f = 7.28, BEv/P = 22.88
- P = (1.0)(30,000)(0.01)/22.88 = 13.16 kips
- $K_o = (13.16)(7.28)/1*2^{1/2} = 67.73$ ksi-in$^{1/2}$

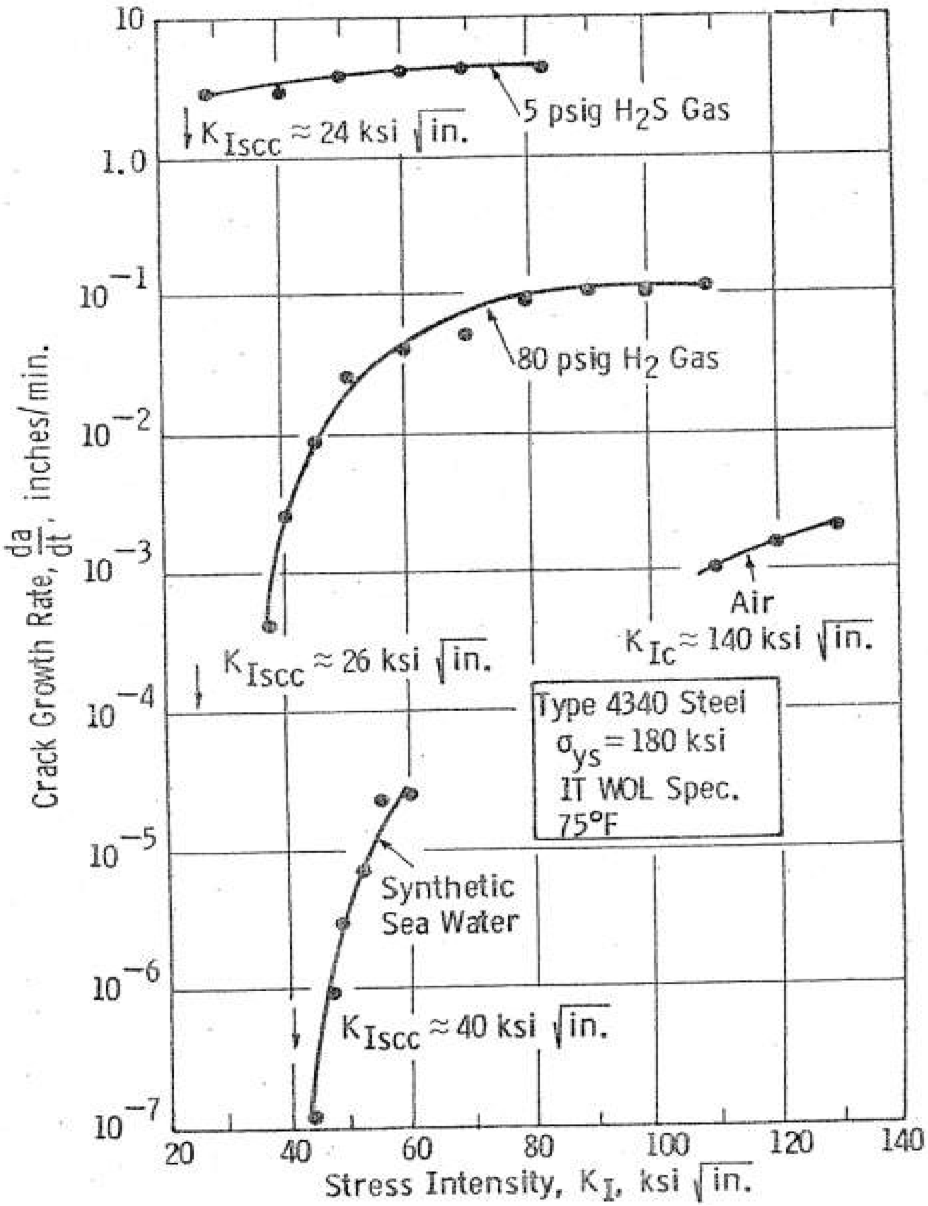
Bolt load calc, cont. - N

- Final state, a_f = 1.5 in
- a/W = 0.75, f = 28.86, BEv/P = 185.36
- Assume $v_f = v_o$ = 0.01in
- P_f = (1)(30,000)(0.01)/185.36 = 1.168
- $K_f = 1.168*28.86/1*2^{1/2}$ = = 33.0 ksi-in$^{1/2}$

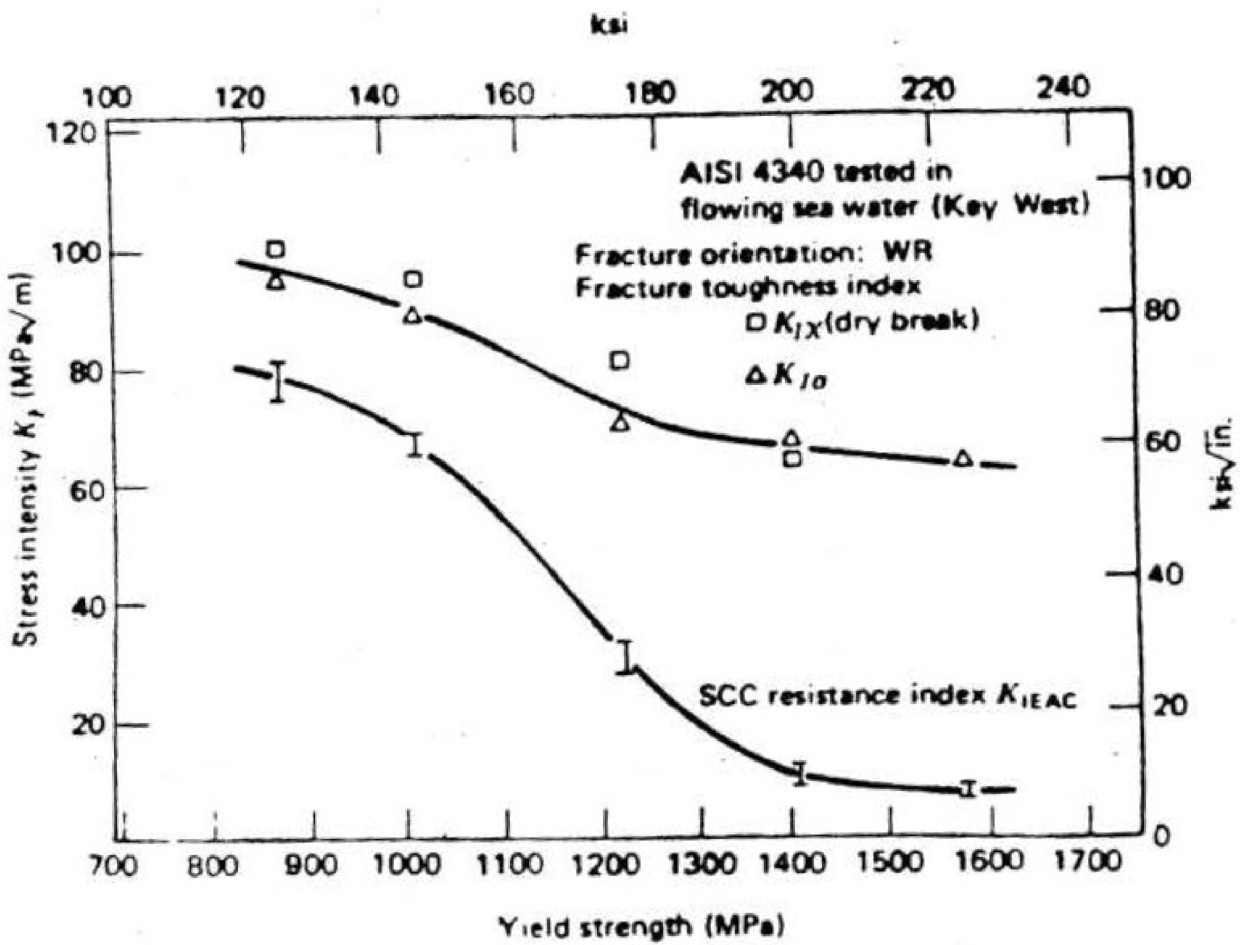
Rising load test

1. Slowly loaded rising load to determine point of crack growth in environment, calculate K at growth point





—Effect of environment on static load crack growth rate (180 ksi yield strength 4340 steel)



- *Effect of yield strength on* K_{Ic} *and* K_{IEAC} *(in water) in 4340 steel.*

Effect of $H_2 + O_2$

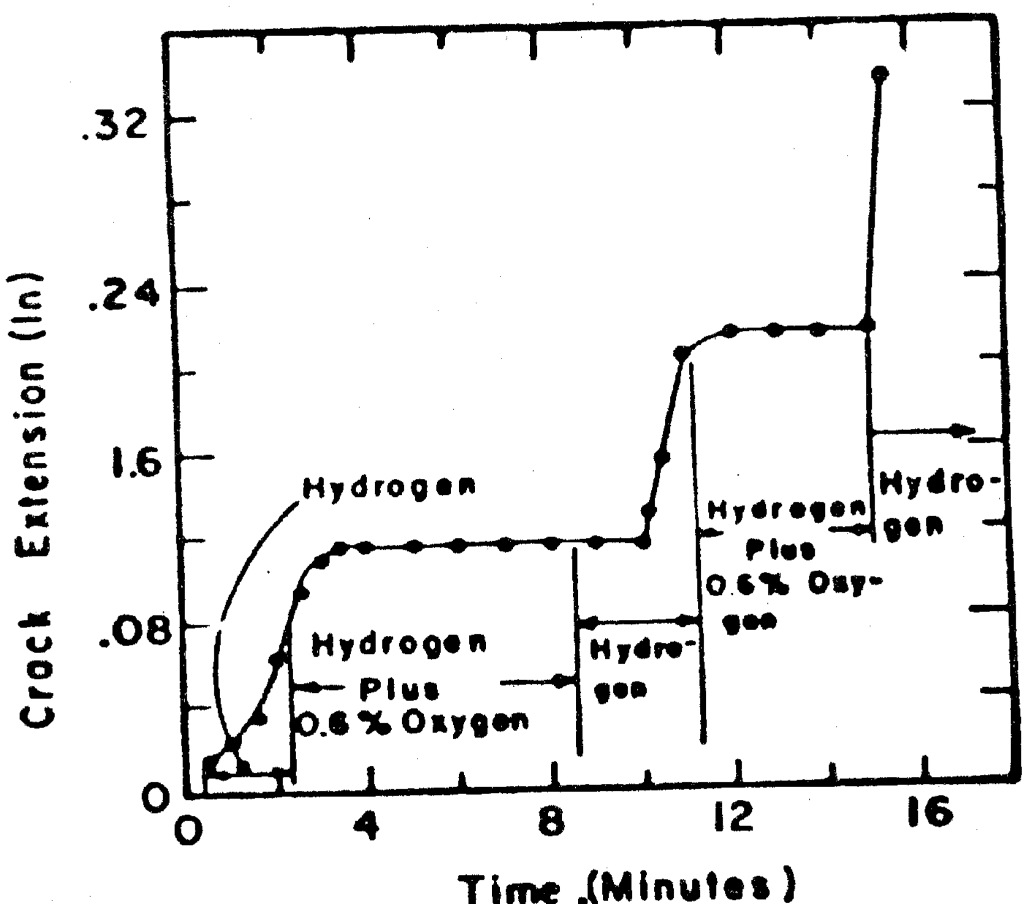


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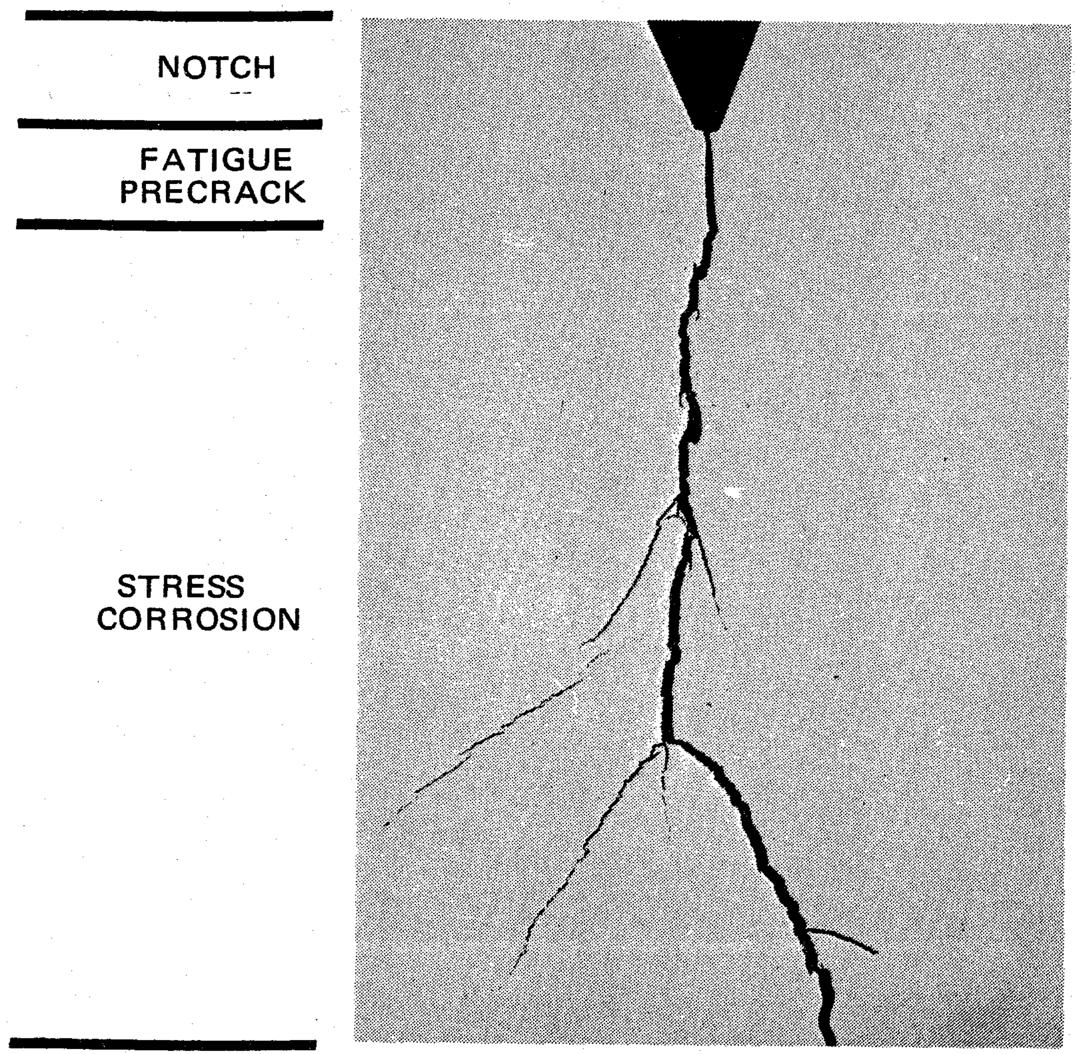
Fig. - Hydrogen-oxygen mixtures and subcritical crack growth, d-11 steel, 230 ksi yield.

Crack branching under EAC



Stress corrosion crack branching in 9Ni–4Co–0·45C (martensitic) steel.

Example of Damage Tolerant HB Data - N

TABLE 3.0.5

STRESS CORROSION CRACKING THRESHOLD DATA FOR STEEL ALLOYS AT ROOM TEMPERATURE

ALLOY	CONDITION/HT	PRODUCT FORM	SPECIMEN ORIENTATION	K_{Iscc} $(Ksi\sqrt{in.})$				
				ENVIRONMENTS				
				SIMULATED SEA WATER	SEA WATER	DISTILLED WATER	3.5 % NACL	SUMP TANK WATER
D6AC	1550F AQ 650F 4HR	Sheet	L-T			7.0		
	1550F AQ 950F 4HR	Sheet	L-T			45.2		
HP9-4-.20	GTA Weld	Plate	---	65.0				
	Quenched and Tempered	Plate	---				110.0(2)	
	1525F 2HR OQ -100F 2HR 1025F 4HR	Plate	L-T					105.0(3)
			T-L					97.4(5)
		Forged Bar	L-T					110.0
			T-L					107.0(2)
			S-T					78.3(3)
HP9-4-.45	475F	Plate	---				20.0	
H-11	Quenched and Tempered at 1100F	Plate	---				30.0	
12Ni-5Cr-3Mo	Electric Furnace	Plate	---	40.0				
	GTA Welded	Weldment	---	33.0				
	Low Residual	Plate	---	108.0				
	1550F, 900F 20HR AC	Plate	L-S				80.0	
			T-S				70.0	

Data from Hertzberg

TABLE 11.2 Selected K_{IEAC} Data[47]

Metal	Environment	Test Orientation	Yield Strength MPa	Yield Strength ksi	K_{IC} or $(K_{IX})^a$ MPa$\sqrt{m}$	K_{IC} or $(K_{IX})^a$ ksi$\sqrt{in.}$	K_{IEAC} MPa$\sqrt{m}$	K_{IEAC} ksi$\sqrt{in.}$	Test Time, Hours
Aluminum Alloys									
2014-T6	Synth. seawater	S-L	420	61	21	19	18	16	—
2014-T6	NaCl solution	S-L	—	—	—	—	≈8	≈7	≈10,000[b]
2024-T351	3 1/2% NaCl	S-L	325	47	(55)	(50)	11	10	—
2024-T351	NaCl solution	S-L	—	—	—	—	≈9	≈8	≈10,000[b]
2024-T852	Seawater	S-L	370	54	19	17.6	15	14	—
2024-T852	NaCl solution	S-L	—	—	—	—	≈17	≈15	≈10,000[b]
2024-T851	Dist. water	L-T	410	59	21	18.6	24	22	—
7075-T6	3 1/2% NaCl	S-L	505	73	25	23	21	19	—
7075-T6	NaCl solution	S-L	—	—	—	—	≈8	≈7	≈10,000[b]
7075-T7351	3 1/2% NaCl	S-L	360	52	26	24	23	21	—
7075-T7351	NaCl solution	S-L	—	—	—	—	≲22	≲20	≈10,000[b]
7075-T7351	3 1/2% NaCl	T-L	365	53	32	29	26	24	—
7175-T66	3 1/2% NaCl	—	525	76	32	29	≲6.6	≲6	—
7175-T66	NaCl solution	S-L	—	—	—	—	7	6	≈10,000[b]
7175-T736	NaCl solution	—	455	66	27	25	21	19	>1029
Steel Alloys									
18 Ni(300)-maraging	″	T-L	1960	284	80	72	8	7.5	>150
4340	″	T-S	1335	194	79	72	9	8.5	>333
4340	″	L-T	1690	245	56	51	17	15	>58
4340	Seawater	T-L	1550	225	(69)	(63)	6	5	>20
″	″	″	1380	200	(65)	(59)	11	10	—
″	″	″	1205	175	(83)	(75)	30	27	—
″	″	″	1035	150	(94)	(85)	65	59	—
″	″	″	860	125	(98)	(89)	77	70	—
300M	3.5% NaCl	L-S	1735	252	70	64	22	20	—
″	″	T-L	1725	250	61	56	20	18	—

Corrosion Fatigue

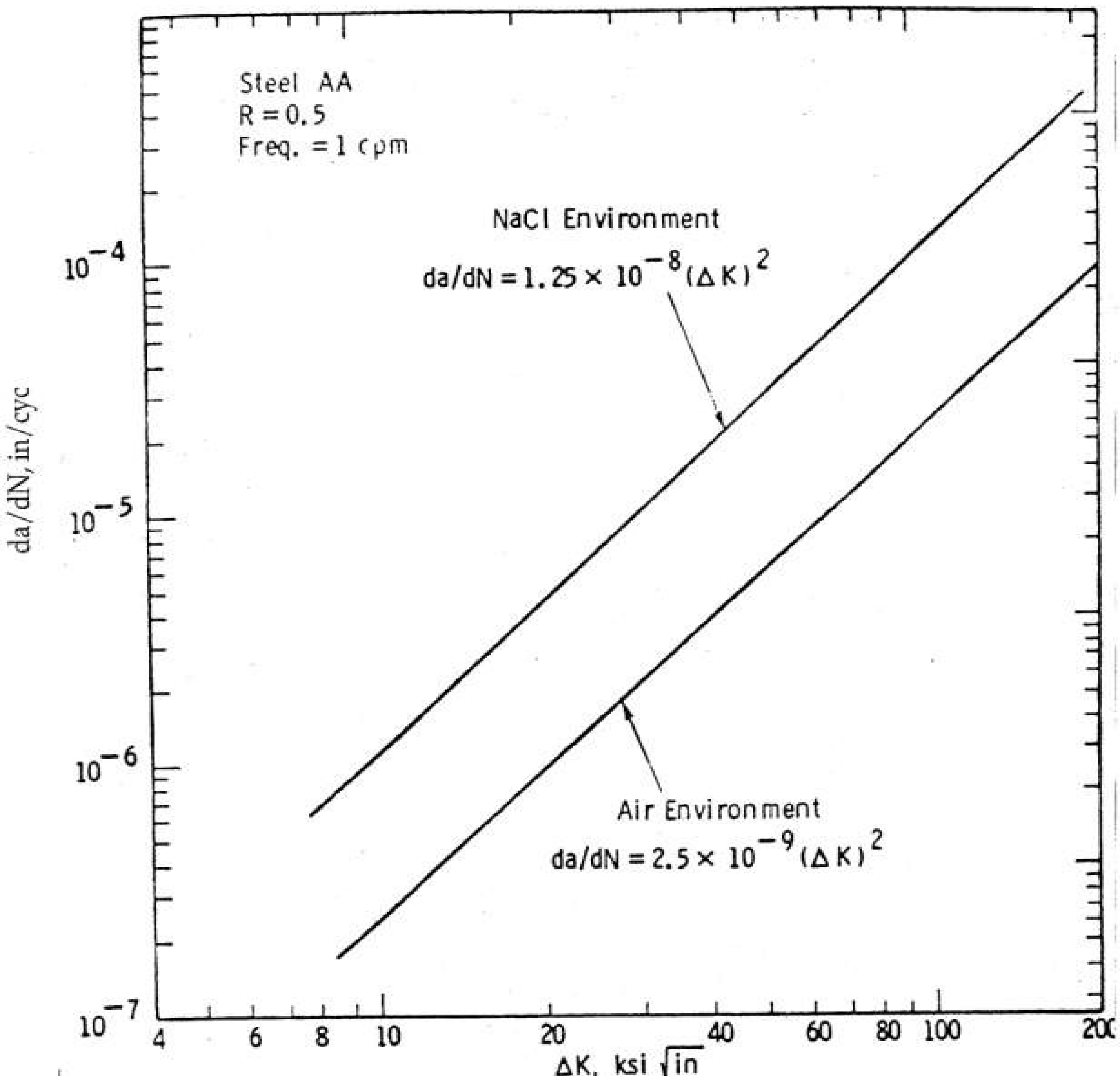
1. The combination of fatigue loading and an aggressive causes corrosion fatigue

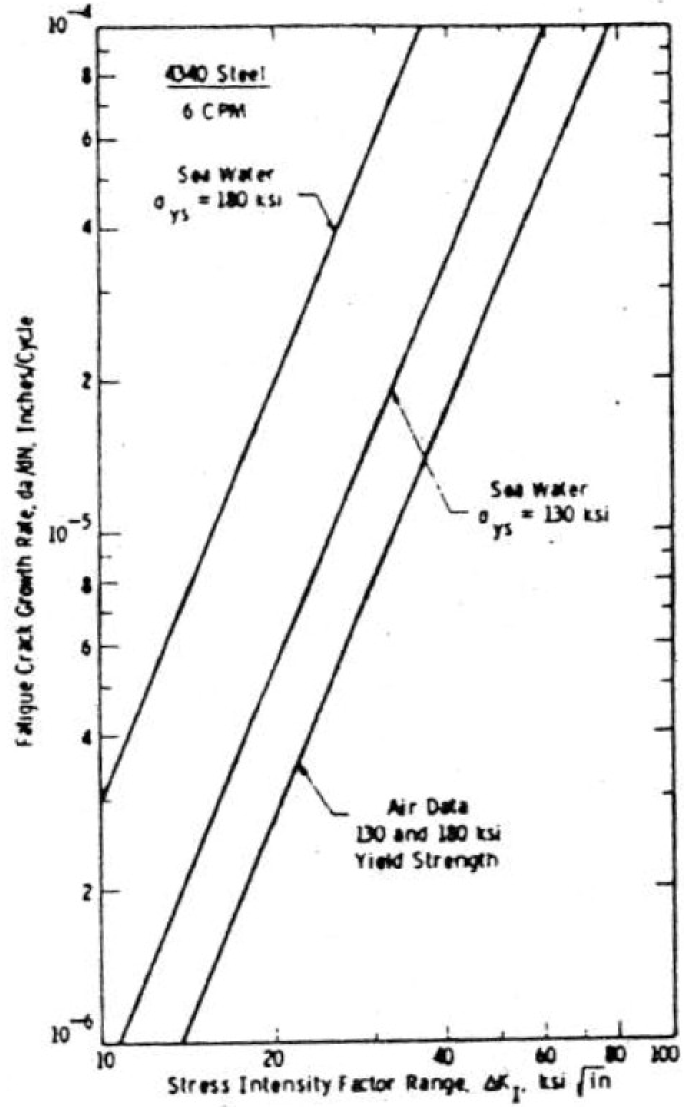
2. The environment accelerates crack growth over none corrosive conditions

3. More susceptible materials have faster crack growth

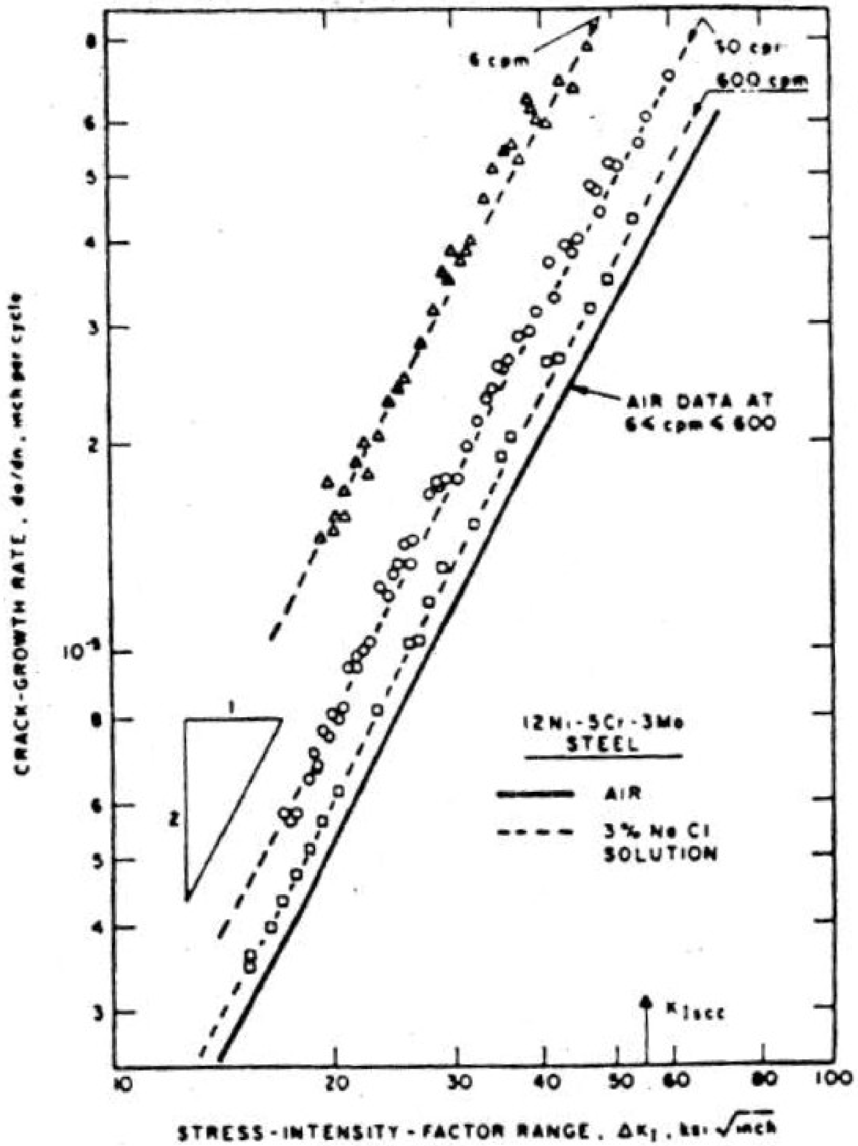
4. Slower frequency has faster crack growth

Fatigue crack growth, effect of environment





- Effect of seawater on the fatigue crack growth rate properties of AISI 4340 steel at two strength levels.



- Effect of loading frequency on corrosion-fatigue crack growth rate.

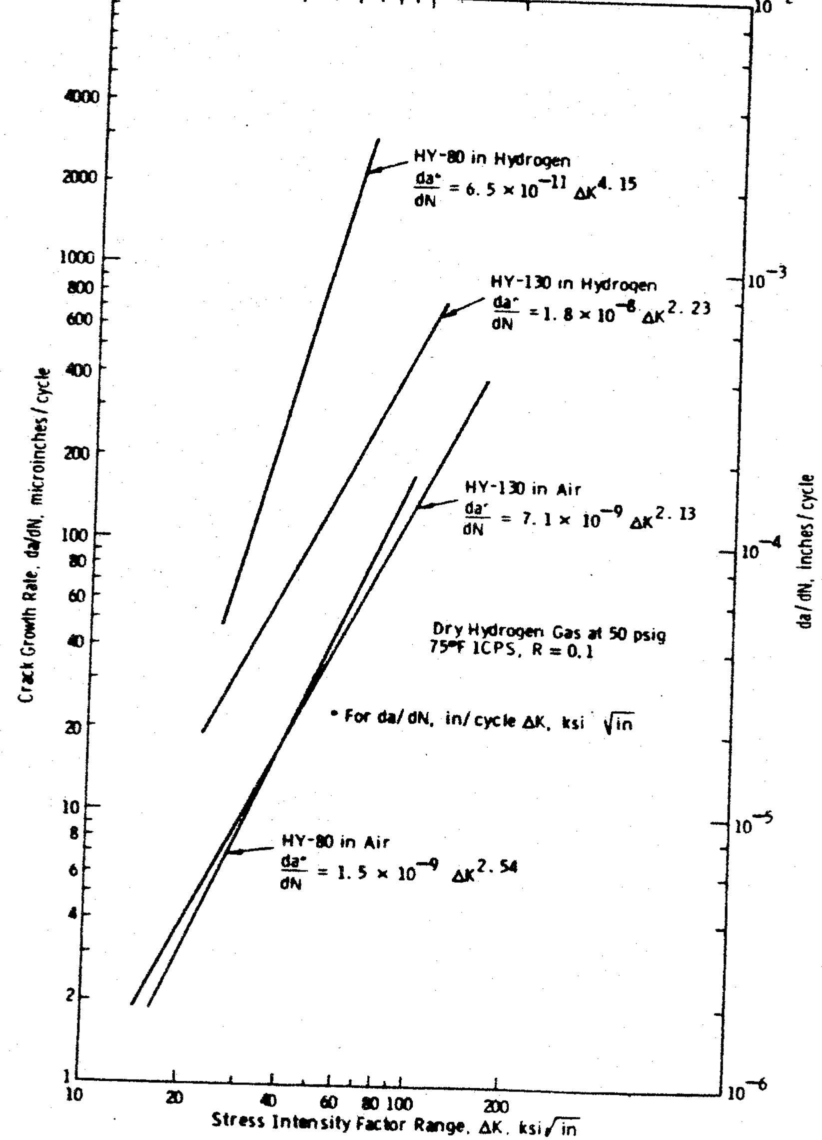


Fig. 47 - Effect of hydrogen gas on the fatigue crack growth rate behavior of HY80 and HY130 steels.

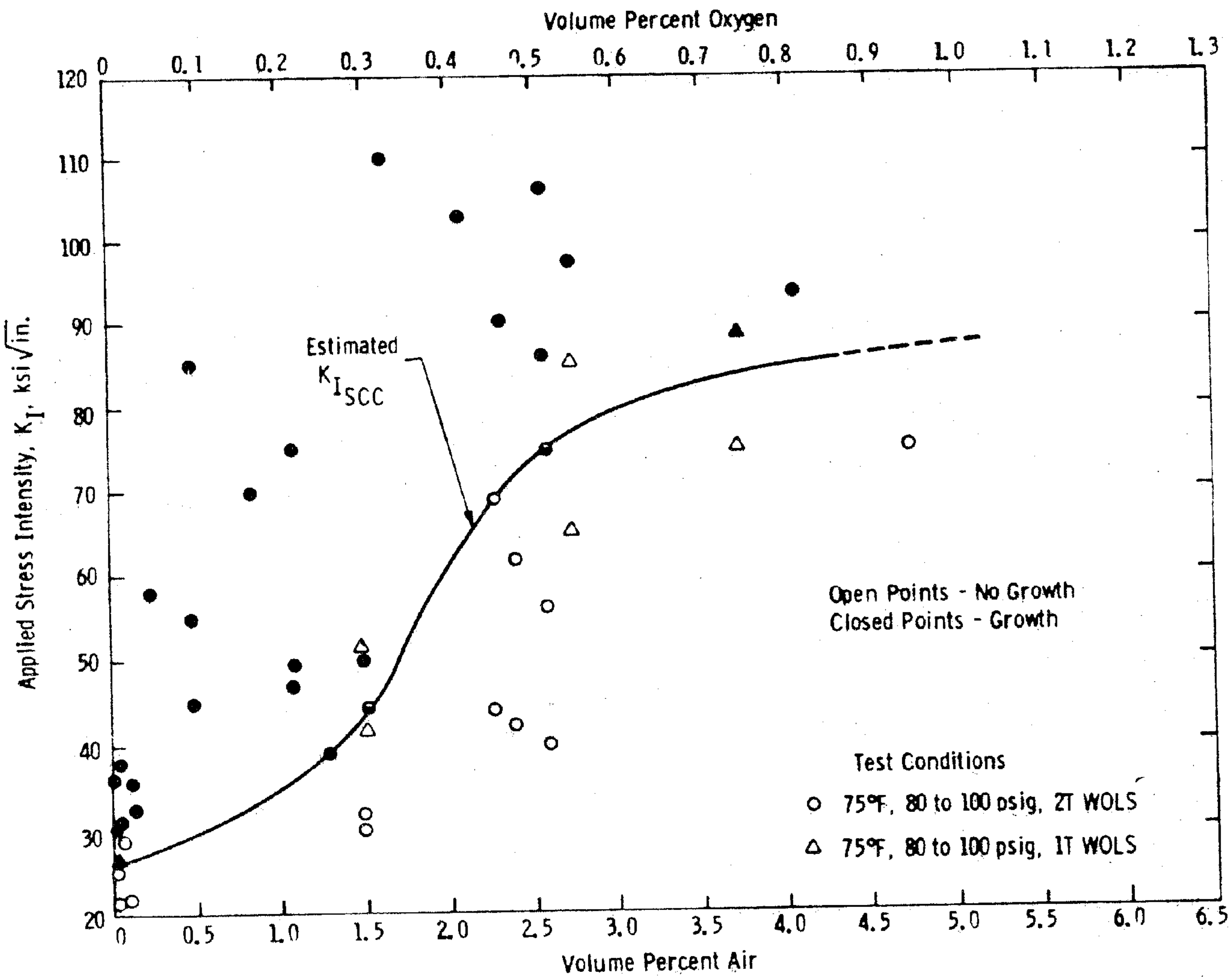


Fig. 49 - Effect of gas chemistry on hydrogen induced static crack growth in 180 ksi yield strength 4340 steel.