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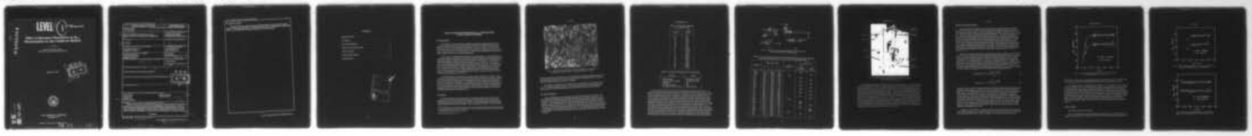

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Effect of Specimen Dimensions on K_{Iscc} Determination by the Cantilever Method

C. T. Fujii

Metals Performance Branch
Material Science and Technology Division

May 31, 1978

NAVAL RESEARCH LABORATORY
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

There is a critical need for standardization of K_{Iscc} test procedures to assure the documentation of only valid data. An important area of concern is the development of realistic specimen requirements which are applicable to K_{Iscc} tests rather than adopting those used in K_{Ic} determinations. The present studies were aimed at systematically evaluating the effects of specimen thickness, ligament length, and initial crack length on the threshold for stress-corrosion crack growth K_{Iscc} by the cantilever method.

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20. Abstract (Continued)

The experimental results suggest that specimen thickness and ligament length which are approximately 50 percent that required for K_{Ic} tests are sufficient for valid K_{Iscc} determinations of high-strength steels. K_{Iscc} was independent of initial crack length for the SEN bend specimen.

CONTENTS

EFFECT OF SPECIMEN DIMENSIONS OF K_{Iscc} DETERMINATION BY THE CANTILEVER METHOD

INTRODUCTION

The application of elastic fracture mechanics principles for characterizing the stress corrosion cracking (SCC) behavior of materials in terms of the threshold stress intensity factor K_{Iscc} has been widely accepted and practiced for over a decade.* All of this work, however, has been carried out without the benefit or guidance of standardized test procedures. Thus, at least some of the existing K_{Iscc} data may be invalid because of questionable testing practice such as use of undersized specimens.

In the absence of standardized procedures for determining K_{Iscc}, some have followed a conservative course in evaluating this parameter and adopted the specimen requirements for determining fracture toughness (K_{Ic}) under plane strain conditions [1]. The dimensional requirements for K_{Ic} specimens are given by B and $W - a_0 \geqslant 2.5(K_{Ic}/\sigma_y)^2$, where B, $W - a_0$, and σ_y are the thickness, ligament length, and yield strength respectively. For tough materials with relatively high SCC resistance, the adoption of such procedures for establishing K_{Iscc} would necessitate the use of large specimens and correspondingly large test equipment. However, recent studies on high-strength precipitation-hardenable stainless steels suggest that smaller specimens than that prescribed for K_{Ic} tests may be entirely adequate for determining valid K_{Iscc} values [2, 3].

It would facilitate testing, reduce costs, and increase confidence in new K_{Iscc} data if, instead of continuing the practice of either adopting overly conservative measures or simply ignoring specimen size effects, minimum specimen dimensions required for determining K_{Iscc} are independently established. Accordingly the present experimental evaluations are focused on the effects of specimen thickness, ligament length, and initial crack length on K_{Iscc} measurements by the cantilever method. The results are pertinent to efforts by the American Society for Testing and Materials (ASTM) which are in progress for developing standard test procedures to determine K_{Iscc}.

MATERIAL

The material used in these experiments, a 51-mm-thick plate of HY-130 steel, was produced by electric furnace (EF)/air melt practice and heat treatment which included austenitizing, quenching, and tempering. Figure 1 is a photomicrograph of a polished-and-etched section of this as-received material. The microstructure of the HY-130 steel, which

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*K_{Iscc} is defined as the stress intensity factor above which stress corrosion crack growth is initiated within some arbitrary time interval (such as 1000 hours). It is generally assumed that longer periods under sustained load would not lower this threshold.

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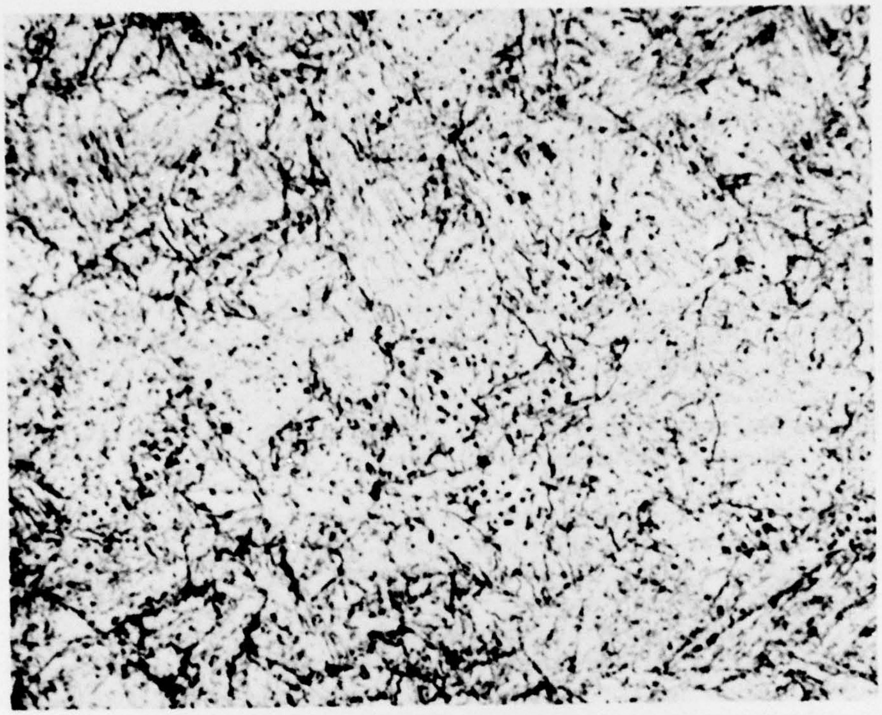

Fig. 1 — Microstructure of HY-130 steel: relatively uniform grain size, tempered martensite, fine carbides (etchant: 1% Nital; magnification: ≈1000 X)

featured a relatively uniform grain size, was predominately tempered martensite with some fine spheroidized carbides. The chemical composition of the material is given in Table 1, and the mechanical properties are given in Table 2.

All of the SCC experiments were conducted on the material in the as-received condition. The smaller specimens (25 mm, 13 mm, and 8 mm thick) were obtained from the broken halves of the full-plate-thickness (51-mm) specimens, which were tested first.

SCC TEST METHOD

Figure 2 illustrates the SCC specimen and method used in these experiments. The specimens were single-edge notched (SEN), side grooved, and fatigue precracked in conformance with the recommended procedures for plane-strain fracture-toughness testing of metals [1]. The differently sized specimens were proportioned to maintain a constant height-to-thickness (W/B) ratio of 2. All SCC specimens were fabricated in the LT orientation, that is, with the crack plane perpendicular to the final rolling or longitudinal direction L and parallel to the long transverse direction T [4]. The critical dimensions of the SEN bend specimens used in these experiments are listed in the third, fourth, and fifth columns of Table 3.

Table 1 — Chemical Composition of HY-130 Steel Plate

Element	Content (wt-%)
Ni	4.97
Cr	0.49
Mo	0.51
V	0.052
Mn	0.76
Si	0.26
C	0.10
O	0.0046
S	0.004
N	0.010
P	0.004
Cu	0.021
Al	0.020
Co	0.02
Ti	0.007
Sn	0.006
Sb	0.001
As	0.004

Table 2 — Mechanical Properties of HY-130 Steel Plate

Property	Value
Yield strength	876 MPa (127 ksi)
Ultimate tensile strength	931 MPa (131 ksi)
Elongation	19%
Reduction in Area	65%
C_v energy at 255.4 K (0°F)	100 J (74 ft-lb)

The cantilever test method, introduced and described by Brown [5], was used to determine the threshold stress intensity factors in air (K_{Ix}) and in saltwater (K_{Iscc}) under freely corroding and zinc-coupled conditions. For the SCC tests the corrodent was 3.5% sodium chloride (NaCl) solution contained in a polyethylene reservoir around the crack. This corrodent was changed each work day during the experiment, which typically ran for several hundred hours. The electrochemical potentials of the specimens were measured periodically during these tests against a silver/silver chloride (Ag/AgCl) reference electrode. All of the experiments were conducted at a room temperature of approximately 24°C. The experiments on specimens which were 25 mm or less thick were conducted on a conventional weight-loaded cantilever beam as shown schematically in Fig. 2b. The 51-mm-thick specimens, which required heavier loads, were tested in a hydraulically loaded system shown in Fig. 3 and described in detail in Ref. 6. The Kies equation given in the lower portion of Fig. 2a, where M is the moment and a, W, and B are respectively the crack length, height, and thickness of the specimen, was used to calculate the threshold stress intensity factors [7].

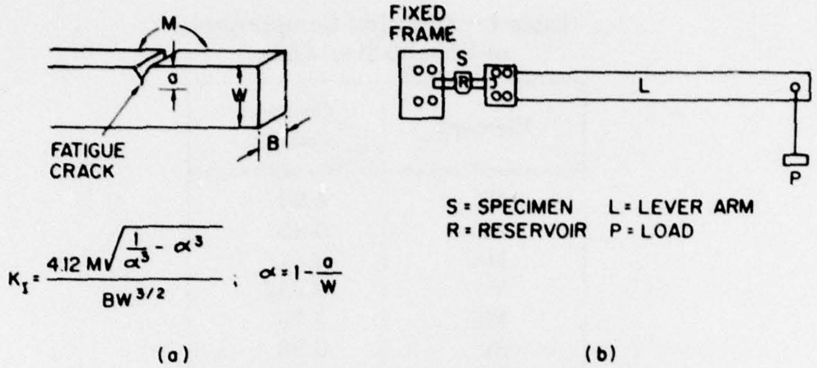

Fig. 2 — Schematic of (a) the precracked SEN bend specimen and (b) the cantilever test method for determining K_{Iscc}

Table 3 — Critical Dimensions of the HY-130 SEN Bend Specimens and the Threshold Stress Intensity Factors in Air (K_{Ix}) and in 3.5% NaCl Solution (K_{Iscc})

Specimen	Dimensions (mm)			K_{Ix} (MPa·m$^{1/2}$)	K_{Iscc} (MPa·m$^{1/2}$)	
	B	W	a_0		Freely Corroding	Zn Coupled
V22-1	52.8	101.6	50.8		156	
V22-2	52.3	101.6	48.3			135
C-12	27.9	49.5	24.6	174		
D-1	25.4	50.8	24.4		154	
C-11	27.9	49.5	24.4			125
D-2	25.1	49.5	12.2		154	
D-4	26.2	49.5	12.6			130
B-11	27.4	49.5	6.3		161	
B-12	26.7	49.5	5.6			131
7-3	25.4	49.5	17.3		153	
7-4	25.4	49.5	18.5			123
3-2	25.4	49.8	21.8		152	
3-1	25.4	49.5	22.1			124
4-2	25.4	49.3	33.5		141	
4-1	25.1	49.5	34.0			112
B-9	12.5	24.4	13.2	141		
B-8	12.4	24.6	12.3		119	
C-10	11.7	19.9	10.4		128	
C-7	11.9	24.4	12.7			104
C-9	11.4	24.3	5.8		126	
C-8	11.4	24.3	5.8			103
B-10	12.6	20.6	5.7			103
C-1	7.6	12.3	4.2	105		
C-2	7.5	12.2	4.1		89	
C-3	7.6	12.3	4.2			77

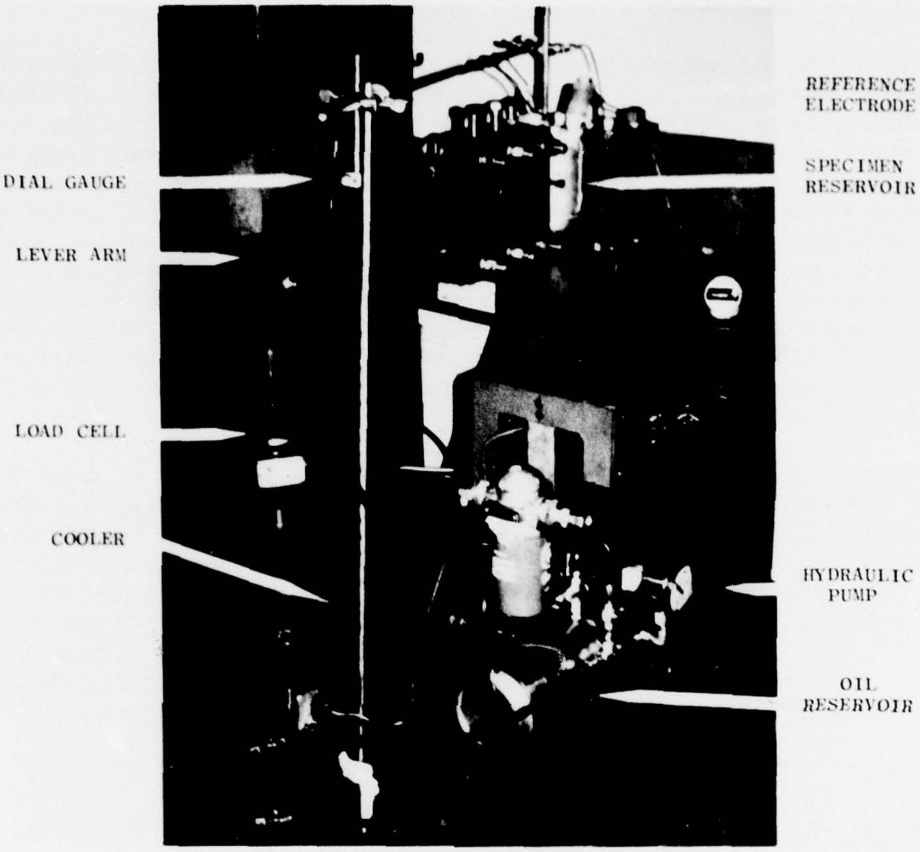

Fig. 3 — Hydraulic SCC test equipment developed at NRL for testing large cantilever bend specimens

A step-loading bracketing procedure was used to determine K_{Iscc}. The stress intensity factor for fast fracture in air K_{Ix} was first mentioned and subsequently used to guide load settings for the SCC tests. The initial loads for the K_{Iscc} tests were approximately 50 to 70% of that used to establish K_{Ix} values—closer to 50% for the zinc-coupled specimens and closer to 70% for the freely corroding specimens. Loads were increased incremently every 150 to 200 hours until crack growth was initiated, as indicated by a precision dial gauge positioned to detect movement of the lever arm. Each load increment was equivalent to an increase in K of approximately 11 $\mathrm{MPa \cdot m^{1/2}}$ (10 $\mathrm{ksi \cdot in.^{1/2}}$). Upon completion of each SCC test, stress corrosion crack growth was verified by visual and microscopic examination of the fracture surfaces. The actual threshold was considered to be bracketed between the K_I which initiated crack growth and subsequent fracture and the highest K_I which failed to do so for hold times of approximately 150 to 200 hours. Thus, K_{Iscc} was determined by averaging the K_I values associated with the final two loads.

RESULTS AND DISCUSSION

The critical stress-intensity factors for fast fracture in air (K_{Ix}) and crack growth in 3.5% NaCl solution (K_{Iscc}) under freely corroding or zinc-coupled condition are listed in the last three columns of Table 3. The SCC data have been used to construct Figs. 4, 5, and 6 to illustrate the effect of thickness (B), ligament length ($W - a_0$), and crack length (a_0) on K_{Iscc} for the two electrochemical conditions of the specimen. The data represented by filled-circle and filled-triangle symbols in these figures are those obtained on the full-plate-thickness (51-mm) specimens from which the thinner specimens were fabricated. In each figure the average K_{Iscc} values of the valid data points for the freely corroding and the zinc-coupled conditions are indicated by the solid lines. The experimental reproducibility of the cantilever beam method is indicated in each figure by the width of the shaded zones enveloping the solid lines representing the average K_{Iscc} values. This experimental uncertainty which is associated with each K_{Iscc} determination is approximately ± 6 MPa·m$^{1/2}$ (± 5 ksi · in.$^{1/2}$).

Figure 4 shows that for determining a thickness-independent (valid) K_{Iscc} for HY-130 steel in a saltwater environment using a fatigue precracked SEN specimen and the cantilever method, a minimum thickness B of approximately 25 mm is required for both the freely corroding and zinc-coupled conditions. There is a comparable requirement for ligament length ($W - a_0$) to assure valid K_{Iscc} measurements, as indicated by Fig. 5. Similar to the relationships used to specify minimum specimen dimensions for plane-strain crack-toughness testing [8], these empirically derived results for SCC testing of HY-130 steel may be expressed in terms of the ratio of the threshold stress intensity factor (K_{Iscc}) to yield strength (σ_y) for the freely corroding (FC) and zinc-coupled (Zn) conditions as follows:

$$B \text{ and } (W - a_0) \geqslant 0.8\left(\frac{K_{Iscc},\ FC}{\sigma_y}\right)^2 , \qquad (1)$$

$$B \text{ and } (W - a_0) \geqslant 1.2\left(\frac{K_{Iscc},\ Zn}{\sigma_y}\right)^2 . \qquad (2)$$

Equations 1 and 2 specify the minimum specimen thickness and ligament length that are required to obtain valid K_{Iscc} values for the freely corroding and zinc-coupled conditions respectively. The coefficients 1.2 and 0.8 are approximately 2 and 3 times less than the 2.5 given in the recommended practice for K_{Ic} tests [8] but are comparable to Rolfe and Novak's value of 1.0, which they suggest as being adequate to define B in subthickness specimens for approximate K_{Ic} determination of high-strength steels [9]. Previous studies on the effect of specimen thickness on K_{Iscc} values of 17-4 PH and 15-5 PH steels showed that $B \geqslant 1.0\ (K_{Iscc}/\sigma_y)^2$ was sufficient to give valid results [2, 3]. Thus, growing experimental evidence suggests that for high-strength steels such as HY-130 and 17-4 PH steels, valid K_{Iscc} values may be obtained by tests on smaller specimens than required by strict adherence to standards for K_{Ic} tests.

As shown in Fig. 6, there is no significant effect of initial crack length a_0 on K_{Iscc} for either freely corroding or zinc-coupled specimens if the requirements for thickness and ligament length as given by Eqs. 1 and 2 are fulfilled. The open-symbol data points were

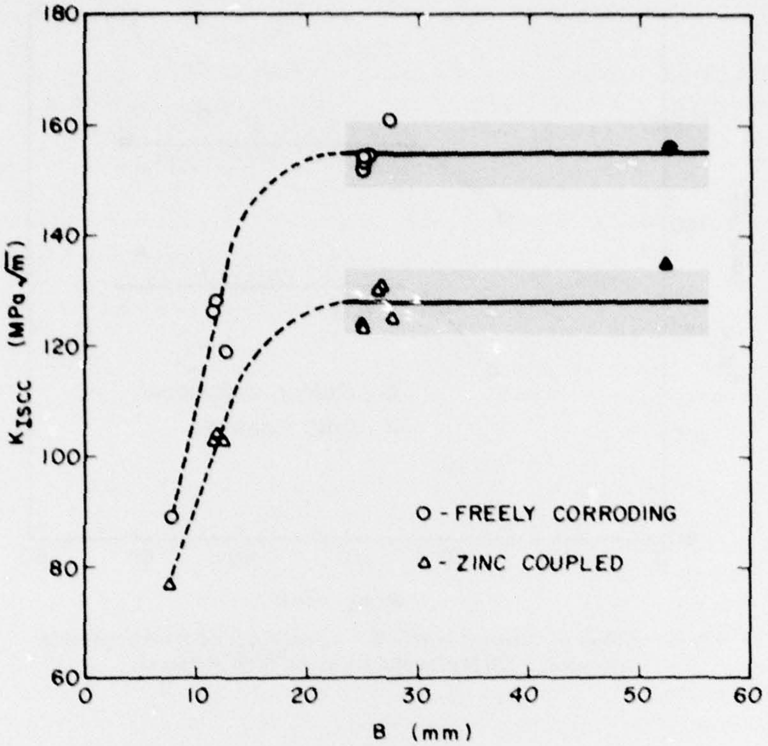

Fig. 4 — Effect of thickness B on K_{Iscc} of HY-130 steel in quiescent 3.5% NaCl solution at 24°C ($a/W \leq 0.5$)

obtained from SCC tests on 25-mm-thick specimens with a W/B ratio of 2. Included in Fig. 6 are the K_{Iscc} data for the full-plate-thickness (51-mm) specimens (filled symbols).

The similar specimen-size requirements (B and $W - a_0 \geq 2.5$-mm) for the two electrochemical conditions—freely corroding and zinc coupled—are somewhat unexpected. Based on experiences with K_{Ic} testing, one might intuitively anticipate that a proportionately smaller specimen would be sufficient to obtain valid K_{Iscc} measurements for the material and environmental conditions that give lower K_{Iscc} values compared to conditions that lead to higher K_{Iscc} values. The explanation may be related to changes in fracture modes which are observed with changes in electrochemical potential, which in turn is relatable to availability of atomic hydrogen. However, elucidation of important interactive crack-tip processes are at present largely conjectural, and experimental clarifications are clearly required.

CONCLUSIONS

Thus the conclusions are as follows:

- For the determination of the threshold SCC parameter K_{Iscc} of HY-130 steel in a saltwater environment by the cantilever test method, the critical specimen dimensions are

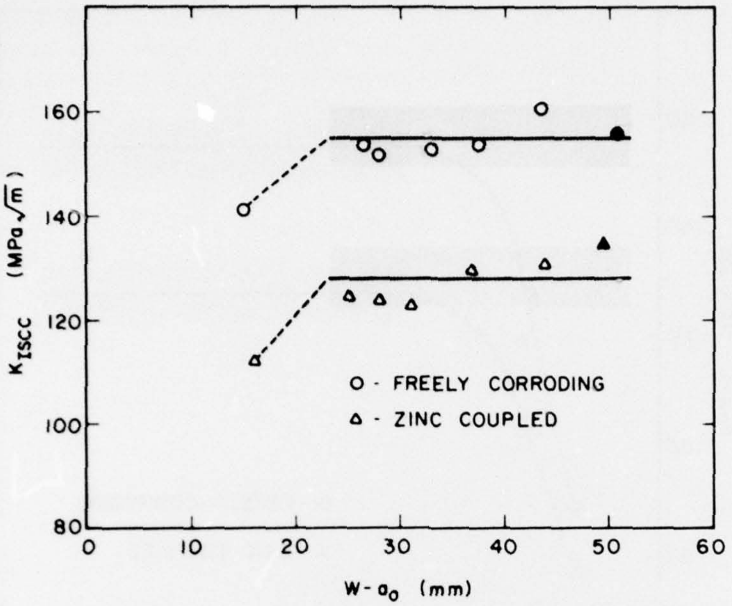

Fig. 5 — Effect of ligament length W - a_0 on K_{Iscc} of HY-130 steel in quiescent 3.5% NaCl solution at 24°C (B ⩾ 25mm)

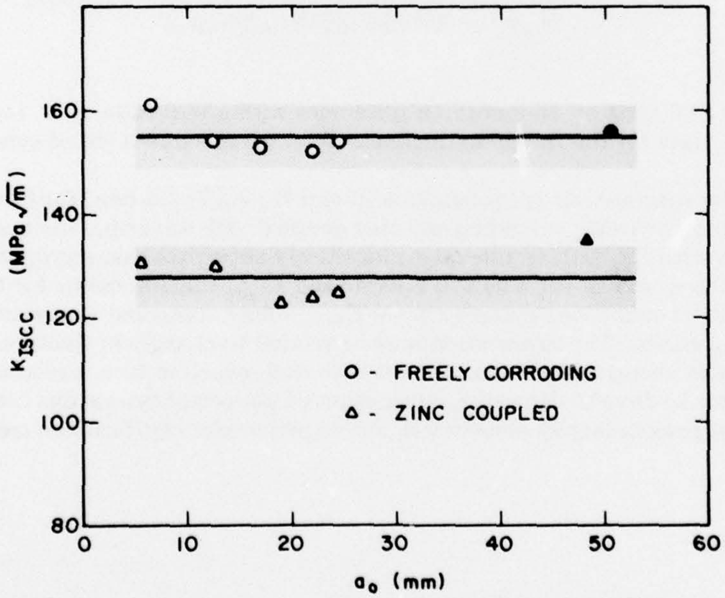

Fig. 6 — Effect of crack length a_0 on K_{Iscc} of HY-130 steel in quiescent 3.5% NaCl solution at 24°C (B ⩾ 25 mm; a/W ⩽ 0.5)

given by B and $W - a_0 \geq 0.8(K_{Iscc}/\sigma_y)^2$ for the freely corroding condition and B and $W - a_0 \geq 1.2(K_{Iscc}/\sigma_y)^2$ for the zinc-coupled condition. In either case, a minimum thickness B and ligament length $W - a_0$ of 25 mm is sufficient to permit the measurement of K_{Iscc} which remains invariant when specimens with larger dimensions are used. This is approximately 1/3 to 1/2 the minimum specimen dimensions which would be required if plane-strain fracture-toughness testing specifications are followed for SCC work.

- K_{Iscc} is independent of initial crack length a_0, provided the other dimensional requirements for the SEN specimen are fulfilled.

- The present experimental results augment previous studies which suggest that the minimum specimen dimensions required for establishing valid K_{Iscc} values of high-strength steels are satisfied by the empirically derived criteria cited above. General applicability of these criteria for K_{Iscc} testing to other materials needs to be demonstrated with more extensive and systematic studies.

ACKNOWLEDGMENT

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