NRL Report 6988

Procedures for Stress-Corrosion Cracking Characterization and Interpretation to Failure-Safe Design for High-Strength Steels

R. W. Judy, Jr., and R. J. Goode

Strength of Metals Branch
Metallurgy Division

November 29, 1969

NAVAL RESEARCH LABORATORY
Washington, D.C.

CONTENTS

ABSTRACT

The recently evolved Ratio Analysis Diagram (RAD) procedure is a useful engineering tool for generalized assessment of the fracture resistance of high-strength steels. Failure-safe design of large complex structures also requires consideration of subcritical crack growth caused by stress-corrosion cracking (SCC). Procedures developed to incorporate SCC characterizations into the RAD concept provide a more complete analysis of a material's resistance to fracture. The SCC-Dual RAD for high-strength steels presents simplified interpretations of the critical flaw size-stress instability conditions for both slow fracture (SCC) and fast fracture of these materials.

PROBLEM STATUS

This report completes one phase of the problem; work on other aspects of the problem is continuing.

AUTHORIZATION

NRL Problems M01-25, F01-17, and M04-08A
Projects RR 007-01-46-5432, SF 51-541-012-14628
SF 51-541-001-12380, SF 51-541-003-12383,
S-4607-11894, and ARPA Order 878

Manuscript submitted September 16, 1969.

PROCEDURES FOR STRESS-CORROSION CRACKING CHARACTERIZATION AND INTERPRETATION TO FAILURE-SAFE DESIGN FOR HIGH-STRENGTH STEELS

INTRODUCTION

Steels are the primary metals used by design engineers for structures throughout the world. Although conventional structural steels (below about 70-ksi yield strength) have widest use in engineering structures, designers are beginning to require higher strength steels to improve structural performance and efficiency. Over the last decade, a number of heat-treatable, high-strength steels have emerged that have desirable fracture toughness characteristics for general engineering; however, some of these steels have been found to be susceptible to stress-corrosion cracking (SCC) in salt water and other liquid environments. The degree of SCC susceptibility has been found to be strongly influenced by the same metallurgical factors that cause variations in other mechanical properties of these materials. For a steel of low resistance to SCC, slow crack growth (subcritical crack growth) occurs at flaw sizes and stress levels considerably below those required to cause fast fracture. However, for most high-strength steels, the growth of a stress-corrosion crack to critical size for fracture requires times in the order of hundreds of hours. For susceptible titanium alloys, the critical crack size for fracture is achieved in a matter of minutes under similar conditions (1).

Procedures based on linear-elastic fracture mechanics theory provide for defining the resistance of metals to initiation of subcritical and fast fracture in terms of the critical crack tip stress-intensity value K. Expressions have been derived for different flaw geometries which relate a material's characteristic K value to the size of the flaw and level of stress required for failure. At present, accurate definition of crack tip instability conditions is achieved only under the condition of plane strain. This condition is attained when maximum mechanical constraint is imposed (usually by increased thickness), causing the crack tip plastic zone size to be minimized. The K value determined for maximum constraint conditions is termed K_{Ic} and is considered a material constant.

For conditions of plane stress for which maximum constraint is not attained, the plastic zone is larger and the K value obtained depends on the specimen geometry. This K value is termed K_c. Approximate lower-bound flaw-size determinations can be made for crack instability from K_c - K_{Ic} relationships; however, such calculations require consideration of the actual thickness of the specimen in relation to the critical thickness required for plane strain K_{Ic} conditions. Procedures have been evolved for determining the approximate flaw size-stress level requirements for fast fracture, which have proven useful for engineering usage of steels (2). This report is concerned with providing a preliminary analysis of the interpretability of fracture mechanics K_{Iscc} methods to failure-safe design for structures of high-strength steels subject to saltwater SCC.

FRACTURE MECHANICS ASPECTS

In recent years, the resistance of materials to saltwater stress-corrosion cracking (SCC) has been characterized in terms of the threshold level of crack tip stress intensity above which SCC can be shown to occur. The characteristic threshold level is defined in linear-elastic fracture mechanics terminology as "K_{Iscc}."

The chief advantage of the application of linear-elastic fracture mechanics technology to SCC is that it combines the stress level and flaw-size factors into a single K_I parameter, which is independent of the geometry of the test specimen. Another advantage of defining SCC properties in terms of K_I is that this parameter can be translated into a critical flaw size-stress level relation for crack growth by SCC for different flaw geometries using appropriate fracture mechanics equations. Characterization of SCC resistance in terms of critical flaw depth is very useful, since the design of many structures is based on a maximum allowable flaw size usually determined by the capabilities of the methods of nondestructive inspection used.

A variety of fracture mechanics specimen types have been used to determine the SCC characteristics for structural metals. The precracked cantilever bend test developed by B.F. Brown (3) has been the most widely used because of the inherent simplicity of the loading apparatus; this is a major factor when loading times of hundreds of hours are required.

Of the variables which must be considered in determining the stress-intensity factor K, the thickness of the specimen is the most significant, because thickness determines the degree of crack tip constraint present in the specimen. At the tip of a crack in a stressed body, a volume of plastically deformed material called the plastic zone is formed as illustrated in Fig. 1. The material at the surface is not constrained and can flow in the thickness direction. The material at the center has a triaxial stress state which limits, or constrains, the flow of metal along the edge of the crack. A plane strain condition exists when triaxial stress conditions dominate. Full plane stress conditions occur when the entire thickness must be stressed above the yield strength before the onset of fracture. The transition between these two extremes is called the plane stress-mixed mode condition.

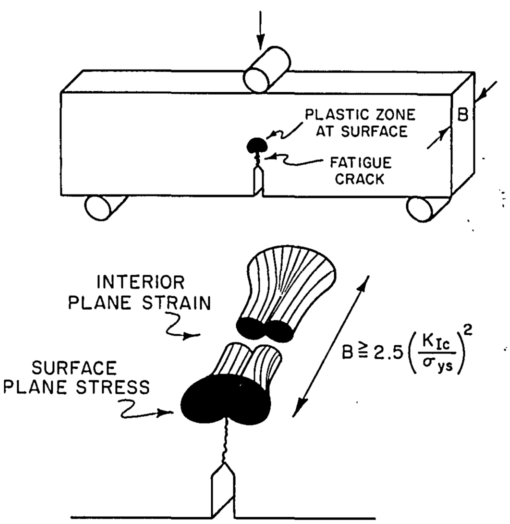

Fig. 1 - Illustration of the effect of biaxial (specimen surface) and triaxial stresses (specimen interior) on constraint of plastic zone size at the tip of a crack

The fast fracture resistance of a material can be measured in terms of the K parameter as either K_{Ic} or K_c, depending on the degree of constraint present in the specimen. A valid K_{Ic} value is independent of specimen geometry effects and therefore is a property of the material; plane strain conditions are necessary for determining K_{Ic}. The ASTM recommended practice (4) thickness requirement for valid K_{Ic} measurement is

$$B \geq 2.5\,(K_{Ic}/\sigma_{ys})^2, \qquad (1)$$

where B = thickness and σ_{ys} = yield strength of material. Full plane stress K_c values and K_c mixed-mode values depend highly on specimen geometry and therefore are not a constant material property. This dependence occurs because the derivation of equations defining the K parameter assumes that the stress field can be represented as two dimensional and that plasticity effects at the crack tip are negligible; both of these conditions are violated by the plane stress state.

The significance of these considerations for the use of fracture mechanics for the characterization of the SCC properties of structural metals is that SCC is usually associated with regions of plane strain. Such conditions are required across the major part of the crack front to assure applicability of the fracture mechanics equations for accurately defining the environmental effects. For this reason, only the SCC characterization data obtained under conditions of plane strain should be denoted as K_{Iscc} values. Values of K obtained under plane stress or plane stress-mixed mode conditions may not represent the characteristic value for the materials involved. Such values of K are designated "apparent K_{Iscc}" in this report.

The SCC resistance of a material can be made from a comparison of the K_{Iscc} value with its level of fracture toughness (fast fracture resistance). For example, a value of K_{Iscc} approaching the level of K_{Ic} fracture toughness signifies a high degree of SCC resistance; conversely, a low value of K_{Iscc} compared to K_{Ic} indicates sensitivity to the environment. The K_{Iscc} parameter by itself does not denote whether or not the material is sensitive to the environment. This is because K_{Iscc} values cannot be larger than K_{Ic}; i.e., materials with low K_{Ic} values will always be limited to low values of K_{Iscc}.

The thickness requirements of the ASTM recommended practice cited earlier presently provide the best guidance for valid K_{Iscc} determinations. In the determination of minimum B, the value of K_{Iscc} is used in place of K_{Ic} in Eq. 1.

RATIO ANALYSIS DIAGRAM FOR FAST FRACTURE

A simplified procedure for characterizing fracture toughness in terms of the critical flaw depth for fast fracture has been evolved for steels (2) and applied to titanium alloys (5) and aluminum alloys (6). The procedure is based on a relationship between two indices of fracture toughness — K_{Ic} and Dynamic Tear test energy.

The Dynamic Tear (DT) test was developed at NRL to determine the fracture toughness properties of structural metals over the full range of fracture behavior, i.e., elastic and plastic fracture. The features of the test are shown schematically in Fig. 2. Dynamic loading of the specimen which contains a deep, sharp flaw constitutes the most severe fracture condition. The indicator of the level of fracture toughness in this test is the energy required to fracture a standard specimen.

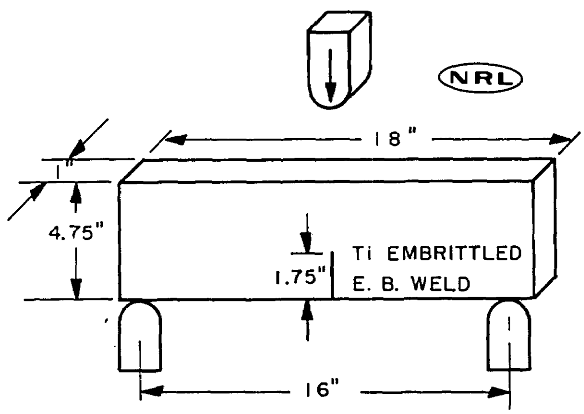

Fig. 2 - DT specimen for testing 1-in.-thick steel plate

A diagram showing DT energy (fracture toughness) as a function of yield strength (σ_{ys}), Fig. 3, is used to display the fracture toughness characteristics of high-strength steels. The "Technological Limit" line represents the best obtainable DT fracture toughness over the entire σ_{ys} range. The relationship of DT energy and K_{Ic} is indicated by the placement of the DT and K_{Ic} scales.

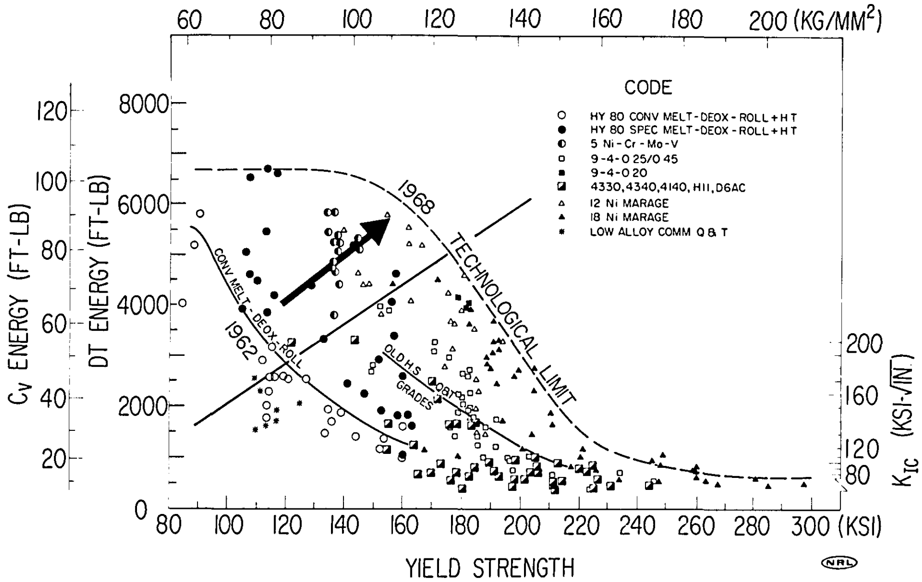

Fig. 3 - Technological Limit diagram for steels. Data points relate to 1-in. DT test values. The K_{Ic} and DT scales indicate the relationship between K_{Ic} and DT energy.

The fracture mechanics expression

$$K_{Ic}/\sigma_{ys} = 1.1(\sigma/\sigma_{ys})\sqrt{\pi a/Q}, \tag{2}$$

where a = crack depth, Q = flaw geometry factor, and σ = stress level, can be used to calculate from K_{Ic} values the critical flaw depth for surface flaws. This equation can be conveniently represented in graphical form as shown in Fig. 4. In this chart the critical crack depth at a given nominal stress level depends on the ratio K_{Ic}/σ_{ys} — a ratio of two material properties. Note that as the ratio increases the critical flaw size increases dramatically, especially for lower levels of nominal stress. For general engineering interpretation, the chart can be separated into three general regions according to the size of the critical flaws:

1. Below ratio 0.5 — Critical flaw depths at any stress level are extremely small.

2. For increasing ratios from 0.5 to "∞" — Critical flaw depths range from very small to very large, which makes calculation of the critical flaw size a practical procedure.

3. Above the ratio "∞" — Plastic deformation of the metal is necessary for fracture even in the presence of large flaws; thus, the ratio ∞ defines the upper limit for practical application of linear-elastic fracture mechanics technology.

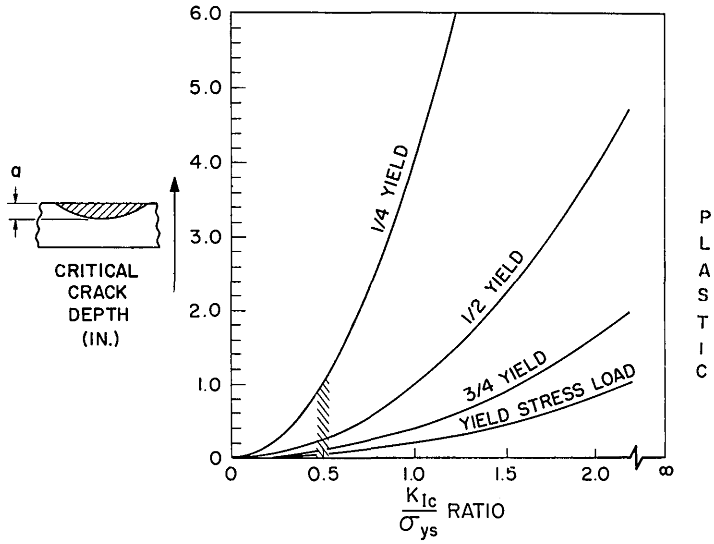

Fig. 4 - General relationship of flaw size-stress requirements for crack instability as a function of increasing K_{Ic}/σ_{ys} ratio

The Ratio Analysis Diagram (RAD) for steels, Fig. 5, was evolved by overlaying a system of lines of constant ratio of K_{Ic}/σ_{ys} on the Technological Limit diagram. This provided a simple procedure for engineering interpretation of the fracture toughness characteristics of various families of steels in terms of the expected critical flaw depths for fast fracture. Interpretation is provided by indexing the location of fracture toughness data (DT or K_{Ic}) with respect to the system of ratio lines. The significance of the ratio lines is derived from linear-elastic fracture mechanics calculations and are essentially those given for Fig. 4.

1. Below K_{Ic}/σ_{ys} = 0.5 — Materials in this region have characteristically low resistance to elastic fracture, i.e., low levels of fracture toughness. Critical flaw sizes for these materials are so minute that the flaws can escape detection by even the best nondestructive testing techniques. The only practical way to use materials in this region is to periodically proof test the structure for assurance that no critical flaws exist. Hence, the area below K_{Ic}/σ_{ys} = 0.5 is called the "Proof Test" region.

2. For ratios from 0.5 to "∞" — An increase from low to high resistance to elastic fracture is signified for the thicknesses indicated with critical flaw sizes large enough to be detectable by NDT techniques. Thus, this area is denoted by "Flaw Size Calculations Practical."

3. Above K_{Ic}/σ_{ys} = "∞" — The notation of an infinity ratio simply indicates the practical upper limit of applicability of linear-elastic fracture mechanics principles. Even for very thick sections, gross plastic deformation and very large flaws are required for fracture. This area is denoted as the "Ductile Fracture" region.

The dashed line noted as the infinity (∞) ratio represents the most optimistic estimate that can be made at this time of the limit to which unstable plane strain fracture toughness can be measured by K_{Ic} tests of large section size. These measurements would relate to K_{Ic}/σ_{ys} ratio 2.0 value or higher and, thus, would require specimens of section size in excess of 10 in. The high metallurgical ductility of steels with C_v and 1-in. DT test shelf energy values in excess of this line is amply demonstrated by

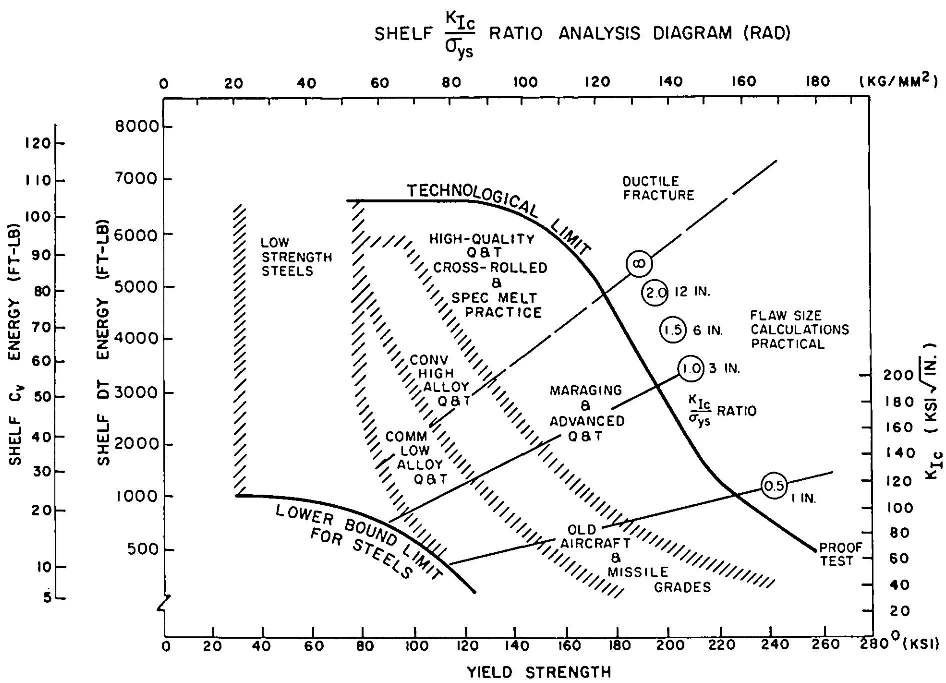

Fig. 5 - Ratio Analysis Diagram (RAD) for high-strength steels

highly ductile fracture for section sizes in the order of 3- to 4-in. thickness. There is no basis for expectations of developing unstable plane strain fracture as the result of increasing section size to 12-in. thickness for such ductile metals.

The 1.5 and 2.0 ratio lines must lie in the narrow gap remaining between the ∞ and the 1.0 ratio lines. No attempt is made to define the location of these lines, because the significance of K_{Ic} values for ratios in excess of 1.0 is subject to question. These involve questions of the significance of K_{Ic} instabilities which are followed by rising load, as well as the procedures for plastic zone corrections of K_{Ic} values. Thick-section K_{Ic} tests will be required to better define the area of uncertainty between the 1.0 ratio level and the general location of the ∞ ratio estimate. Accordingly, the K_{Ic} scale has proper meaning to about the general level of the 1.0 ratio line or slightly higher; it should not be used for design purposes at higher levels at the present state of knowledge. The section sizes required for improved definitions of the K_{Ic} scale are indicated by the thickness notations associated with the ratio values. In summary, these relationships indicate that as the valid 1.0 ratio correlation to DT energy is exceeded, there is a rapid increase in K_{Ic}/σ_{ys} ratio values (7,8).

SCC-DUAL RATIO ANALYSIS DIAGRAM

Considerable data on saltwater SCC of high-strength structural steels are available from the literature (9-23); however, very little effort has been made to organize these data into a meaningful approach to structural application. To determine the influence of a particular environment on steels, it must first be recognized that SCC does not represent a degradation of the inherent resistance to fast fracture of the material. However, if fracture toughness parameters and SCC parameters are both expressed in terms of a common index of structural performance, the effect of an environment on a steel can be accurately evaluated by comparison of the two terms. Such an index is the critical flaw size as determined for initiation of fast fracture and for SCC for the same level of nominal stress. The RAD provides good engineering approximations of the flaw size-stress requirements for the occurrence of fast fracture in steels. Incorporation of the SCC characteristics of the same steels on this diagram provides for direct comparison of conditions for fast fracture and SCC. This dual SCC-fracture toughness RAD approach has already been applied to high-strength titanium alloys (24).

The K_{Iscc} data obtained from NRL studies and from the literature for a wide variety of steel plate and weld metals in 3.5% salt water with the precracked cantilever bend (SCC) test are shown in Fig. 6. The diagram is the same as that of Fig. 5 with the ratio lines and zonal designations eliminated. The data points are coded according to nominal specimen thickness without consideration of side grooves. (Side grooves are used to promote a straight crack front and suppress shear-lip formation. Their use does not modify the thickness requirements for attainment of plane strain conditions.) The maximum specimen thickness used was 1 in.

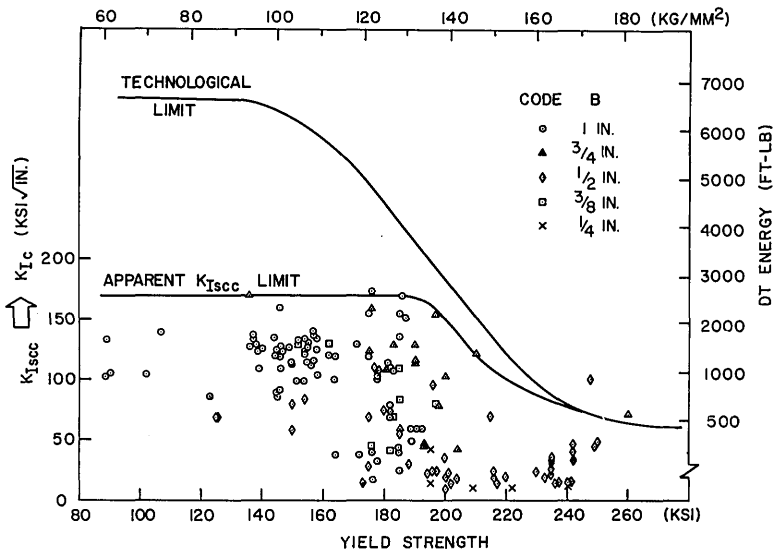

Fig. 6 - Summary of K_{Iscc} data for spectrum of high-strength steels using a range of specimen thicknesses (B)

The "Apparent K_{Iscc} Limit" is analogous to the Technological Limit in that it depicts the highest K_{Iscc} values reported. The same types of steels were used to establish the location of both limit lines. The effects of the lack of constraint due to insufficient specimen thickness can be shown by the relative positions of the Technological Limit and the Apparent K_{Iscc} Limit lines. At σ_{ys} levels of 220 to 240 ksi or greater, the lines effectively coincide. At this σ_{ys} level, even the best materials have a low level of fast fracture toughness so that valid K_{Ic} numbers can be determined from 1-in.-thick plate; hence, the K_{Iscc} values for environmentally insensitive materials approach the K_{Ic} values. Separation of the two limit lines below 220 to 240 ksi indicates the inability of the 1-in.-thick specimens to define fast fracture and SCC resistance for the best materials in terms of fracture mechanics parameters. For example, the thickness requirements for steels are such that materials at the highest part of the Technological Limit line do not manifest plane strain fast fracture at thicknesses of 6 to 12 in. Thus, high K_{Iscc} values reported for SCC specimens of 1-in. thickness or less must be viewed with suspicion when obtained for tough high-strength steels.

The SCC-Dual RAD resistance of high-strength steels to saltwater SCC is shown in Fig. 7. The upper limit of strictly valid K_{Iscc} measurements are indicated for B thickness of 0.25, 0.5, and 1.0 in. as Limit-SCC Plane Strain lines. The position of these limit lines was determined from Eq. 1 for a range of σ_{ys} levels, and they correspond to constant ratios of K_{Iscc}/σ_{ys}. For the 1-in.-thick specimens, the Limit-SCC Plane Strain line corresponds to a K_{Iscc}/σ_{ys} ratio of 0.63; for thinner specimens, the lines correspond to smaller ratios.

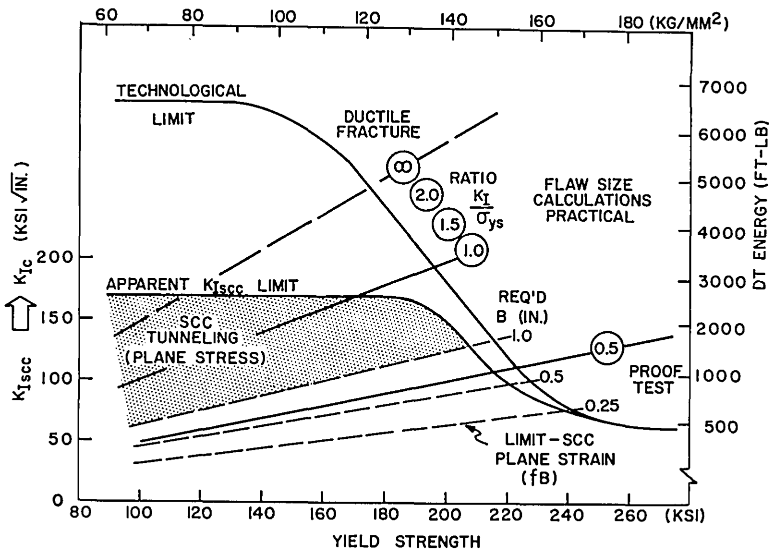

Fig. 7 - Dual Ratio Analysis Diagram (RAD) showing fast fracture and SCC aspects for steels of 1-in.-thick sections

The Limit-SCC Plane Strain line for a given specimen thickness, in conjunction with the Apparent K_{Iscc} Limit line, defines a region where subcritical crack growth and fast fracture conditions are either plane stress or plane stress-mixed mode. This is the SCC tunneling (plane stress) region noted in Fig. 7 for 1-in.-thick sections, in which SCC occurs by advancing in the plane strain ligament in the central portion of the specimen. Although the tunneling action is indicative of SCC and apparent K_{Iscc} values can be obtained, the accuracy of the values cannot be determined. Critical flaw depth-stress level requirements for SCC cannot be inferred for materials falling in this region of the diagram. Specimens of thickness greater than B are required to accurately define the conditions for SCC for such materials. Increased specimen thickness might move the tunneling region of the SCC-Dual RAD to higher K_I/σ_{ys} ratios — additional studies are needed to determine this. In any event, the function of the tunneling region of the diagram is primarily to assure that a material's resistance to subcritical crack growth due to SCC in salt water is accurately represented by SCC test methods. Apparent K_{Iscc} values which fall into the tunneling region can only be considered to give, at best, rough qualitative assessments of environmental sensitivity. Use of such values might result in a highly conservative estimate of capabilities of a highly SCC resistant steel, whereas overly optimistic estimations might result for sensitive materials.

The degree of degradation of a steel's resistance to the presence of flaws due to SCC sensitivity is indicated by comparing the location of the fast fracture and SCC data points on this diagram. For this purpose, the K_{Iscc}/σ_{ys} ratio is compared to the K_{Ic}/σ_{ys} ratio. If a metal of characteristically high fracture toughness (above K_{Ic}/σ_{ys}

ratio 2.0) has a low K_{Iscc}/σ_{ys} ratio (approximately 0.6 or less for 1-in.-thick specimens), extreme sensitivity to the environment is inferred. In this case, considerable SCC crack extension would occur before fast fracture because of the high fracture toughness of the material. Materials with a low level of inherent fracture toughness (below ratio 1.0) could withstand only a small amount of crack extension by SCC before the onset of fast fracture. SCC of very low toughness materials (below ratio 0.5) is not really important for general design consideration, since the critical flaw size for fast fracture in these metals is minute.

SUMMARY

An investigation of the spectrum of high-strength structural steels available for structural applications reveals a wide range of SCC behavior in salt water. Tests based on linear-elastic fracture mechanics theory provide the best definition of SCC resistance in terms of a crack tip stress-intensity parameter K_I. The minimum (threshold) value of K_I for SCC to occur is termed K_{Iscc}. Essentially any plane strain fracture mechanics test can be used to determine K_{Iscc}; however, for this report, only precracked cantilever bend data are considered. Regardless of which fracture mechanics test is used, the thickness, B, requirement is critical for valid K_{Iscc} measurements. Flaw size-stress conditions for subcritical crack growth due to SCC can be calculated from the K_{Iscc} value.

Recently evolved RAD procedures for characterization of resistance to fast fracture and for interpretation to failure-safe design were extended to cover the case for SCC in high-strength titanium alloys. A similar extension can be made for high-strength steels to provide dual engineering definitions of flaw size-stress level requirements for failure of the material by fast fracture and by SCC. The dual RAD features K_I/σ_{ys} ratio lines which index the general flaw size-stress conditions for failure. It also features an Apparent K_{Iscc} Limit line that defines the highest K_{Iscc} values obtained with 1-in.-thick precracked cantilever bend specimens. Finally, it features plane strain (maximum constraint) limit lines which indicate the upper limit of valid K_{Iscc} measurement as well as accurate K_{Iscc}/σ_{ys} ratio interpretation to flaw size-stress conditions for SCC with B of 0.25, 0.5, and 1.0 in. A region of full and mixed-mode plane stress is defined by the Apparent K_{Iscc} and Limit-SCC Plane Strain lines for which SCC occurs by tunneling in the plane strain (central) portion of the specimen. Accurate K_I/σ_{ys} ratio interpretations to flaw size-stress conditions for SCC cannot be made for this region. The Plane Strain SCC Limit lines can be raised to higher K_I/σ_{ys} ratios with specimens of increased B (possibly requiring material of increased thickness), permitting the engineering interpretations to extend to higher K_I/σ_{ys} ratios.

ACKNOWLEDGMENT

These investigations were supported in part by the Deep Submergence Systems Project Office, Code DSSP-221; the Naval Ship Systems Command, Code 03422; the Office of Naval Research; and the Advanced Research Projects Agency of the Department of Defense as part of the ARPA Coupling Program on Stress Corrosion Cracking (ARPA Order 878).

REFERENCES

1. Judy, Jr., R.W., and Goode, R.J., "Stress-Corrosion Cracking Characteristics of Alloys of Titanium in Salt Water," NRL Report 6564, July 21, 1967

2. Pellini, W.S., "Advances in Fracture Toughness Characterization Procedures and in Quantitative Interpretations to Fracture-Safe Design for Structural Steels," Welding Res. Council Bull. 130, May 1968

3. Brown, B.F., "A New Stress-Corrosion Cracking Test for High-Strength Alloys," Mater. Res. and Stand. 6 (No. 3): 129-133 (1966)

4. "Proposed Method of Test for Plane-Strain Fracture Toughness of Metallic Materials," ASTM Standards on "Physical and Mechanical Testing of Metals; Nondestructive Test," Part 31, pp. 1099-1114, May 1969

5. Goode, R.J., Judy, Jr., R.W., and Huber, R.W., "Procedures for Fracture Toughness Characterization and Interpretations to Failure-Safe Design for Structural Titanium Alloys," Welding Res. Council Bull. 134, Oct. 1968

6. Judy, Jr., R.W., Goode, R.J., and Freed, C.N., "Fracture Toughness Characterization Procedures and Interpretations to Fracture-Safe Design for Structural Aluminum Alloys," Welding Res. Council Bull. 140, Apr. 1969

7. Pellini, W.S., and Loss, F.J., "Integration of Metallurgical and Fracture Mechanics Concepts of Transition Temperature Factors Relating to Fracture-Safe Design for Structural Steel," Welding Res. Council Bull. 141, June 1969

8. Pellini, W.S., "Evolution of Engineering Principles for Fracture-Safe Design of Structural Steels," NRL Report 6957, Sept. 23, 1969

9. Novak, S.R., and Rolfe, S.T., "K_{Ic} Stress Corrosion Tests of 12Ni-5Cr-3Mo and 18Ni-8Co-3Mo Maraging Steels and Weldments," U.S. Steel Applied Research Laboratory Report 39.018-00 (34) (S-23309-2), Jan. 1, 1966

10. Benjamin, W.D., and Steigerwald, E.A., "Stress Corrosion Cracking Mechanisms in Martensitic High Strength Steels," Air Force Materials Laboratory Technical Report TR-67-98, Apr. 1967

11. Peterson, M.H., Brown, B.F., Newbegin, R.L., and Groover, R.E., "Stress Corrosion Cracking of High Strength Steels and Titanium Alloys in Chloride Solutions at Ambient Temperature Corrosion," Corrosion 23 (No. 5) May 1967

12. Novak, S.R., and Rolfe, S.T., "K_{Iscc} Tests of HY-180/210 Steels and Weld Metals," U.S. Steel Applied Research Laboratory Report 39.018-007 (12) (B-63105, B63304), Aug. 1, 1967

13. Novak, S.R., "Effect of Plastic Strain on the K_{Iscc} of HY-80, HY-130(T), and 12Ni-5Cr-3Mo Steels," U.S. Steel Applied Research Laboratory Report 39.018-007 (20) (B-63201), Jan. 1, 1968

14. Smith, J.H., and Rolfe, S.T., "Effects of Welding Position and Process on the K_{Iscc} of HY-130(T) Weld Metals," U.S. Steel Applied Research Laboratory Report 39.018-016 (7) (B-33204), Jan. 1, 1968

15. Conner, L.P., Porter, L.F., and Rolfe, S.T., "Third Progress Report: Development of an HY-180/210 Weldment," U.S. Applied Research Laboratory Report 39.018-007 (21) (B-60000-2), Jan. 1, 1968

16. Smith, J.H., and Rolfe, S.T., "K_{Iscc} Behavior of Weld Metals Used in Fabrication of an HY-130 (T) Steel Structure," U.S. Steel Applied Research Laboratory Report 39.018-015 (4) (B-10000-3), Jan. 1, 1968

17. Smith, J.H., and Rolfe, S.T., "Effect of Composition on the K_{Iscc} of Experimental HY-150 Steels," U.S. Steel Applied Research Laboratory Report 39.018-016 (10) (B-23104), Dec. 20, 1968

18. Dabkowski, D.S., Konkol, P.J., Novak, S.R., and Porter, L.F., "Evaluation of the HY-9-4-20 Steel Weldment System," U.S. Steel Applied Research Laboratory Report 39.018-007 (30) (B-61209-1), Jan. 2, 1969

19. Webster, D., "The Use of Deformation Voids to Refine the Austenite Grain Size and Improve the Mechanical Properties of AFC 77," The Boeing Company Document D6-23879, Feb. 1969

20. Carter, C.S., "Stress Corrosion Crack Branching in High Strength Steels," Presented at ASM/WESTEC Conference, Los Angeles, California, Boeing Document D6-23871, Mar. 1969

21. Carter, C.S., "The Effect of Silicon on the Stress Corrosion Cracking Resistance of Low Alloy High Strength Steels," Boeing Document D6-23872, Mar. 1969

22. Sandoz, G., and Newbegin, R.L., "Stress-Corrosion Cracking Resistance of an 18Ni-200 Grade Maraging Steel Base Plate and Weld," NRL Memorandum Report 1772, Mar. 1967

23. Sandoz, G., and Brown, B.F., unpublished data

24. Judy, Jr., R.W., and Goode, R.J., "Stress-Corrosion Cracking Characterization Procedures and Interpretations to Failure-Safe Use of Titanium Alloys," NRL Report 6879, Apr. 8, 1969; The American Society of Mechanical Engineers Publication 69-MET-7 (to be published in the ASME Journal of Basic Engineering)

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

PROCEDURES FOR STRESS-CORROSION CRACKING CHARACTERIZATION AND INTERPRETATION TO FAILURE-SAFE DESIGN FOR HIGH-STRENGTH STEELS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final report on one phase of the problem; work is continuing on other phases.

5. AUTHOR(S) *(First name, middle initial, last name)*

R.W. Judy, Jr., and R.J. Goode

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 29, 1969	16	24

8a. CONTRACT OR GRANT NO. NRL Problems M01-25, F01-17, and M04-08A b. PROJECT NO. RR 007-01-46-5432 S-4607-11894 c. SF 51-541-012-14628 SF 51-541-001-12380 SF 51-541-003-12383 d. ARPA Order 878	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 6988 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Department of the Navy (Deep Submergence Systems Project Naval Ship Systems Command, and Office of Naval Research) and Advanced Research Projects Agency, Washington, D.C. 20360

13. ABSTRACT

The recently evolved Ratio Analysis Diagram (RAD) procedure is a useful engineering tool for generalized assessment of the fracture resistance of high-strength steels. Failure-safe design of large complex structures also requires consideration of subcritical crack growth caused by stress-corrosion cracking (SCC). Procedures developed to incorporate SCC characterizations into the RAD concept provide a more complete analysis of a material's resistance to fracture. The SCC-Dual RAD for high-strength steels presents simplified interpretations of the critical flaw size-stress instability conditions for both slow fracture (SCC) and fast fracture of these materials.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
High-strength steels Stress-corrosion cracking						