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STANDARD METHOD OF TEST FOR PLANE-STRAIN STRESS-CORROSION-CRACKING RESISTANCE OF METALLIC MATERIALS

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The long-term integrity of marine structures depends heavily on the inherent resistance of the structural material to the initiation and propagation of cracks in the seawater environment. In military structures, applied loads are very complex and the design models and laboratory verification experiments are correspondingly complex; however the utility of materials for many applications is decided by the simple characterization of the stress-corrosion-cracking sensitivity in terms of the linear-elastic threshold stress intensity K_{Iscc}. Because this parameter is important in selecting materials and designing marine structures, it is necessary to formulate a

(Continued)

standard method of test to insure uniformity of test results. This report is concerned with the cantilever method for determining K_{Iscc} for metallic materials.

CONTENTS

STANDARD METHOD OF TEST FOR PLANE-STRAIN STRESS-CORROSION-CRACKING RESISTANCE OF METALLIC MATERIALS

INTRODUCTION

The use of high-strength materials in modern naval structures to attain higher levels of performance requires application of the best available technology for dealing with expected problems. A sharp decline of fracture resistance with increasing yield strength is a phenomenon that has been known for many years; recently it has become apparent that increasing yield strength also carries the penalty of rapidly increasing sensitivity to crack propagation by saltwater stress-corrosion cracking (SCC), sustained-load cracking (SLC), and fatigue and corrosion-fatigue crack growth. Materials that are transitional with respect to crack growth are being used in critical components of prototype and fleet ships; the long-term reliability of these and other structures depends almost entirely on the resistance to crack growth inherent to the material.

Because the deleterious effects of accelerated crack growth in structures designed to carry high stresses for extended lifetimes are the dominant factors defining lifetime integrity of marine structures, an organized approach to designing reliability into the product from the beginning is an essential first step toward preventing long-term maintenance problems. The evolving methodology for this purpose is called *structural integrity* (SI) technology; SI technology deals with all phases of crack propagation and fracture, the characterization of material properties formulation of crack growth laws, design use of this information, and life-cycle monitoring of critical components and structures. Implementation of SI technology as a contract obligation in Navy hardware-acquisition projects is a present course of action, following the approach taken by the Air Force.

The present test methods for defining the properties of materials related to SCC initiation and growth were founded by Brown [1] at NRL. His development of the cantilever test was the first application of linear elastic fracture mechanics to characterize the threshold level of stress intensity K_{Iscc} above which SCC could be shown to occur. Subsequent work resulted in other test specimen configurations and concepts to measure the K_{Iscc} parameter [2,3], massive characterization of materials suspected of being sensitive to SCC, adaption of the Ratio Analysis Diagram (RAD) for combined analysis of SCC and fracture properties [4-7], and efforts devoted to verifying the significance of the K_{Iscc} parameter and the structural analyses derived from it.

The technology has developed to the point where standardization of the test method has become essential; the primary impetus for this is the mandatory use of the K_{Iscc} parameter in hardware design by Navy contractors. There is an effort in ASTM to standardize methods for measurement of K_{Iscc} ; however it will be some time before the practice attains the status of a full ASTM Standard. For Navy purposes the cantilever test specimen offers advantages that outweigh other factors, particularly for transitional type materials; the primary reason is the positive identification of crack propagation in test specimens. Since the cantilever method is preferred, a standard method of test has been drafted along the lines of ASTM standards previously published for fracture.

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1. SCOPE

This method covers the determination of the plane-strain stress-corrosion-cracking (SCC) resistance of metallic materials by a cantilever bend test of a notched and fatigue-cracked specimen having a thickness of 0.25 in. or greater.

2. APPLICABLE DOCUMENTS

Ref. A: Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials, ASTM Standard E399-72, Annual Book of ASTM Standards, Part 31, July 1972, p. 955.

3. SUMMARY OF METHOD

The method involves cantilever loading of fatigue-cracked bend specimens to determine the threshold stress intensity for the onset of SCC. A bracketing technique using measured values of stress intensity (K_I) for conditions of "crack growth" (K_{Icg}) and "no-crack growth" (K_{Incg}) is used to find the threshold stress-intensity level, K_{Iscc}. Values of K_I are calculated from existing equations defining the elastic-stress analysis for the cantilever specimen. Similarities of SCC tests with fracture toughness tests have resulted in referencing of sections of Ref. A, particularly those pertaining to preparation of the test specimen. Because of complexities in using the technology developed for fracture to define crack-growth phenomena, requirements for establishing the presence of environmental crack growth on the test specimen and tests of specimens in an inert environment are included in the specification.

4. SIGNIFICANCE

4.1 The property K_{Iscc} determined by this method characterizes the resistance of a material to crack growth due to combined effects of applied stress intensity and an aggressive environment. SCC is detrimental to the performance of all structures in that it can lead to fracture or can cause severe inspection, repair, and maintenance problems in structures that must operate in aggressive environments. The parameter K_{Iscc} provides a means of analyzing the crack growth in quantitative terms, based on existing fracture mechanics technology.

4.2 The plane-strain K_{Iscc} value is a property of the material that must be determined under controlled laboratory conditions to insure uniformity of test results. Application of test results to a design problem must be made with an awareness of differences in laboratory procedures and field conditions that often are not expressed in exact terms. It is noted that K_{Iscc} defines only the threshold of stress intensity for initiation of SCC from a preexisting crack. The test conditions used to define K_{Iscc} are such that crack growth may be expected at applied K_I levels above K_{Iscc}, but crack growth below K_{Iscc} at times longer than the test duration is not ruled out.

4.3 The advantages of cantilever-bend tests are the use of inexpensive test equipment for long-time tests and the increasing K field with crack growth that provides positive evidence of SCC initiation.

5. DEFINITIONS

5.1 *Stress-intensity factor* (K_I) is a measure of the stress-field intensity near the tip of an ideal crack in a linear elastic medium when deformed so that the crack faces are displaced apart, normal to the crack plane (opening mode or mode I deformation). K_I is directly proportional to applied load and depends on specimen geometry.

5.2 *Stress-corrosion cracking* (SCC) is the growth of a crack by any micromechanism due to the combined effect of stress and an aggressive environment.

5.3 *SCC threshold stress intensity* (K_{Iscc}) is the material resistance to crack growth measured in terms of the plane-strain stress intensity factor K_I by the operational procedure specified in this test method.

5.31 In this method measurement of K_{Iscc} is based on the combination of the lowest applied level of stress intensity at which significant measurable crack growth occurs and the highest applied level at which no crack growth occurs for a specified time period. Significant crack growth must be demonstrated to be due to environmental effects, either by microscope analysis or by testing of a control specimen by the same procedures in an innocuous environment. In many cases plane-strain K_I values may be measured to comply with all requirements except that of crack growth; such results are not attributable to environmental effects and are thus not defined as K_{Iscc} .

6. APPARATUS

6.1 The procedure involves testing of fatigue precracked specimens by deadweight-loaded or by hydraulically loaded cantilever test machines. The required measurements are load and time to final failure of the specimen.

6.2 Any stable test machine capable of withstanding the required applied loads can be used for cantilever tests. The load arm should be sufficiently stiff that defections due to load do not cause significant deviation of the applied load from the normal to the test section, i.e., that the moment calculated as force times distance is not significantly in error due to arm deflection.

6.3 Some means should be employed to determine whether crack growth is taking place during the test. Two methods are suggested: a standard beam-type clip gage as described in Ref. A and a simple dial gage to monitor displacement of the arm. Both of these methods provide indications of the crack opening associated with crack growth.

7. SPECIMEN CONFIGURATIONS, DIMENSIONS, AND PREPARATION

Specimen size and preparation specifications shall meet the requirements of Ref. A, paragraph 7, that pertain to bend specimens.

8. PROCEDURE

8.1 The number of tests is that required to define K_{Iscc}, as described in paragraph 9

8.2 All specimen dimensions, tolerances, and methods of measurements shall be defined in Ref. A, paragraph 8.2.

8.3 To initiate a test, set up the test rack or machine so that the fixed end of the specimen is clamped securely and the extension arm will be horizontal at the expected load. Apply the test environment to the specimen before the load is applied. Load the specimen such that the rate of stress-intensity increase is within the range of 30,000 to 150,000 psi$\sqrt{\text{in.}}$ per minute. In the case of deadweight loading the load should be applied by lowering the load pan by means of a hydraulic jack or crane, etc., rather than by step increases.

8.4 Continue the test until the specimen fractures or until it becomes apparent that crack growth is not present. If the crack is not growing, the K_I value calculated from the initial loading can be used as a K_{Incg} point. Because of effects of plastic flow and general corrosion to blunt the fatigue crack, subsequent loading of the specimen cannot be used to calculate K_{Incg} points. Although the K_I values calculated from load increments applied subsequent to the initial loading cannot be reported as valid data points, they may be useful in bracketing the K_{Iscc} value.

9. CALCULATION AND INTERPRETATIONS OF RESULTS

9.1 For determination of K_{Iscc} with the cantilever specimen configuration, it is necessary to measure the specimen dimensions as outlined in section 8. Using these dimensions, calculate an applied K_I by the equation

$$K_I = \frac{4.12\ M\sqrt{\frac{1}{\alpha^3} - \alpha^3}}{BW^{1.5}},$$

where

$\alpha = 1 - a/W$,

M = applied moment (in.-lb),

B = thickness of specimen (in.),

W = depth of specimen (in.),

a = depth of machined notch plus fatigue crack (in.).

Side grooves or face notches may be employed to maintain a straight crack front during fatique precracking. The depth of each side groove is limited to 5% of the specimen thickness, or 10% total reduction of specimen width. To correct for side grooves, multiply the applied K determined from the above equation using the full specimen width (neglecting side grooves) by $(B/B_n)^{1/2}$, where B_n is thickness of specimen minus depth of side grooves. Check the applied K_I for validity according to the dimensional criteria

$$a, B \geq 2.5\,(K_I/\sigma_{ys})^2\ .$$

The results that are used to determine K_{Iscc} must meet this and the following requirements:

- K_{Incg} points are those determined from the first application of load on the specimen.
- K_{Icg} points are those determined from the first or second application of load.
- The minimum time for a K_{Incg} point shall be 1.5 times the maximum time measured for complete specimen fracture in a valid K_{Icg} point, or 100 hours for titanium and 1000 hours for steel, whichever is higher.
- The maximum difference of K_{Iscc} between the highest K_{Incg} point and the lowest K_{Icg} point shall be 10% of the average:

$$K_{Icg} - K_{Incg} \leq 0.10\,\frac{(K_{Icg} + K_{Incg})}{2}\ .$$

- K_{Iscc} shall be the average of the highest K_{Incg} point and the lowest K_{Icg} point determined as above.

9.2. Suggested experimental procedures.

9.2.1 Bracketing method for short-time tests.

1. Determine the tensile yield strength and (if possible) the fracture resistance (K_{Ic} or Dynamic Tear test energy) of the test material. From the above information, estimate the expected K_{Iscc} value.

2. From preliminary measurement of the specimen dimensions calculated the load necessary to give an applied K_I equal to the estimated K_{Iscc}. Load the specimen and maintain the load for the minimum time to get a K_{Incg} data point.

3. If crack growth is observed on the first specimen, calculate the K_{Icg} value. Repeat step 2 for a new specimen at a lower estimated K_{Iscc} value.

4. If no crack growth is observed during the initial loading period, increase the load to a K_I value approximately 20% higher and maintain the load at this level for the minimum time period.

5. If no crack growth occurs in this time period, repeat step 4. If the specimen should evidence crack growth, allow the crack to grow until complete failure of the specimen.

6. For subsequent specimens the initial K_I should be the average of the highest K_{Incg} point and the lowest K_{Icg} point. By repeating the process the difference should quickly narrow to a valid K_{Iscc} value.

7. The final K_{Iscc} value is defined as the average of the highest K_{Incg} point and the lowest K_{Icg} point.

9.2.2 Bracketing method for long-time tests.

1. When long runout times are expected, it is advantageous to simultaneously test a series of specimens at different values of initial applied K_I to bracket K_{Iscc} . For example a series of eight specimens loaded at 10-ksi$\sqrt{in.}$ increments from 20 to 100 ksi$\sqrt{in.}$ might be used to locate the range of K_{Iscc} to within 10 ksi$\sqrt{in.}$ on the first series of tests. Tests of additional specimens for more accurate definition of K_{Iscc} may be necessary. It is cautioned that effects of incubation in many steels might lead to long-term runout values; therefore the experiments should not be terminated too quickly from results indicating early crack growth at the higher values of applied K.

9.3 Paragraph 9.7 of Ref. A shall be used to describe crack-plane orientation in bend specimens.

10. REPORT

The report shall include the following for each specimen tested:

Thickness B,

Depth W,

Crack length measurements,

Fatigue precracking conditions including

  Maximum stress intensity K,

  Number of cycles for terminal fatigue cracking,

  Stress intensity for terminal crack extension,

  Composition of environment,

  Test time,

  Load history,

  Crack plane orientation,

  Fracture appearance, including evidence of crack growth,

  Yield strength (0.2% offset),

  K_{Icg} and/or K_{Incg} .

  Calculation for validity according to specimen dimensions.

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