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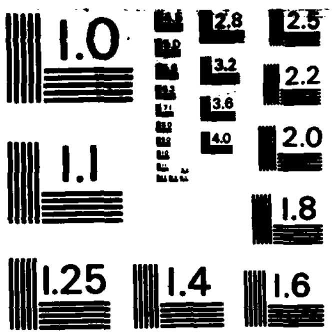

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

High-strength alloys exposed to a marine environment may undergo stress-corrosion-cracking (SCC). To obtain a reliable data base of SCC information, it is necessary to formulate standard methods of test to assure uniformity of results. This document sets forth recommended procedures for the two most popular SCC tests methods, single-edge-notched cantilever bend and wedge-opening-loaded (WOL).

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11. TITLE (Include Security Classification)

DRAFT STANDARD METHOD OF TEST FOR PLANE-STRAIN STRESS-CORROSION-CRACKING RESISTANCE OF METALLIC MATERIALS IN MARINE ENVIRONMENTS

18. SUBJECT TERMS (Continued)

Bolt-loaded wedge-opening-loaded test
K_{Iscc} parameter

CONTENTS

DRAFT STANDARD METHOD OF TEST FOR PLANE-STRAIN STRESS-CORROSION-CRACKING RESISTANCE OF METALLIC MATERIALS IN MARINE ENVIRONMENTS

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INTRODUCTION

The use of high strength alloys in naval applications introduces the possibility of stress-corrosion cracking (SCC) - cracking under sustained tensile stress in a corrosive environment. In the mid 1960's, Brown [1] at NRL developed a cantilever bend test method for determining a fracture mechanics based threshold value for stress-corrosion cracking, K_{Iscc}. K_{Iscc} was defined as the limiting stress-intensity factor below which no SCC growth would occur. Later, alternate test methods were developed to determine K_{Iscc} [2, 3]. Two test methods emerged from the 1970's as the most widely used, the bolt-loaded wedge-opening-loaded (WOL) and the cantilever bend. Much work has been done using both test methods. However, no standard test method has been adopted, although there has been progress towards standardization by ASTM [4] and NRL [5].

The development and application of a Navy materials data base requires standard test methods. Experience has shown that in the absence of common experimental procedures, interlaboratory variability amongst data can be quite large and can lead to questions on the validity of the basic technology, when in actuality it is the test method which is at fault. This test method document has been prepared to serve as an aid in developing reliable K_{Iscc} data for the Navy.

1. SCOPE

1.1 This method covers the determination of the plane-strain stress-corrosion cracking (SCC) resistance of metallic materials exposed to aqueous marine environments. Single-edge-notched cantilever bend and bolt-loaded WOL specimens are covered.

1.1.1 SCC resistance can be measured by the threshold stress intensity factor, K_{Iscc}, and by crack growth kinetics, da/dt vs K_I.

Manuscript approved January 4, 1984.

2. APPLICABLE DOCUMENTS

2.1 E 399-81, "Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials", in 1982 Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, 1982, Part 10, pp. 592-622.

2.2 E 616-81, "Standard Terminology Relating to Fracture Testing", ibid, pp. 736-745.

2.3 E 647-81, "Standard Test Method for Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10^{-8}m/Cycle", ibid, pp. 772-790.

2.4 G 3-74, "Standard Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing", ibid, pp. 884-892.

2.5 G 15-82, "Standard Definitions of Terms Relating to Corrosion and Corrosion Testing", ibid, pp. 917-921.

2.6 R. W. Judy, Jr. and R. J. Goode, "Standard Method of Test for Plane-Strain Stress-Corrosion-Cracking Resistance of Metallic Materials", NRL Report 7865, March 17, 1975.

2.8 J. A. Joyce, D. F. Hasson, and C. R. Crowe, "Computer Data Acquisition Monitoring of the Stress Corrosion Cracking of Depleted Uranium Cantilever Beam Specimens", Journal of Testing and Evaluation, Vol. 8, No. 6, November 1980, pp. 293-300.

2.9 NMAB-386, "Characterization of Environmentally Assisted Cracking for Design", National Materials Advisory Board Report 386, National Academy Press, Washington, DC, 1982.

2.10 S. R. Novak and S. T. Rolfe, "Modified WOL Specimen for K_{Iscc} Environmental Testing," Journal of Materials, JMLSA, Vol 4, No. 3, September 1969, pp. 701-728.

2.11 A. Saxena, and S. J. Hudak, Jr., "Review and Extension of Compliance Information for Common Crack Growth Specimens", International Journal of Fracture, Vol. 14, (1978), pp. 453-468.

2.12 T. W. Crooker, F. D. Bogar and G. R. Yoder, "Standard Method of Test for Constant-Load-Amplitude Fatigue Crack Growth Rates in Marine Environments", NRL Memorandum Report 4594, August 6, 1981.

3. SUMMARY OF METHOD

3.1 The method involves both constant-load cantilever bend testing and constant-displacement WOL testing.

3.1.1 Cantilever loading of fatigue-cracked specimens is used to determine the SCC threshold stress intensity factor, K_{Iscc}. A bracketing technique using measured values of initial K_I for conditions of "crack growth" and "no crack growth" is used to determine K_{Iscc}.

3.1.2 Cantilever loading of fatigue-cracked specimens can also be used to obtain crack growth kinetics of SCC, da/dt vs K_I. By use of a crack length measurement technique, (e.g. a crack opening displacement (COD) clip gage and the appropriate compliance equation given in 2.10) crack length, a, can be determined and crack growth rates can be computed.

3.1.3 Bolt loading a precracked WOL specimen gives a constant displacement loading, which results in a decreasing K_I as the crack extends. With an appropriate initial displacement (and corresponding K_I) stress-corrosion cracking will initiate in the WOL specimen but will then arrest as the crack extends and K_I decreases. The K_I value at arrest is K_{Iscc}.

3.1.4 By measuring crack length (e.g. with an optical microscope) appropriate values of a, da/dt, and K_I can be calculated during a WOL test. These values define crack growth kinetics of SCC.

SIGNIFICANCE

4.1 Many materials exhibit susceptibility to cracking in a marine environment at static stress intensities well below fracture levels obtained under monotonic loading. This method offers a quantitative, fracture mechanics based measure of a material's stress-corrosion cracking performance. The property, K_{Iscc}, determined by this method characterizes the resistance of a material to SCC. 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 marine environments.

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 for a finite test time. 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 Crack growth rates, da/dt, as a function of K_I, determined by this method are useful in optimization and sensitivity studies; and for the case of the bolt-loaded WOL offers a measure of the approach of crack arrest.

5. DEFINITIONS

5.1 crack length, a - the physical crack length used to determine the crack growth rate and the stress intensity factor. For the WOL specimen, "a" is measured from the load line (centerline of bolt).

5.2 crack (mouth) opening displacement, COD - the displacement at the crack mouth, normally measured by a clip gage spanning the crack at the specimen edge.

5.3 crack (mouth) opening displacement calibration, COD-calibration - a mathematical expression, based on experimental or analytical results that relates crack (mouth) opening displacement to crack length for a specific specimen geometry.

5.4 crack plane orientation - an identification code of the plane and direction of a crack in relation to product geometry. Code definition is found in 2.1.

5.5 stress-corrosion cracking, SCC - crack extension caused by the simultaneous action of a sustained tensile stress and an aggressive environment.

5.6 stress-intensity factor, K - a measure of the crack-tip stress field in a linear-elastic material. In this method, Mode I (opening mode) crack extension is assumed.

5.7 stress-corrosion cracking threshold, K_{Iscc} - a level of sustained loading, as defined by linear elastic fracture mechanics, below which SCC does not occur in a specified combination of material and environment.

6. APPARATUS

6.1 The cantilever bend procedure involves testing of fatigue precracked specimens by constant loading. The required measurements are load and time. Crack growth rate measurements are optional.

6.1.1 Any stable test frame capable of withstanding the required applied loads can be used for cantilever tests. The frame and load arm should be sufficiently stiff that deflections 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.

6.1.2 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 2.1 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.

6.2 The bolt-loaded WOL procedure requires no special equipment for the test. However, some means of accurately measuring the final load is required. A suggested means is the use of a clip gage and servohydraulic test machine to duplicate the COD once the loading bolt is removed.

6.2.1 Visual or COD-compliance measurements of crack growth are recommended. Other means such as ultrasonic or potential drop may be used if accuracy of ± 0.005 inch can be assured.

7. SPECIMEN CONFIGURATION, SIZE AND PREPARATION

7.1 Standard Specimens - The geometries of standard cantilever bend and WOL specimens are given in Fig. 1 and Fig. 2, respectively. Bolts used for loading must be SAE Grade 8 or equivalent and the load pins must be Rockwell C 50 or harder.

7.2 Specimen Size - For determination of valid K_{Iscc} the critical specimen dimensions are thickness, B, and uncracked ligament, W-a. A conservative requirement for these dimensions is given in 2.1: i.e. B and $(W-a) \geq 2.5 (K_{Iscc}/\sigma_{ys})^2$, where σ_{ys} is yield strength. However, recent studies suggest that requiring B and $W-a \geq 1.0 (K_{Iscc}/\sigma_{ys})^2$ is sufficient. Special note should be made of test values which fail to meet the former criterion but are valid per the latter criterion.

8. PROCEDURE

8.1 Number of Tests

8.1.1 The number of tests for the cantilever method is that required to define K_{Iscc} as described in 8.3.3.

8.1.2 It is recommended that replicate tests at the same starting K_I level be conducted for the WOL method.

8.2 Specimen Machining and Precracking - Specimens shall be machined to the dimensions shown in Fig. 1. Applicable detail dimensions and tolerances shall be per 2.1. Precracking shall be in accordance with 2.1 and may be conducted in air. Side grooving is recommended, to a maximum 20% total thickness, with a V-notch with tip radius < .010 inch.

8.3 Cantilever Bend Test Procedure

8.3.1 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 less than 150 ksi $\sqrt{in.}$ 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., or by small step increases.

8.3.2 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} (K_I with no crack growth) 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 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 detemining K_I values to be used in subsequent tests.

8.3.3 Bracketing procedure for cantilever specimen:

8.3.3.1 Long Runout Tests - 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 at low K_I values should not be terminated too quickly.

8.3.3.2 Short Time Tests - When short time tests are run, results (either crack growth or no crack growth) from one test can be used to determine the load for the next specimen. If no crack growth occurs in the test time, increase the K_I level 20% and repeat until crack growth occurs. Then load to the average of K_I and K_{Icg} and repeat until a sufficiently narrow step is used. Alternately, if at first crack growth occurs step down 20% until no crack growth occurs and then decrease the step size until a sufficiently small step is used. The final K_{Iscc} value is defined as the average of the highest K_{Incg} point and the lowest K_{Icg} point.

8.4 WOL Test Procedure

8.4.1 Measure initial crack length (based on W-a measurements) on both specimen surfaces. The end of the crack tip can be seen most clearly if a small (much less than the test load) bolt loading is applied to the specimen while measuring the crack. A piece of tape or other suitable protection should be placed on the back edge of the specimen to preserve the reference surface for future crack length measurements.

8.4.2 Using an average value of measured initial crack length, a_o, compute the necessary initial crack mouth opening displacement (measured at the front face of the specimen), V, for the desired initial stress intensity factor, K_{Io}, from eq. (1):

$$V = \frac{K_{Io}\sqrt{a}}{EB} \cdot \frac{C_6\ (a/W)}{C_3\ (a/W)} \qquad (1)$$

where: $$C_3\ (a/W) = 30.96\ (a/W) - 195.8\ (a/W)^2 + 730.6\ (a/W)^3 - 1186.3\ (a/W)^4 + 754.6\ (a/W)^5 \qquad (2a)$$

$$C_6\ (a/W) = \exp\left(4.495 - 16.13\ (a/W) + 63.838\ (a/W)^2 - 89.125\ (a/W)^3 + 46.815\ (a/W)^4\right) \qquad (2b)$$

These expressions are from 2.10 and are correct for crack mouth opening measurements made at the front face of the specimen (i.e. when integral knife edges are used as shown in Fig. 1). If a different location is used (e.g. removeable knife edges), different expressions are necessary and a procedure similar to the method used in 2.11 must be used to find the applicable expression. The range of applicability is a/W from 0.30 to 0.80.

8.4.3 It is important that initial loading take place in the test environment. To accomplish this apply tape (cellophane, adhesive, etc.) to both sides of the specimen along the crack to form a "dam" and place a few drops of test solution in the notch before applying the load. Be sure the crack tip is wetted by the solution. The tape strips should be removed immediately prior to placing the specimen into the actual test solution.

8.4.4 Using a clip gage to measure crack mouth opening, bolt-load the specimen in a vise to the desired V_o.

8.4.5 Place the specimen in the test solution such that the bolt and loading pin do not contact the test solution and that the crack tip is at least 1/4 inch below the solution surface.

8.4.6 Test Termination - WOL Specimen. After the prescribed time interval or when it is determined that the crack has arrested, the specimen should be removed from the test solution.

8.4.6.1 Visually measure crack length on both surfaces.

8.4.6.2 Measure crack mouth opening displacement, V_f, unload specimen and again measure COD, this change in crack mouth opening displacement is ΔV_T unloading.

8.4.6.3 Reload specimen in a tensile test machine to the measured ΔV_T. The load required to produce a crack mouth opening displacement equal to ΔV_T is taken as the applied load at test termination, P_f.

8.5 <u>Crack Growth Measurement - If Required</u>. Any method of crack length measurements that can be verified accurate within $\pm$0.005 inch may be used.

8.5.1 Cantilever bend crack length measurements must be made with the specimen in place. Clip gage readings in conjunction with COD calibration expressions may be used. See 2.8.

8.5.2 WOL specimen crack growth measurements may be made optically or by other means, such as an internally strain-gaged bolt to measure load. Visual measurements are made with the specimen removed from the test solution. The surfaces may need to be lightly cleaned. ("Scotch Brite" or silicon-carbide abrasive may be used.) Measurements should be taken on both sides to obtain accurate readings. Maximum recommended time out of the test solution is 20 minutes, and should be kept to an absolute minimum.

8.6 <u>Final Crack Length Determination</u>. At test termination if the specimen is not fractured, either of two methods may be used to mark the end of the SCC cracks.

8.6.1 Chill specimen to liquid nitrogen temperature and load specimen to failure, or

8.6.2 Fatigue specimen (same load used for precracking) so crack extends at least 0.05 inch, then load to failure.

8.6.3 Final crack length, a_f, is determined from the average of five measurements across the crack front, one at each specimen surface, one at each quarter thickness plane, and one at the mid-thickness plane. Crack lengths are obtained from measured ligament (W-a) values.

8.7 Environmental Considerations

8.7.1 Environmental parameters can have a profound effect on test results. Therefore, careful control and monitoring is recommended. Temperature, pH, conductivity, dissolved oxygen, and electrochemical potential are variables which should be monitored.

8.7.2 It is recommended that the test solution be continuously changed i.e. use of a circulating system with a flow rate equal to the reservoir volume per minute. However, if a quiescent system is used the test solution must be changed at least once per week, preferably more often.

8.7.3 For tests which involve maintaining the specimen at a controlled corrosion potential, use of a potentiostat is recommended rather than use of sacrificial anodes.

9. CALCULATIONS AND INTERPRETATION OF RESULTS

9.1 Determination of Stress-Intensity Factor, K_I

9.1.1 For the cantilever specimen the following expression can be used:

$$K_I = \frac{4.12\ M \left(\frac{1}{\alpha^3} - \alpha^3\right)^{0.5}}{B\ (W)^{1.5}} \qquad (3)$$

$\alpha = 1 - a/W$
M = applied Moment (in-lb)
B = thickness of specimen (in)
W = depth of specimen (in)
a = depth of notch plus fatigue crack (in)

Side grooves or face notches may be employed to maintain a straight crack front. The depth of each side groove is limited to 10% of the specimen thickness or 20% total reduction. To correct for side grooves, multiply the applied K determined by the above equation using the full specimen width (neglecting side grooves) by $(B/B_n)^{1/2}$ where B_n is the thickness of specimen minus depth of side grooves.

9.1.2 For the bolt-loaded WOL specimen the following expression can be used:

$$K_I = \frac{VEB}{\sqrt{a}} \frac{C_3}{C_6} \qquad (4)$$

where C_3 and C_6 are defined in paragraph 8.4.2.

9.1.3 Knowing the displacement at the front face, V, the following expression can be used to calculate the load, P, for a given crack length for the WOL specimen:

$$P = \frac{EBV}{C_6} \tag{5}$$

where C_6 is defined in paragraph 8.4.2.

$$V_{Load\ Line} = \left(\frac{a}{a+c_1}\right) V \tag{6}$$

where c_1 = distance from the front face to the load line

Use the value of P from Eq. (5) to find K_I:

$$K_I = \frac{P}{B\sqrt{a}} C_3 \tag{7}$$

9.1.4 If an instrumented bolt is used to determine the load, then Eq. (5) may be inverted to find a/W:

$$\frac{a}{W} = -.17958 - .11772 \left[\ln\left(\frac{EVB}{P}\right)\right] + .12522 \left[\ln\left(\frac{EVB}{P}\right)\right]^2 - .01571 \left[\ln\left(\frac{EVB}{P}\right)\right]^3 + .00044 \left[\ln\left(\frac{EVB}{P}\right)\right]^4 \tag{8}$$

and then K_I may be calculated using Eq. (7). Expressions in paragraphs 9.1.3 and 9.1.4 are applicable for a/W = .3 to a/W = .8. Side grooves may be accounted for by replacing B with $\sqrt{BB_n}$ where B_n is the thickness of the specimen minus the total depth of the side grooves.

9.1.5 Other valid expressions for K_I and P (e.g. reference (10)) may be used but clear, concise descriptions of the procedures must be contained in the report. The equations shown here are based on the assumption of an infinitely rigid bolt and tup. Document 2.10 discusses the consequences of not considering the elastic compliance of the bolt and tup and found the error to be small and conservative.

9.2 <u>Determination of Crack Growth Rate, da/dt</u>. Crack growth rate data are calculated from crack length, a, versus elapsed time, t, data. Any appropriate method (e.g. 7 point polynomial, secant, simple $\Delta a/\Delta t$) of obtaining da/dt may be employed. The procedure used must be detailed in the final report.

9.3 Crack Front Curvature. Some degree of crack front curvature of a tunneling nature may occur in fatigue precracking and in SCC growth. After testing, the fracture surfaces should be examined for evidence of crack tunneling. If there is visual evidence of a significant degree of crack front curvature, crack length correction procedures as detailed in Ref. 2.3 should be applied. However, if the crack front curvature correction results in a calculated stress intensity correction greater than 20%, the test is invalid.

9.4 Time. An extremely important consideration in any SCC testing is test duration. Crack incubation times for the material to be tested must be considered when determining the time to be used for K_{Iscc} definition. If no information is available on the material of interest the following times should be used as an absolute minimum:

Titanium	100 hours
Steels	1,000 hours
Aluminum	10,000 hours

10. REPORT

10.1 The report shall include the following information for each specimen tested.

10.1.1 Specimen type and principal dimensions, including thickness and width, for each specimen tested.

10.1.2 Descriptions of test equipment, crack length measurement equipment (if used), environmental chamber and all equipment used for environmental monitoring and/or control.

10.1.3 Description of the test material, including all relevant chemical, metallurgical and mechanical information available, including crack plane orientation as defined in 2.1.

10.1.4 Details of fatigue precracking, inclulding maximum K_I.

10.1.5 Composition of bulk solution.

10.1.6 Analysis methods for K, a, da/dt and P.

10.1.7 Fracture appearance, including evidence of crack growth and crack front curvature.

ACKNOWLEDGMENTS

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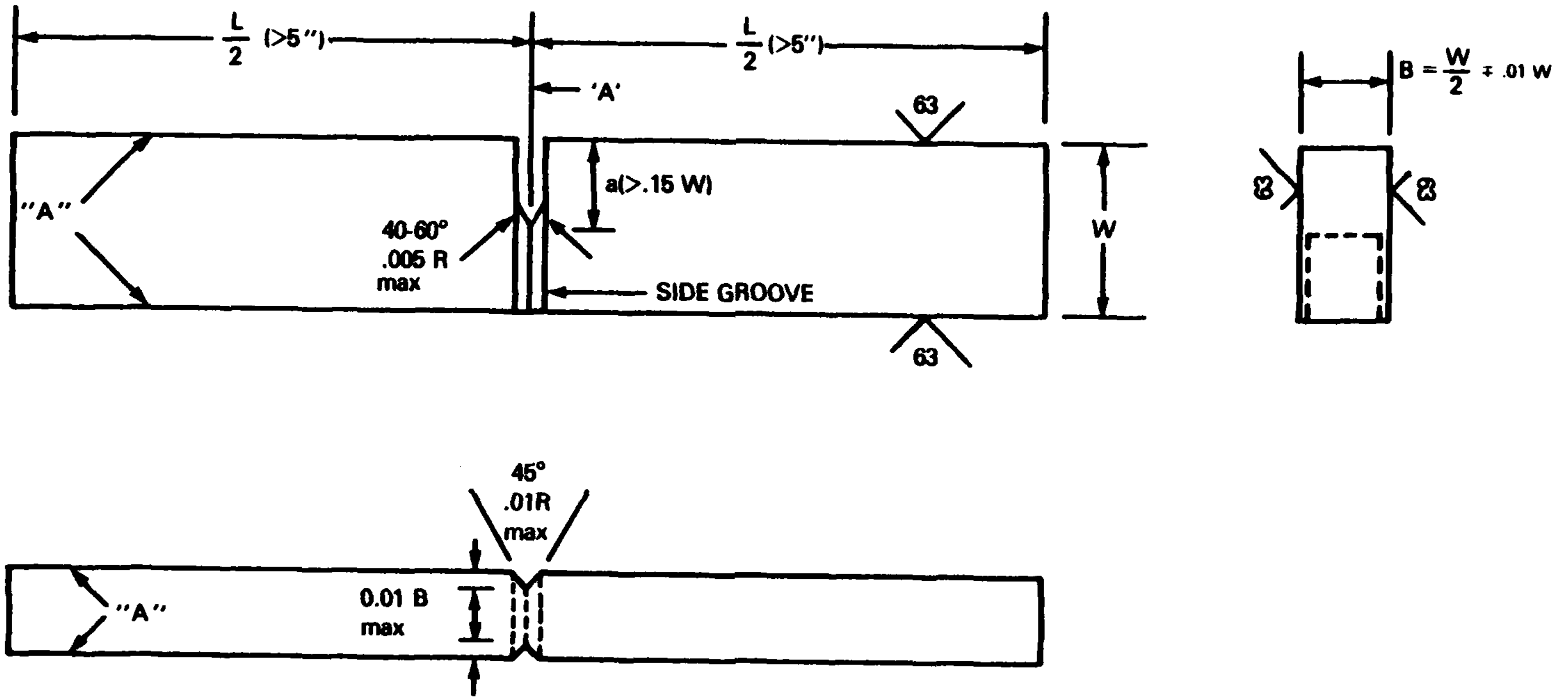
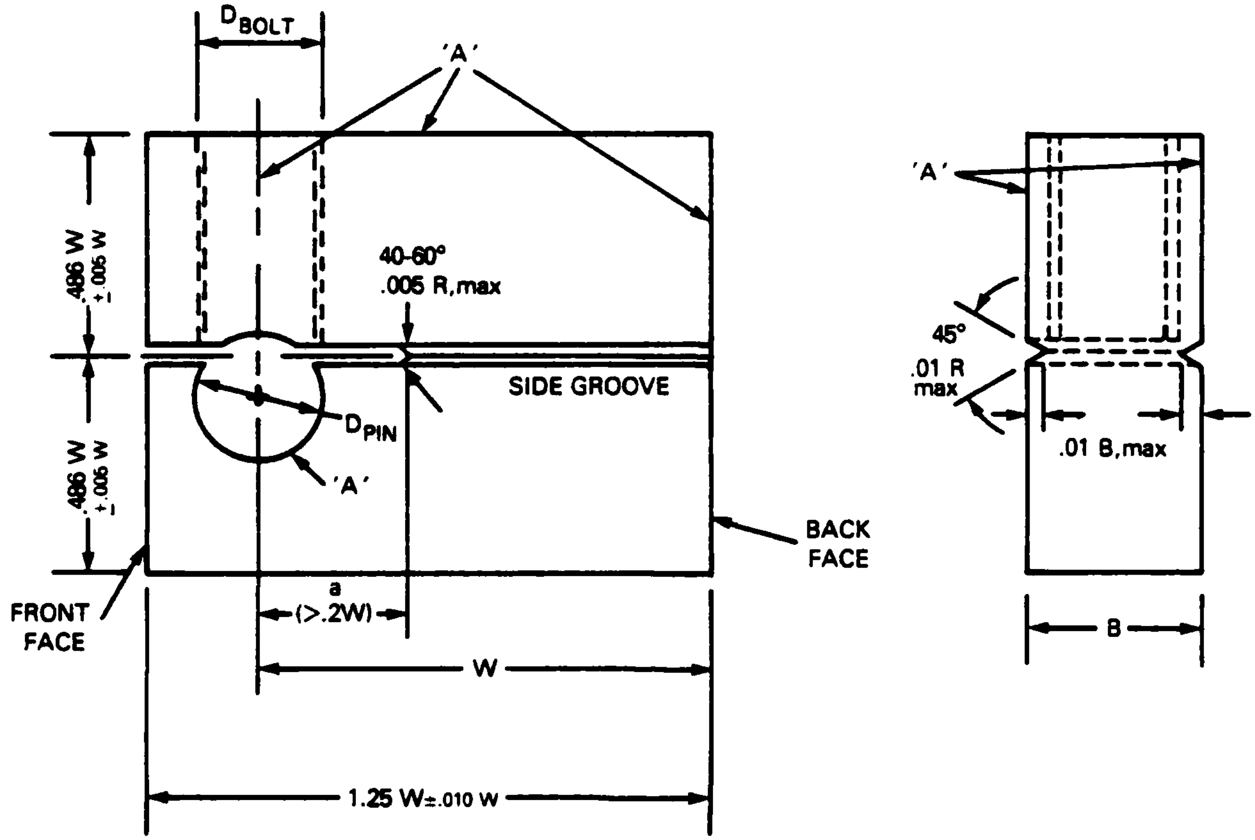


NOTE 1. "A" SURFACES TO BE ⊥ and ||, AS APPLICABLE, WITHIN .003 W TIR

Fig. 1 - Cantilever bend specimen



NOTE 1: ALL SURFACES 63√ OR BETTER
NOTE 2: "A" SURFACES TO BE ∥ AND ⊥, AS APPLICABLE, WITHIN .003 W TIR

FOR B = 1": D_{BOLT} = 5/8"-18 UNF

D_{PIN} = 7/8"

B = 2" D_{BOLT} = 1"-14 UNF

D_{PIN} = 1.125"

Fig. 2 - Bolt-loaded wedge-opening-loaded (WOL) specimen

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