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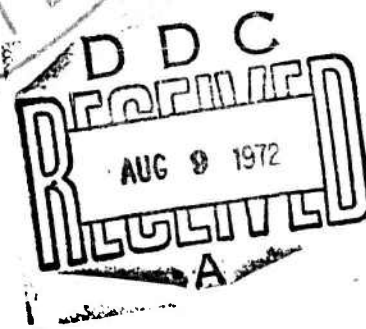
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DEVELOPMENT OF A STRESS CORROSION CRACKING TEST FOR ARMOR ALLOYS

DANIEL B. DAWSON
METALS DIVISION

June 1972

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ABSTRACT

A stress corrosion test has been developed for use with high-hardness armor alloys: it is self-loaded, and it can be used with any armor plate thickness. Initial trials have proven the validity of the test method, although several refinements are recommended. Further study is needed to determine whether or not the test method can be applied to specification and qualification test procedure. Data produced to date on one plate of XAR-30 high-hardness steel armor show that it is very susceptible to stress corrosion with K_{Isc} values from 15 to 19 ksi $\sqrt{\text{inch}}$.

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INTRODUCTION

High-strength materials are frequently found to have poor resistance to stress corrosion cracking (SCC). In particular, high-strength steels (yield strength over 200 ksi) which contain a crack or a sharp notch are often susceptible to SCC in water, or even in humid air.¹ Several failures of high-hardness armor plate in Army weapons systems have recently been attributed to stress corrosion.²

The present study was undertaken to develop a stress corrosion cracking test which could be used to evaluate armor plate of varying thicknesses, and to provide engineering data on the SCC resistance of several plates of high-hardness XAR-30 steel armor for use in specifications.

BACKGROUND

There is no universally acceptable test method for susceptibility to stress corrosion cracking. Until the recent development of SCC specimens designed using fracture mechanics principles, the most common types of SCC tests used smooth, uncracked specimens (e.g., tensile, U-bend, and bent beam specimens). However, in certain alloy systems, tests using unnotched specimens are not sufficiently discriminating. For instance, some high-strength steels in humid air or water environments,¹ and some titanium alloys in aqueous chlorides,³ are susceptible to SCC if a sharp crack is present, but are not susceptible in the absence of such a crack.

The Charpy test has traditionally been used to evaluate the toughness of materials, but it has certain limitations when applied to the high-strength materials which have been developed in recent years. For these materials, fracture-toughness tests provide a much better measure of resistance to flaw growth in noncorrosive environments, but the resultant values of K_{IC} are still not an adequate measure of resistance to SCC. For example, in a recent study for the Army Tank Automotive Command, Mostovoy and Ripling² have studied the SCC behavior of several plates of high-hardness armor steel. Of the four plates studied, two had cracked in service, one had cracked in storage, and one was procured direct from the producer (having been picked as representative of "good" material). The three failures had all occurred in circumstances indicative of stress corrosion cracking, even though measured values of fracture toughness were considered adequate in all three cases. However, stress-corrosion tests of all four plates, using precracked specimens, showed that the good plate had a threshold SCC stress intensity (K_{ISCC}) of approximately 40 ksi $\sqrt{\text{inch}}$, whereas the three failed plates exhibited K_{ISCC} values of 10 ksi $\sqrt{\text{inch}}$ or less.² From this, it is evident that fracture toughness tests alone are not a good measure of resistance to SCC for high-hardness armor alloys.

In summary, it may be concluded that SCC resistance of high-strength armor alloys cannot be adequately measured by mechanical properties tests such as toughness or fracture toughness tests, or by the traditional SCC tests using smooth specimens. Stress corrosion testing should be conducted with precracked fracture mechanics-type specimens in corrosive atmosphere representative of actual service

environments (such as moist air or aqueous solutions). The threshold stress intensity below which a crack will not propagate in a corrosive environment is commonly referred to as K_{Isc} , or K_{th} . It is this value which should be of primary interest when considering the SCC behavior of armor alloys.

SPECIMEN DESIGN

Design Considerations

In designing a fracture mechanics-type test for armor alloys, there are several factors of primary importance as well as several secondary considerations. The following were considered to be primary factors:

1. XAR-30 high-hardness steel armor and dual-hardness steel armor are difficult to machine by conventional techniques. Therefore, SCC specimens of these materials must be capable of being produced using electric discharge machining (EDM) and grinding.
2. Armor is used in a wide range of thicknesses. Either a single SCC specimen configuration must be found which is applicable to any thickness, or several tests may be used, each useful for a particular range of plate thicknesses. For obvious reasons, a single test is preferable.

Secondary factors, which are nonetheless important, include:

1. The specimen should be self-loaded. Self-loading enables a large number of specimens to be loaded and placed in corrosive environments, without requiring the continuous use of loading equipment (particularly such items as tensile and/or fatigue test machines) during the course of a test. Only the self-loading fixtures are in continuous use.
2. The specimen should be a crack-arrest type. As described in the following section, in a crack-arrest specimen, the crack opening displacement at the load line is held constant. As the crack propagates, the load (and hence the stress intensity) decreases, and the crack will stop when the stress intensity decreases to K_{Isc} . Thus, K_{Isc} can be determined from a single specimen,⁴ whereas other methods require numerous specimens.⁵
3. Since one purpose of this investigation was to develop a quality control type stress corrosion test for armor alloys, it is desirable for the test method (including specimen loading and measurement of K_{Isc}) to be as simple as possible, consistent with obtaining a valid measurement of K_{Isc} .

Stress Corrosion Cracking Specimen Designs

Two fracture mechanics specimens have been used extensively for SCC testing, and several others have seen more limited applications. Brown⁵ was the first to propose use of fracture mechanics in stress corrosion testing, and his cantilever beam specimen has been used to generate a large proportion of the K_{Isc} data available today. For armor applications, however, it has two drawbacks. First,

it is a constant load rather than a constant displacement (crack-arrest) specimen. More important, it is not applicable to thin plate thicknesses.

Novak and Rolfe⁴ proposed a modification of the WOL-T crack-line-loaded specimen geometry for SCC testing. It is a self-loaded specimen (bolt loaded) of the crack-arrest type. The bolt loading method has two serious drawbacks for our application, in that the necessity for producing the bolt hole requires a thickness of one inch or more, as well as drilling and tapping the hole. However, despite the difficulties inherent in the loading method, the basic principles of the self-loaded crack-arrest specimen put forward by Novak and Rolfe have been utilized in the specimen configuration selected for the armor SCC program.

The WOL-T geometry belongs to a large class of fracture specimens, frequently referred to as "crack-line-loaded" (CLL) or "double cantilever beam" (DCB) specimens. They are distinguished chiefly by (1) their method of loading, and (2) their H/W ratio. H/W is a geometrical factor relating H, the half-height of the specimen, and W, the distance from the load line to the end of the specimen (see Figure 1 for an explanation of how these dimensions relate to the WOL-T geometry, where $H/W = 0.486$). For a given H/W ratio, the compliance of a specimen should be unchanged regardless of the choice of the actual H and W dimensions.⁶

The specimen geometries belonging to the CLL or DCB class include:

1. Wedge-Open Loading, WOL-T ($H/W = 0.486$). This is the geometry used by Novak and Rolfe for their crack-arrest specimen.⁴ Scaling the H and W dimensions by a factor of two, this geometry was used for our initial armor SCC specimens, as reported here. This specimen is referred to as a WOL-2T geometry, despite the fact that a true WOL-2T has a thickness of 2 inches.

2. Compact Tension, CT ($H/W = 0.60$). In its pin-loaded variation, the compact tension geometry is widely used today for the measurement of fracture toughness. For reasons to be discussed subsequently, we have recommended that all further armor crack-arrest SCC specimens be made to the CT geometry rather than the WOL-T geometry.

3. Contoured DCB or Ripling Specimen ($H/W = \text{variable}$). The tapered test section of the contoured DCB keeps the stress intensity at the crack tip constant.⁷ It is useful for measuring stress corrosion crack velocities as a function of stress intensity, but is not applicable to K_{ISCC} measurements of the crack-arrest type.

4. Small H/W specimens. Several investigators have reported SCC tests using CLL specimens where H/W is quite low. Mostovoy and Ripling² report the use of a specimen where H/W is approximately 0.2, and Hyatt⁸ uses a specimen where H/W is approximately 0.1. The advantages and disadvantages of using a low H/W specimen are discussed below.

Choice of a specimen with a given H/W ratio entails several considerations. In a crack-arrest specimen, where stress intensity at the crack tip decreases with crack growth, the stress intensity which is reached as the crack grows completely through the specimen will depend on the initial stress intensity (which

Wedge-Loading of Crack-Line-Loaded Specimens

The specimen design chosen for initial SCC trials was the WOL-2T geometry (Figure 1). As noted, it is now recommended that the compact tension (CT2) geometry be used for all further tests. The only difference between the CT2 and the WOL-2T as shown in Figure 1 is the W dimension as shown in Table I.

The disadvantages inherent in Novak and Rolfe's bolt-loaded WOL-T specimen were overcome by using the wedge-loading system devised by Heyer and McCabe.^{9,10} This system, which is applicable to both the WOL-T and CT geometries, was originally devised for plane-stress testing of thin sheet materials.⁹ However, it is also applicable to stress corrosion testing, in which application it possesses several distinct advantages over other SCC test methods. It is a self-loaded crack-arrest-type specimen, which can be applied to any thickness of armor plate, from thin sheet to thick plate. And it is capable of being produced using only EDM and grinding.

Instead of pin-loading or bolt-loading the specimen at the load line, the specimen is loaded by forcing a wedge between two semicircular segments, which have been inserted in a 1.5-inch-diameter hole (see Figures 1, 2, and 3). Figure 2 is a photograph of the loading setup, and Figure 3 shows a section through the loading setup located at the load line. The essential features of loading process are shown in Figure 3. Both the wedge and the split segments have matching 3° tapers. The wedge is driven between the segments by the descending head of a Wiedemann-Baldwin tensile test machine, and the segments in turn force the crack in the specimen open. Because of the stick-slip nature of the motion of the wedge between the segments, it is essential that some form of displacement control rather than load control be employed on the machine being used to load the wedge.

The specimen rests on a loading block or fixture, with a thin Teflon sheet between them to allow free opening of the crack as the wedge is inserted. To prevent the segments from being pushed through the hole during insertion of the wedge, there are two support blocks which rest in a channel in the loading block. Their only purpose is to position the segments, and they are free to slide if pushed sideways by the descending wedge. Several hold-down clamps are provided to keep the specimen in place during loading. Their necessity is doubtful during loading of 1/2-inch-plate specimens as reported here, but they become increasingly important as specimen thickness decreases, since buckling of the specimen becomes more likely.

A loaded specimen is shown in Figure 4, with wedge and segments in place. Once the specimen is loaded, friction holds the wedge and segments in place, then the assembly may be placed in a corrosive bath to propagate a stress corrosion crack.

Table I. DIMENSIONS OF CRACK-LINE-LOADED SPECIMENS

Specimen Type	Wedge-Open-Loaded (WOL-2T)	Compact Tension (CT2)
H/W	0.486	0.600
H	2.48"	2.48"
W	5.10"	4.13"
thickness	(thickness of armor plate)	

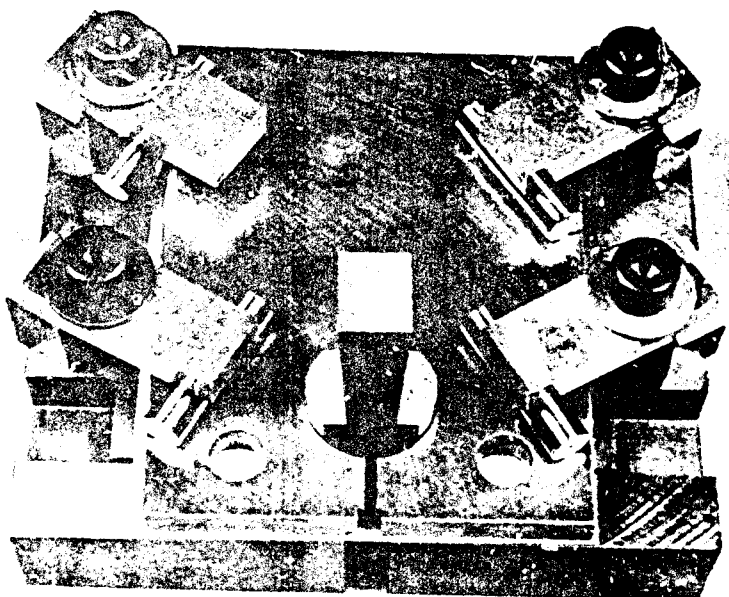


Figure 2. LOADING FIXTURE FOR
WEDGE-LOADED TYPE SPECIMENS
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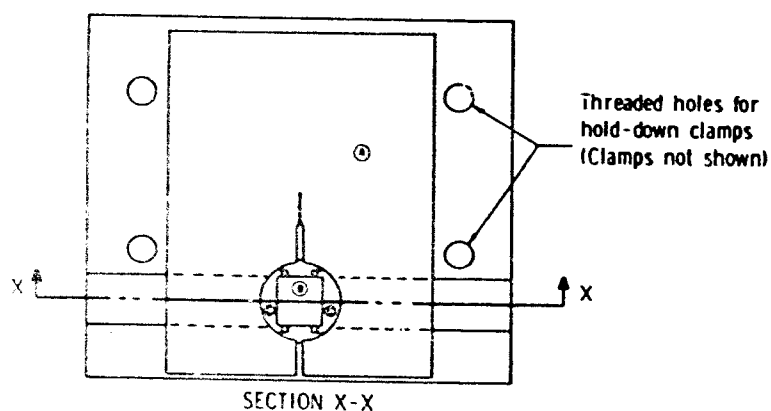
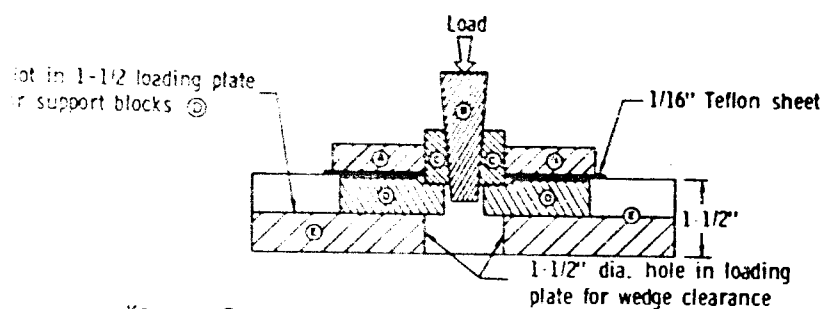


Figure 3. SCHEMATIC
DRAWING OF LOADING
SYSTEM
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- Key:
- ① SPECIMEN (WOL 2T SHOWN)
 - ② TAPERED WEDGE
 - ③ TAPERED SEMI CIRCULAR SEGMENTS
 - ④ SEGMENT SUPPORT BLOCKS
 - ⑤ 1 1/2" THICK LOADING BACKUP PLATE



Figure 4. WEDGE-LOADED WOL-2T
SPECIMEN

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Prior to loading, the specimen is notched to a distance 1.5 inches from the load line, and a fatigue crack is grown from the end of the notch for another 1/4 inch, for a total initial crack length (a_0) of approximately 1.75 inches. In the plane-stress specimen designed by Heyer and McCabe,⁹ it was possible to produce fatigue cracks in the thin sheet by loading split inserts which were placed in the 1.5-inch hole. In our case, this was not possible because of the greater width of the armor specimens. Because of geometrical considerations, it was not possible to design similar fixtures which would not have suffered fatigue fracture after very few stress cycles. For this reason, two 0.625-inch-diameter holes were added to the specimen for the specific purpose of fatigue precracking the stress corrosion specimens. Since the location of the holes does not correspond to the load line of any standard specimen geometry, it was necessary to estimate loads for desired fatigue crack growth rates, based on the data in the Srawley and Gross paper⁶ for arbitrary H/W ratios. This was necessary only for the first attempt at fatigue precracking, since later efforts could be based on the actual crack growth rates in the first specimen.

The procedure for determining the loading conditions, and measuring stress intensities, is reported by Novak and Rolfee.⁴ The stress intensity may be given by:

$$K_I = PC_3(a/w)/Ba^{1/2} \quad (1)$$

where P is the load along the load line
 B is the thickness of the specimen
 a is the crack length (measured from the load line)
 $C_3(a/w)$ is a function of a/w based on the specimen geometry.

Compliance calibrations are usually plotted as $(K_I BW)/(Pa^{1/2})$ versus (a/w) , and are available for both the WOL-T and compact tension geometries. Equation 1 for K_I is merely a rearrangement of this relationship; however, note that for a wedge-loaded system the load, P , is not known. P must be found from a second

relationship, which is based on measurements of the load necessary to produce a given crack opening displacement (COD) at a given value of a/w . Novak and Rolfe express this in the form:

$$P = EBV/C_6(a/w) \quad (2)$$

where V is the COD at the load line

$C_6(a/w)$ is another function of a/w based on the specimen geometry.

In practice, determination of the initial COD necessary to produce a given initial stress intensity, K_{I0} , is made as follows:

1. Knowing a_0 (the initial crack length), and hence $C_3(a/w)$, calculate P_0 for the desired K_{I0} from Equation 1.
2. Using this value of P_0 , and knowing $C_6(a/w)$ for the initial crack length a_0 , calculate the required COD (V_0) from Equation 2.

Once the crack starts to grow, the procedure is reversed. V_0 is fixed, and crack length, a , is measured. Knowing $C_3(a/w)$ and $C_6(a/w)$, P can be calculated from Equation 2. Using this value of P , K_I can be calculated from Equation 1. Combination of Equations 1 and 2 gives the expression:

$$K_I = EV_0/a^{1/2} [C_3(a/w)/C_6(a/w)]. \quad (3)$$

Since $C_6(a/w)$ increases faster than $C_3(a/w)$ with increasing crack length,⁴ it can be seen that the stress intensity at the crack tip will drop as the crack grows. When the stress intensity decreases to the threshold stress intensity K_{Isc} , the driving force for crack growth will disappear, and the crack will stop. A possible complication can occur in systems where the stress corrosion crack velocity decreases gradually as the stress intensity approaches K_{Isc} , as opposed to a discontinuous drop in crack velocity. With a gradual decrease in crack velocity, the time for the stress intensity to fall to K_{Isc} may be quite long. Stress corrosion cracking of steel alloys, including armor steels, is typical of this type of behavior.

For this program, values of $C_3(a/w)$ and $C_6(a/w)$ for the WOL-T geometry were taken from Novak and Rolfe,⁴ while for the compact tension geometry, the $C_6(a/w)$ values were obtained from a paper by Brown,¹¹ and $C_3(a/w)$ from ASTM E399-70T.¹² It should be noted that, for Equation 2 to be independent of specimen size, the crack opening displacement V_y must be measured at the load line. Since V_y cannot be measured directly, it must be measured at some other point and a linear correction applied (see Novak and Rolfe,⁴ Figure 7). The same linear correction must then be applied to $C_6(a/w)$ values which are based on V_y . This must be done whenever there is a change in the position at which V is measured. In the case of the WOL-2T armor specimen, this meant extrapolation of $C_6(a/w)$ values from Novak and Rolfe, Table V in Reference 4, back to V_y , and then extrapolation from V_y to the edge of our specimen, 1.5 inches from the load line. Brown's data¹¹ for the compact tension specimen already applies to load line V_y position.

EXPERIMENTAL

Materials

The material available for this study included XAR-30 high-hardness steel armor plate from two different manufacturers, in thicknesses from 0.125 inch to 0.750 inch. The plates measured 2 ft by 2 ft, having been cut from the 4 ft by 8 ft plates provided by the manufacturers. All specimens used in the tests reported here were cut from a single 2 ft by 2 ft plate of 0.500-inch-thick high-hardness armor, which is identified as plate J13.

The wedge-loaded crack-arrest SCC test, which has been developed in the course of this program, is particularly well suited for the high-hardness steel armor alloy. However, it should be noted that the test should also be applicable to other armor alloys, such as dual-hardness steel, titanium alloys, and aluminum alloys.

Armor Stress Corrosion Cracking Data

Four armor SCC specimens of the WOL-2T geometry have been tested. All four are from a single plate of 0.5-inch-thick high-hardness armor, designated J13, and their orientation designation is WR (crack growing in the rolling direction). The study of Mostovoy and Ripling has shown that three armor plates which cracked in service had K_{ISCC} values of about 10 ksi $\sqrt{\text{inch}}$, whereas a good plate had a K_{ISCC} of about 40 ksi $\sqrt{\text{inch}}$.²

Based on these results, specimen J13-1WR was loaded to an initial stress intensity (K_{I0}) of 49 ksi $\sqrt{\text{inch}}$ and tested in 3.5% NaCl solution. Since K_{min} is only about $K_{I0}/2$ for the WOL-T geometry, it was recognized that the stress corrosion crack would grow almost completely through the specimen for material with poor SCC characteristics. This in fact happened, as illustrated in Figure 5. The test was stopped after nine days when the crack grew beyond an a/w ratio of 0.8, the last point for which a valid measurement of stress intensity may be made. At this point, K was approximately 23 ksi $\sqrt{\text{inch}}$, which indicates marginal stress corrosion cracking behavior. It may be seen from Figure 5 that the crack grew fairly straight along the specimen mid-plane. This was the only one of the four J13-WR specimens which showed a straight undeviated crack growth behavior.

As a result of the behavior of specimen J13-1WR, the other three specimens were loaded to K_{I0} levels between 23 and 27 ksi $\sqrt{\text{inch}}$ and tested in distilled water. The change in environment was made since the chloride content appears to have little effect on the SCC behavior of high-strength steels. The cracks in specimens J13-2WR and J13-3WR deviated somewhat from the mid-plane, but were still considered to give valid K_{ISCC} values. The crack in J13-4WR curved sharply (Figure 6), and data from this specimen cannot be used. The crack deviation problem is discussed in the next section.

The crack behavior of specimens J13-2WR and J13-3WR is shown in Figure 7, which plots the stress intensity at the crack tip (as calculated from crack length measurements) as a function of time in solution. The most important features of this figure are the low apparent K_{ISCC} values for the two specimens: 18.8 ksi $\sqrt{\text{inch}}$

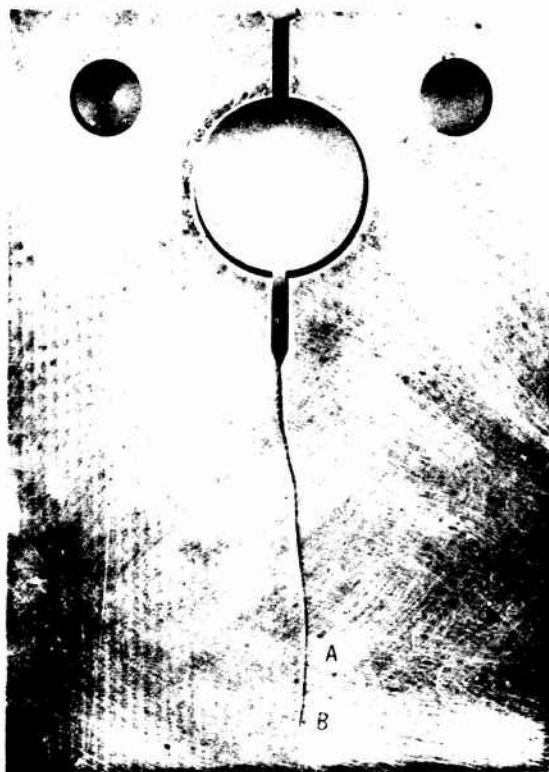


Figure 5. STRESS CORROSION CRACK IN WOL-2T SPECIMEN J13-1WR (A. LIMIT FOR VALID MEASUREMENT OF STRESS INTENSITY ($a/w = 0.8$); B. CRACK TIP) 19-066-819/AMC-71



Figure 6. STRESS CORROSION CRACK IN WOL-2T SPECIMEN J13-4WR (A. CRACK TIP) 19-066-816/AMC-71

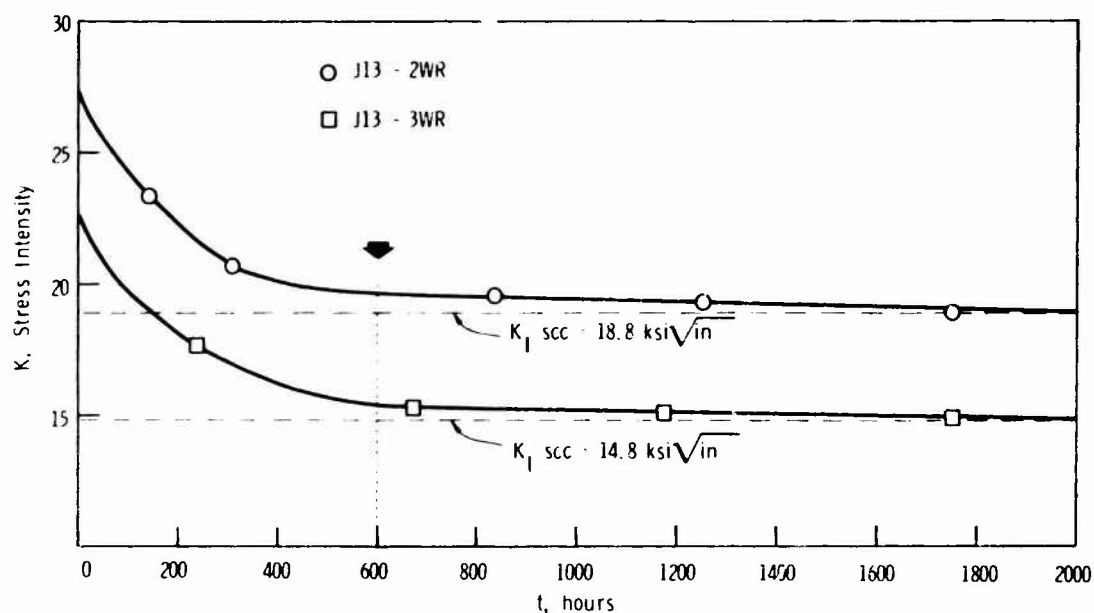


Figure 7. STRESS INTENSITY VERSUS TIME FOR STRESS CORROSION CRACKING OF WOL-2T SPECIMENS

for J13-2WR, and 14.4 ksi $\sqrt{\text{inch}}$ for J13-3WR. Based on the Mostovoy and Ripling results,² it is very probable that this material would be subject to stress corrosion failure in service if high residual stresses were present, or if the material was used in a load-carrying application. Further tests are in progress on J13-RW specimens (crack growing in the width direction), and these will be followed by WR and RW specimens from a 0.50-inch-thick plate of high-hardness steel armor produced by a different manufacturer. K_{ISCC} data from these plates will be correlated with mechanical properties data being generated in a companion program, using hardness measurements, Charpy impact specimens, and fracture toughness specimens cut from the same plates.

Specimen Performance

In general, the concept of the wedge-loaded crack-arrest specimen for measurement of K_{ISCC} has proven successful, although there are several problems which need further study. The most immediate problem is that of the deviation of the stress corrosion crack from the specimen mid-plane. In the first specimen, the crack was quite straight as shown in Figure 5. In the next two specimens, there was a gradual deviation of the cracks, but it was not believed to be serious enough to cause any doubt about the measured K_{ISCC} values. However, the crack in the fourth specimen curved so sharply that it cannot be regarded as being a valid test. This varied behavior is apparently a reflection of the fact that the WOL-T geometry is marginal with respect to maintaining the crack on the specimen mid-plane.* The WOL-T is frequently facenotched as a remedial measure.⁴ This could also be done on the armor SCC specimens, but it would require another machining operation, and it would complicate the matter of locating the crack tip in the groove. Therefore, the first approach to solving this problem will be to change to the compact tension geometry. As shown in Table I, the only difference between the WOL-2T specimen and the CT2 specimen is the dimension W. Thus, it is possible to convert existing WOL-2T specimens to CT2 geometry by cutting a little less than one inch off the end. The compact tension ($H/W = 0.6$) specimen should have greater inherent resistance to crack deviation. In the event that this does not solve the problem, then face grooving can be attempted.

While this SCC test is viewed as a crack-arrest type, it should be noted that none of the cracks in the specimens have, in fact, stopped completely. This is a general problem in stress corrosion testing of steels,⁴ since even the edge-notched cantilever beam test of Brown⁵ takes a very long time to run near K_{ISCC} where it is difficult to determine whether or not the crack is growing. For specimens J13-2WR and J13-3WR, the cracks were still moving very slowly after over 4000 hours and 3600 hours, respectively. However, Figure 7 shows that this small rate of crack growth has virtually no effect on the measured value of stress intensity. In fact, an excellent measure of the value of K_{ISCC} could probably be obtained after 600 hours (arrow on Figure 7), after which further decreases in K are small, and probably predictable. Such an estimate of K_{ISCC} would certainly seem justified for quality control applications. Mostovoy and Ripling² mention another possible estimating procedure for obtaining a measure of SCC resistance in an even shorter time, if such an estimate is needed before the crack has approached arrest. They observed that the crack propagation rate in the first

*McCABE, D. E., private communication.

few days of the stress corrosion test was much higher for the three bad plates than for the good plate. If this can be confirmed, it might provide a screening test for specifications. Specimens 2 and 3 will probably be left in the environment for some time to come, to see when (and if) the cracks will arrest. Meanwhile, all other tests will be terminated in a much shorter time, perhaps 700 to 1000 hours.

CONCLUSIONS AND RECOMMENDATIONS

Tentative conclusions and recommendations at this interim point in the armor SCC program are as follows:

1. The concept of the wedge-loaded crack-arrest specimen has promise for providing a method for measurement of K_{ISCC} of armor steels.

2. The compact tension geometry should be used in all future SCC tests, replacing the WOL-2T geometry.

3. A good measure of K_{ISCC} can be obtained in 600 to 1000 hours, despite some very slow crack growth beyond this time.

4. A rough estimate of relative resistance to SCC may possibly be made in even shorter times, which could be used for qualified product testing or as a preproduction requirement.

5. K_{ISCC} measurements were made for WR-orientation specimens from plate J13, a sample of 0.50-inch-thick high-hardness armor plate. The results were very low (15 to 19 ksi $\sqrt{\text{inch}}$), indicating a marked susceptibility to stress corrosion cracking.

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