Subcritical Crack Growth Characteristics in Welded ASTM A537 Steel

Fracture toughness, fatigue and corrosion fatigue tests indicate the steel can be used in welded marine applications with a high degree of confidence

By D. F. SOCIE AND S. D. ANTOLOVICH

ABSTRACT. Fracture toughness, fatigue, stress corrosion and corrosion fatigue were studied in both the base metal and HAZ of an ASTM A537 grade steel which was welded with heat inputs of 25, 50 and 75 kJ/in. A uniform HAZ was maintained perpendicular to the side planes of the specimen and parallel to the crack by welding a "K-type" joint of different section sizes. The results of this investigation indicate that the subcritical flaw growth properties of this steel tested in 3½% aqueous NaCl are not degraded relative to those of the base metal over the range of welding conditions studied and that this steel can be used for marine applications in the welded condition with a high degree of confidence.

Introduction

Many large engineering structures, such as ships, bridges, and offshore drilling platforms are fabricated by some type of welding. One of the most common modes of failure is the growth of a small flaw or crack to a critical size where catastrophic failure occurs. The purpose of this investigation was to provide some useful design information and to determine the effect of welding on the subcritical flaw growth characteristics of a low temperature high toughness steel. These structural steels are used in a quenched and tempered condition so that the necessary balance of strength and toughness is obtained. During welding, the metal next to the weld joint is affected by the heat required to melt the base metal in order to insure a good weld to base metal bond. This heat can alter the microstructure of the heat-affected zone (HAZ) and significantly change both physical and mechanical properties. Welds often contain small flaws from which cracks originate so that the properties of the material near the weld zone are of considerable importance.

The primary causes of crack growth are cyclic stresses and aggressive environments. Linear elastic fracture mechanics concepts have been successfully used to describe the growth of cracks (Refs. 1-3). It is of value then, to determine the crack growth characteristics under both static and dynamic loading in an aggressive environment such as sea water. With a good stress analysis, life calculations can be made for a structure containing cracks by using the crack growth rates determined in the laboratory.

Experimental Procedure

The steel used in this investigation is covered by ASTM Standard A537-67, "Carbon-Manganese-Silicon Steel Plate, Heat Treated for Pressure Vessels". The chemical composition and mechanical properties are listed in Table 1. The thermal treatment consists of austenitizing at 1700 F (927 C) for one hour and water spray quenching. The plates are then tempered at 1100 F (593 C) for one-half hour.

In order to obtain reliable measurements of the properties of the HAZ the crack must be kept entirely within it. Most studies using conventional "V-type" weld joints result in a non-uniform HAZ where the crack is free to run through the base metal, HAZ, or filler metal depending on the geometry and external stress field (Ref. 4). To avoid this, a HAZ that is not only straight but also perpendicular to the specimen surface was produced using a "K-type" weld joint shown in Fig. 1. The welds were made by the submerged arc process. Three groups of weldments using heat inputs of 25, 50 and 75 kJ/in. were made with Armco W-18 electrodes and Linde 709-5 flux.

Fracture toughness tests were conducted on the base metal using 0.5 in. (12.7 mm) and 2.0 in. (50.8 mm) thick compact tension specimens shown in Fig. 2. These tests as well as all other mechanical testing were done on an MTS closed loop testing system in accordance with the recommended procedure set forth in ASTM specification E399-72. The specimens were fatigue precracked and fractured in monotonic loading.

A tapered specimen as shown in Fig. 3 was used for corrosion tests and is described in detail elsewhere (Ref. 5). This specimen was used because the stress intensity is independent of crack length and only a

---

D. F. SOCIE is associated with Structural Dynamics Research Corp., Cincinnati, Ohio and S. D. ANTOLOVICH is with the University of Cincinnati, Cincinnati, Ohio.

Table 1 — Chemical Composition and Mechanical Properties of ASTM A537 Steel

Chemical composition, w/o

Heat	C	Mn	P	S	Si	Cr	Ni	Mo	Cu
1	.14	1.35	.016	.018	.35	.22	.16	.05	.16
2	.18	1.33	.012	.019	.39	.19	.18	.04	.24
3	.14	1.41	.010	.027	.38	.21	.21	.06	.24

Mechanical properties

Heat	Tensile strength, ksi	Tensile strength, Pa	Yield strength, ksi	Yield strength, Pa	Elongation, %
1	80.9	(5.6×10^8)	63.0	(4.3×10^8)	42
3	82.9	(5.7×10^8)	62.0	(4.3×10^8)	26

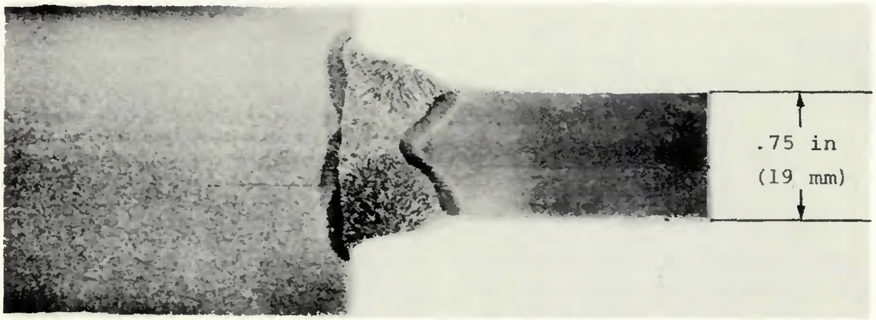

Fig. 1 — Weld joint used to produce uniform heat-affected zone (left side)

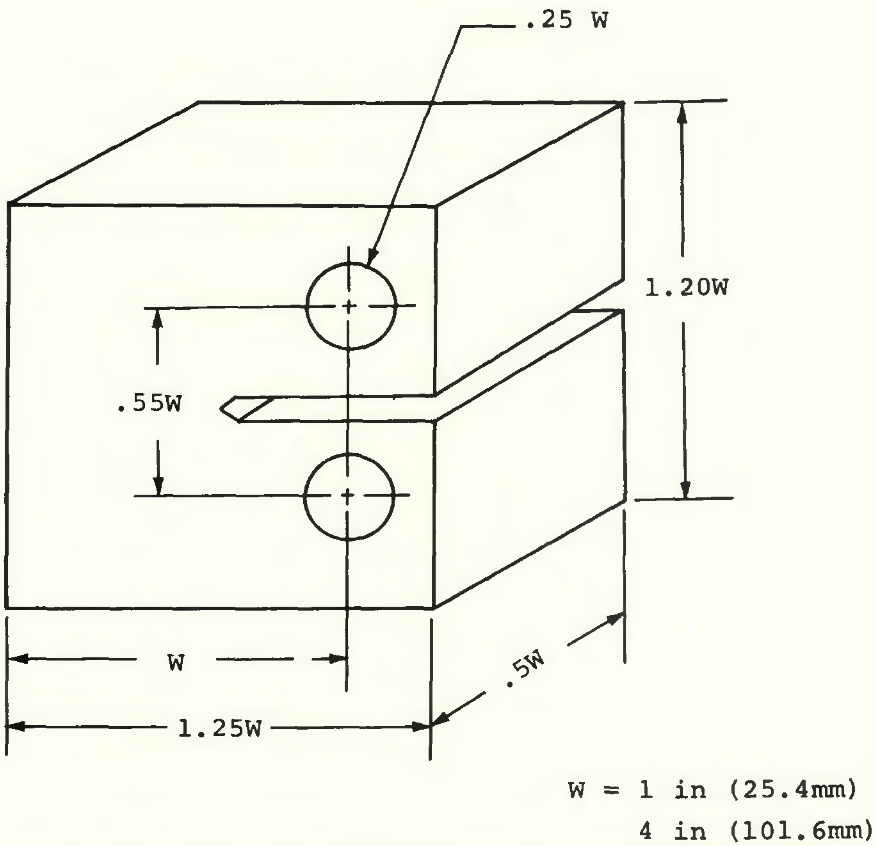

Fig. 2 — Standard proportions of the compact tension specimen

function of applied load. Single edge notch (SEN) specimens shown in Fig. 4 were used to evaluate the fatigue properties in air of both the base metal and the HAZ. The cyclic crack growth rate (da/dN) was calculated by dividing the incremental crack growth (Δa) by the number of cycles (ΔN). The stress intensity was calculated using the average crack length ($\bar{a}$) in the growth interval which was sufficiently small so that the stress intensity did not change by more than 5 percent.

Fractographs were made from the fractured surfaces using conventional two stage replicating techniques.

Results and Discussion

Fracture Toughness

A summary of fracture toughness data appears in Table 2. None of the tests qualify as a plane-strain fracture toughness as specified by ASTM E399 because the crack length and thickness are not greater than

$$2.5\,(K_Q/\sigma_{ys})^2$$

The average toughness at fracture of 77 ksi$\sqrt{\text{in.}}$ (84.6 MPa$\sqrt{\text{m}}$) and 84 ksi $\sqrt{\text{in.}}$ (92.3 MPa$\sqrt{\text{m}}$) for 0.5 in. (12.7 mm) and 2.0 in. (50.8 mm) thick specimens indicate that the toughness of this material does not depend on thickness to a large extent. The macromechanism of crack extension is one of tearing. Fractographs of the fatigue/tensile interface are shown in Fig. 5. Region A shows the crack going over a second phase or grain. Region B shows dimpling initiated by precipitates in the matrix material. No single mechanism is operating at the onset of fracture; however, a tearing mode predominates.

Fatigue Crack Propagation

It has been shown both experimentally and theoretically that the relationship between the stress intensity and the crack growth rate for a wide variety of materials (Ref. 1) is of the form:

$$\frac{da}{dN} = C\,(\Delta K)^m \qquad (1)$$

where the crack growth rate coefficient (C) is a constant that includes environmental and microstructural variables and m is often taken to be equal to 4, the best integer approximation. To obtain the crack growth rate coefficient the data was statistically fitted to a 4th power relationship. Table 3 lists the crack growth rate coefficients and a 90% confidence interval. The data is graphically presented in Fig. 6 It is clearly shown that welding has little or no effect on the fatigue crack growth rate of this material. One of the unique features of fatigue is the formation of striations although the exact mechanism is not well defined. Figures 7A and 7B show striations formed at lower stress intensities while 7C shows branch cracking that is more typical of higher stress intensities.

Stress Corrosion and Corrosion Fatigue

Corrosion tests were carried out in a 3½% aqueous NaCl solution. The threshold stress intensity below which there is no crack growth was determined by fatigue precracking a tapered specimen and then holding it at a constant load while monitoring the crack length. The threshold stress intensity was found to be 40 ksi$\sqrt{\text{in.}}$ (43.6 MPa$\sqrt{\text{m}}$) or about one half of the toughness.

The results of the corrosion fatigue tests of the base metal are graphically shown in Fig. 8. There is no statistical difference between tests conducted in air and 3½% aqueous NaCl at 75 F (24 C). Similar tests were conducted on the 50 kJ/in. weld samples with the same result (i.e. no difference for tests in air and 3½% aqueous NaCl). There is a large difference between tests conducted in 3½% aqueous NaCl at 75 F (24 C) and 30 F (-1 C) indicating that the process is thermally activated. Such a process might be dislocation movement in the plastic zone ahead of the crack tip. The 4th power model can be modified to include temperature as follows:

$$\frac{da}{dN} = \left[1.1 \times 10^{-3} \exp\left(\frac{11000}{RT}\right)\right](\Delta K)^4 \qquad (2)$$

where R is the gas constant and T is the absolute temperature in degrees Kelvin.

Application of Results

Perhaps the best way to demonstrate the usefulness of this type of research is to illustrate a typical life calculation. Let us assume that a large plate such as that on a ship hull has a center crack 0.5 in. long and is subject to a stress varying from 0 to 20 ksi. The stress intensity factor for this crack can be expressed as (Ref. 6):

$$K = \sigma\sqrt{\pi a} \qquad (3)$$

where

σ = stress

$2a$ = crack length

The crack growth rate is given by:

$$\frac{da}{dN} = C(\Delta K)^4 \qquad (4)$$

substituting into eq (4) for ΔK, one obtains

$$\frac{da}{dN} = C(\Delta\sigma)^4 \quad (\pi a)^2 \qquad (5)$$

integrating

$$\int_0^{N_f} dN = \int_{a_o}^{a_f} \frac{da}{C(\Delta\sigma)^4\pi^2 \; a^2} \qquad (6)$$

solving for cycles to failure N_f, one obtains:

$$N_f = \frac{1}{C(\Delta\sigma)^4\pi^2} \; \frac{a_f - a_o}{a_f \; a_o} \qquad (7)$$

The final crack length (a_f) can be evaluated from the toughness at fracture data obtained from this investigation by substituting K_Q into Equation 3.

$$K_Q = \sigma_{max}\sqrt{\pi a_f}$$

$$a_f = 5.1 \text{ in.}$$

Now the equation for cycles to failure can be solved with the result:

$$N_f = 4.8 \times 10^5 \text{ cycles}$$

In principle the above calculations can be carried out for any load/crack geometry providing the stress intensity parameter is known and a good stress analysis is available.

Conclusions

The fracture toughness, fatigue and corrosion fatigue properties of an

Table 2 — Fracture Toughness Data

B, in.	W, in.	P_Q lb	a/w	K_Q
.500	1.000	3800	.50	73
.500	1.000	4200	.48	74
.500	1.000	3100	.61	86
			Average	77 ksi$\sqrt{\text{in.}}$ (85 MPa$\sqrt{\text{m}}$)
2.000	4.000	31,500	.54	85
2.000	4.000	15,000	.71	88
2.000	4.000	39,000	.49	90
2.000	4.000	24,000	.57	74
			Average	84 ksi$\sqrt{\text{in.}}$ (92 MPa$\sqrt{\text{m}}$)

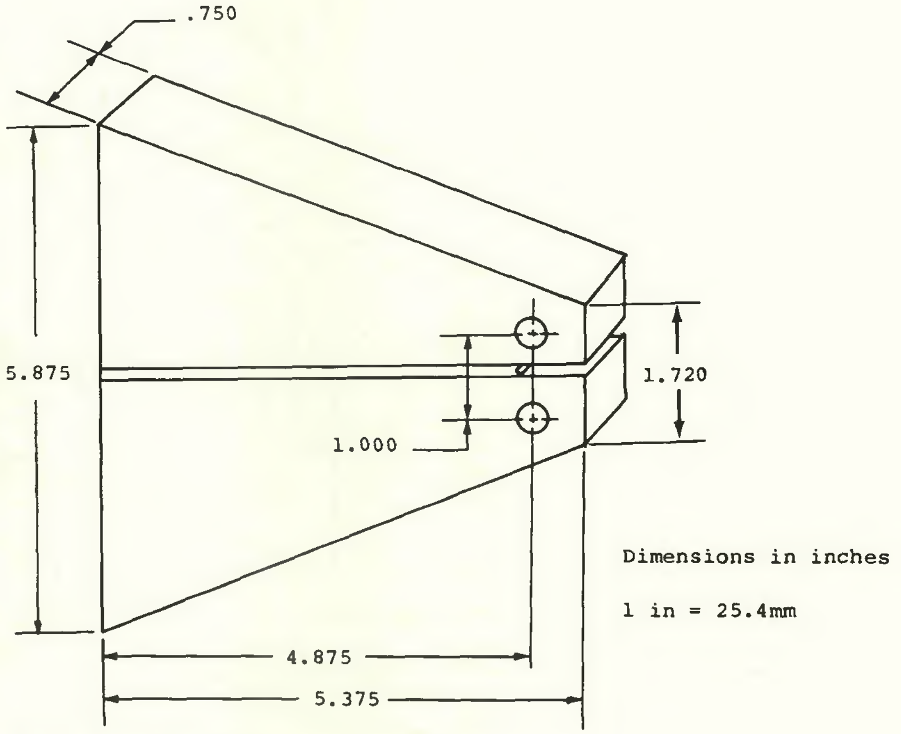

Fig. 3 — Tapered specimen used for corrosion tests

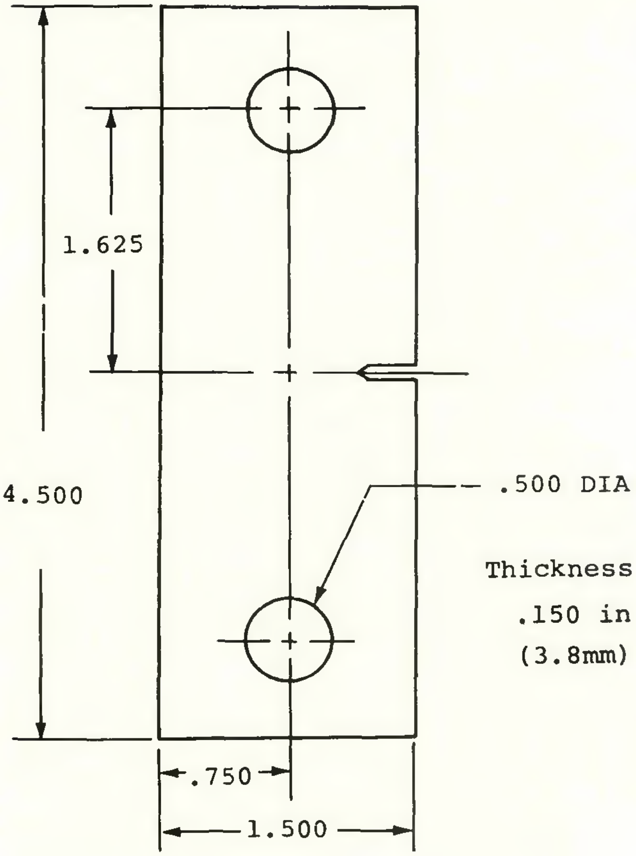

Fig. 4 — Single edge notch specimen used for fatigue tests

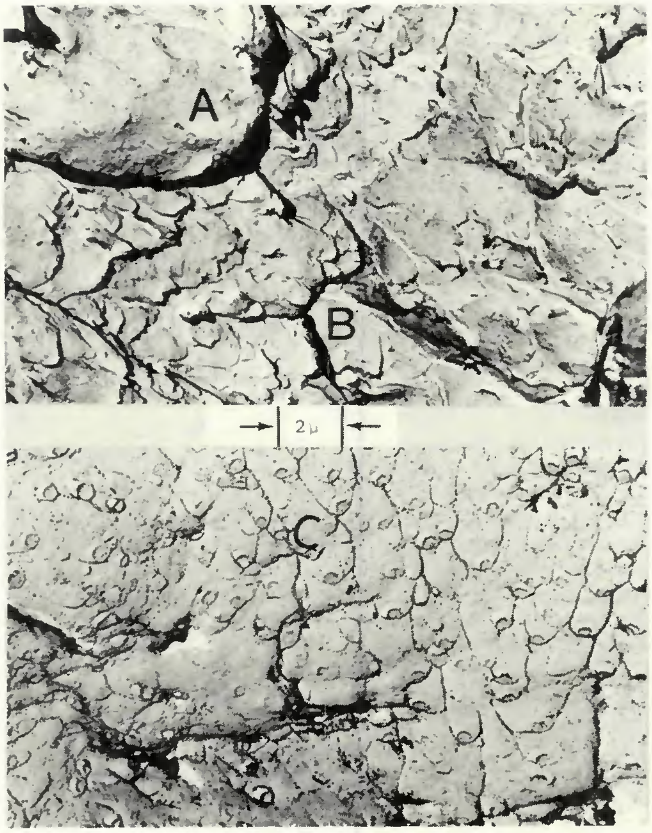

Fig. 5 — Tensile-fatigue interface showing dimpling

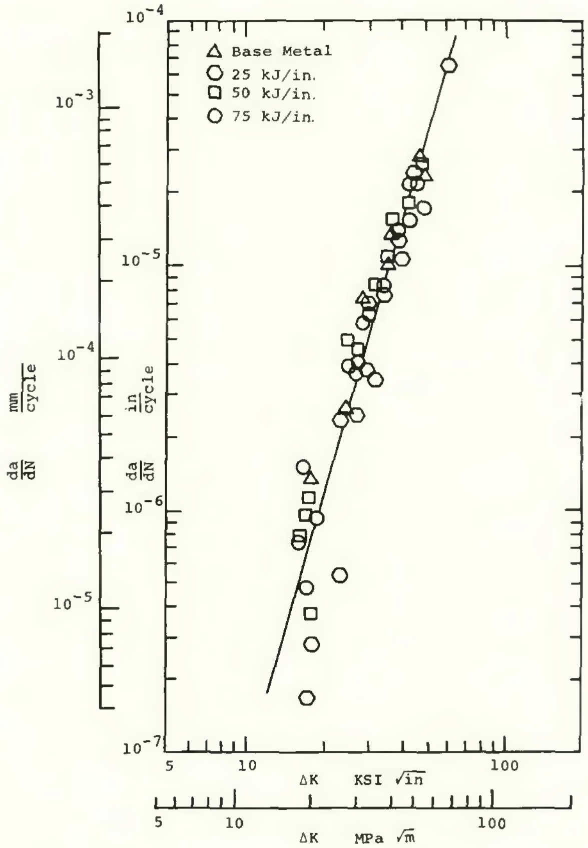

Fig. 6 — Comparison of crack growth rate for welded and unwelded steel

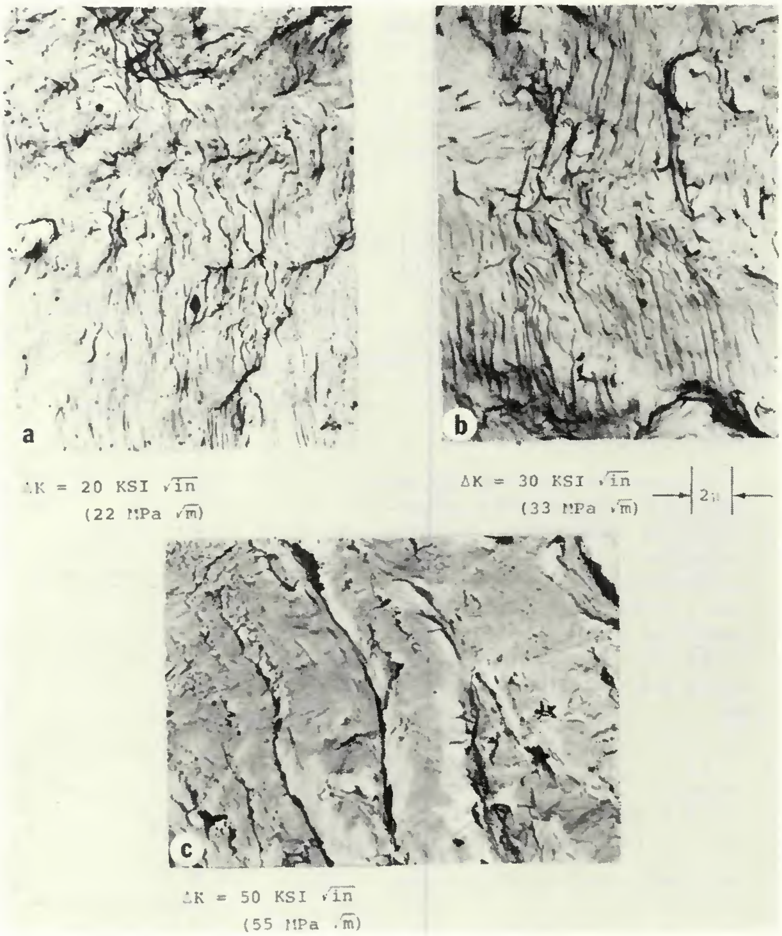

Fig. 7 — Fatigue striations formed at various cyclic stress intensities

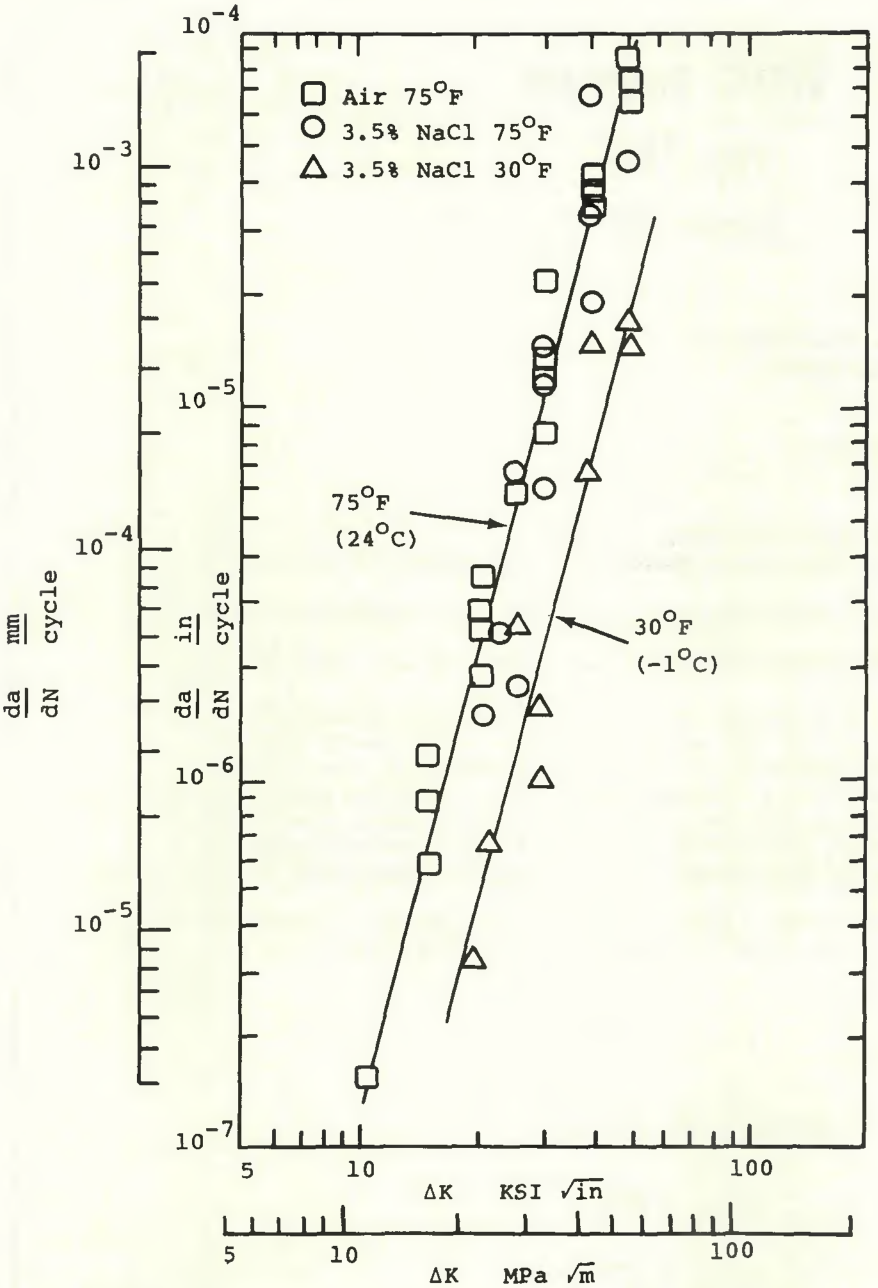

Fig. 8 — Comparison of fatigue crack growth rate in 3½% aqueous NaCl and air at 75 F and 30 F

Table 3 — Crack Growth Rate Coefficients for Fatigue

Specimen	Crack growth rate coefficient, in.^{7}/kips^4	90 percent confidence interval
Base metal	5.4×10^{-12}	$4.2 - 6.5 \times 10^{-12}$
25 kJ/in. weld	5.2×10^{-12}	$2.8 - 7.6 \times 10^{-12}$
50 kJ/in. weld	5.1×10^{-12}	$4.4 - 5.8 \times 10^{-12}$
75 kJ/in. weld	3.8×10^{-12}	$3.2 - 4.4 \times 10^{-12}$

ASTM A537 steel welded by the submerged arc process at heat inputs of 25, 50 and 75 kJ/in. has been evaluated. Tests were carried out in the base metal and HAZ. The main conclusions are:

1. The fracture toughness was relatively independent of specimen thickness over the range in which this steel is used.
2. The fatigue crack growth rate was independent of heat input or the location of the crack (i.e. base metal or HAZ).
3. The crack growth rate in 3½% aqueous NaCl was highly temperature dependent, decreasing by almost an order of magnitude when the temperature was reduced from 75 F (24 C) to 30 F (-1 C).
4. This steel can be used for marine applications with a high degree of confidence. A wide range of heat inputs does not appear to significantly reduce the fracture properties of the HAZ compared to the base metal.

Acknowledgement

The Authors would like to thank the Armco Research Center of Middletown, Ohio for supplying the material and welding the plates. We are also pleased to acknowledge the advice and assistance of Mr. G. Linnert.

References

1. Johnson, H., and Paris, P., "Subcritical Flaw Growth," *Engineering Fracture Mechanics*, 1968, Vol. 1, pp 3-45.
2. Pellini, W., "Evolution of Engineering Principles for Fracture Safe Design of Steel Structures," *NRL Report 6957*, Naval Research Laboratory, Washington D.C.
3. Paris, P., and Erdogan, F., "A Critical Analysis of Crack Propagation Laws," *Journal of Basic Engineering*, Trans. ASME, Vol. 85, pp 528-534.
4. Kies, J., Smith, H., Romine, H., and Bernstein, H., "Fracture Toughness Testing and Its Applications," *STP 381*, American Society for Testing and Materials, 1965, pp 328-353.
5. Socie, D., Antolovich, S., and Chanani, G., "Subcritical Crack Growth Testing in the HAZ of Welded Structural Steel," *Int. Journal of Fracture Mechanics*, Vol. 8, pp 350-352.
6. Paris, P. and Sih, G., "Stress Analysis of Cracks," *STP 381*, American Society for Testing and Materials, 1968, pp 30-83.

WRC Bulletin
No. 184
June 1973

"Submerged Arc Weld Hardness and Cracking in Wet Sulfide Service"

by D. J. Kotecki and D. G. Howden

This study was undertaken to determine:
(1) The causes of higher-than-normal hardness in submerged-arc welds in plain-carbon steels
(2) The levels of strength or hardness which will not be susceptible to sulfide-corrosion cracking
(3) Welding procedures which will assure that nonsusceptible welds will be produced.

Concentration is primarily on weld metal, though some consideration to the weld heat-affected zone is given. The study covered a two-year period. The first year was concerned with a macroscopic view of the weldments. In that first-year study, some inhomogeneities were observed in weldments which are not obvious in a macroscopic view of the weldment. It appeared likely that these inhomogeneities could affect the behavior of the weldment in aqueous hydrogen-sulfide service. Accordingly, their presence and effects were investigated during the second year.

The price of WRC Bulletin 184 is $3.50 per copy. Orders should be sent to the Welding Research Council, 345 East 47th Street, New York, N.Y. 10017.

WRC Bulletin
No. 185
July 1973

"Improved Discontinuity Detection Using Computer-Aided Ultrasonic Pulse-Echo Techniques"

by J. R. Frederick and J. A. Seydel

The purpose of this project, sponsored by the Pressure Vessel Research Committee of the Welding Research Council, was to investigate means for obtaining improved characterization of the size, shape and location of subsurface discontinuities in metals. This objective was met by applying computerized data-processing techniques to the signal obtained in conventional ultrasonic pulse-echo systems. The principal benefits were improved signal-to-noise ratio and resolution.

The price of WRC Bulletin 185 is $3.50 per copy. Orders should be sent to the Welding Research Council, 345 East 47th Street, New York, N.Y. 10017.