Fracture Mechanics Testing Method for Assessing Susceptibility to Stress-Relief Cracking

Application of LEFM tests to simulated heat-affected zones of three ferritic creep resisting steels indicated the order of susceptibility

BY K. PURAZRANG

ABSTRACT. The work reported here used the techniques of fracture mechanics to assess the susceptibility of ferritic creep resisting steels to high temperature cracking in temperature range 550-675 C. These studies were then related to the problem of stress relief cracking in the heat-affected zones of welds.

The major testing procedures were divided into two parts, namely producing a synthetically simulated microstructure of a coarsened grain heat-affected zone where stress relief cracking usually occurs and carrying out stress relaxation tests on compact tension specimens at temperatures ranging from 550-675 C.

A range of stress intensities was applied to the specimens and the technique of potential measurement was used to detect the crack initiation. The results of stress relaxation tests were plotted as applied stress intensities against time to crack initiation at various testing temperatures.

Three very common ferritic creep resisting steels used for numerous components operating at elevated temperatures, namely 2¼Cr-1Mo, ½Cr-½Mo-¼V and ½Cr-¼Mo were examined for their susceptibility to high temperature cracking. The results showed that all three steels were susceptible to stress relief cracking in the temperature range tested. However, the maximum susceptibilities to cracking were found to vary with temperature.

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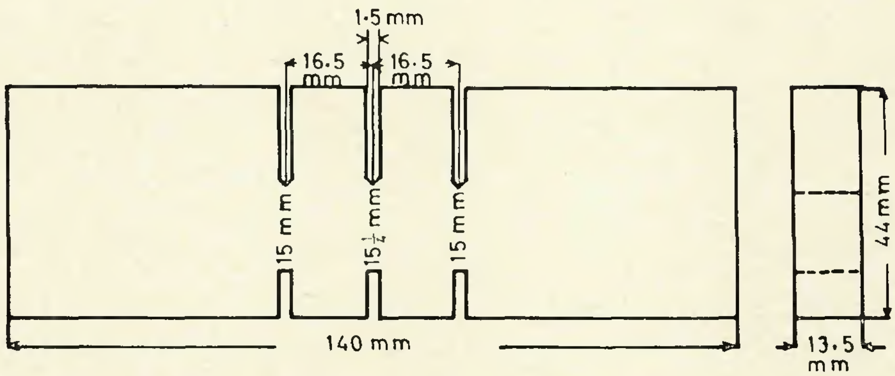

Fig. 1 — Block specimen for thermal cycling

The high temperature cracking results are related to the problem of stress relief cracking in welded joints.

Introduction

The term stress relief cracking is associated with the stress relief heat treatment of welded components. Stress relief (SR) heat treatment is usually applied to the welded structure after welding to reduce or eliminate the residual welding stresses that have formed in the weldment when it has cooled to room temperature. The stress relieving of the residual stresses occurs by creep processes (Refs. 1-2). Materials containing carbide forming alloy elements often exhibit precipitation of the alloy carbides within the grains of the weld heat-affected zone during stress relief heat-treatment and serve to strengthen the matrix in comparison to the grain boundary. The creep strain necessary to relieve the residual stresses is forced into the weakened grain boundary region and consequently extensive grain boundary deformation may induce cracks in the heat-affected zone. Thus this type of cracking has often been called "stress relief cracking" (SRC).

Stress relief cracking appears to be always intergranular in nature and is initiated and propagated along the boundaries of coarsened grains of the weld heat-affected zone near the fusion boundary (Refs. 3-4).

In recent years stress relief cracking has often been observed in various materials and in particular, in certain low alloy ferritic creep resisting steels containing molybdenum and vanadium and also in the austenitic stainless steels (Refs. 1-4). The low alloy creep resisting steels containing chromium, molybdenum and vanadium have increasingly been used in the construction of power plants in the past several years due to their useful high temperature metal-

Table 1 — Chemical Analysis of Steels Tested, wt. %

Steel	C	Si	S	P	Mn	Ni	Cr	Mo	V	Cu	Sn	Al
2¼Cr-1Mo	0.15	0.35	0.025	0.15	0.75	0.25	2.06	0.97	—	0.12	0.012	0.042
½Cr-½Mo-¼V	0.125	0.205	0.026	0.016	0.535	0.06	0.375	0.51	0.215	0.11	0.015	—
½Cr-¼Mo	0.13	0.34	0.013	0.008	1.10	0.85	0.59	0.255	0.07	0.15	0.019	0.01

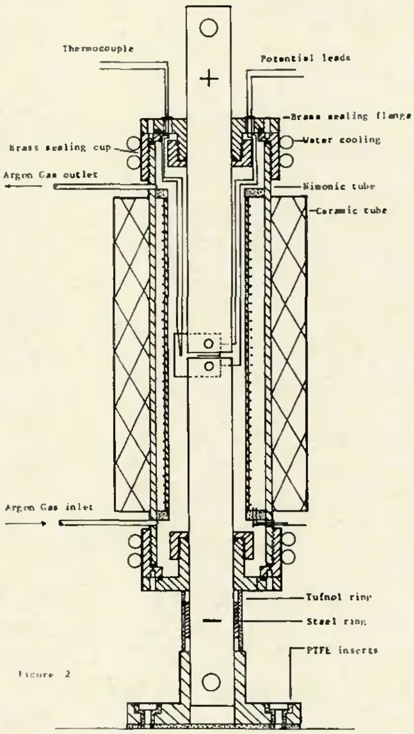

Fig. 2 — A longitudinal profile of heating chamber

lurgical and mechanical properties as well as being economical in comparison with the austenitic stainless steels previously used. Accordingly, the susceptibility to SR cracking of these types of steels has been the subject of intensive investigations. Various types of tests have been employed (Refs. 4-8) to assess the susceptibility to SR cracking of these materials.

However, there is no single type of the test which has been generally accepted, possibly because none of the tests could entirely fulfill the specific of various conditions under which SR cracking occurs in practice. It was the purpose of the present work to use a laboratory testing method which could impose the various metallurgical and mechanical conditions thought to be important in the cracking process, and to use fracture mechanics techniques to estimate the susceptibility of materials to this type of cracking. Fracture mechanics techniques were used because it was believed that under these conditions the closest relationship between the laboratory tests and the practical occurrence of stress relief cracking can be obtained. Also by using these techniques to assess the susceptibility of the steels to stress relief cracking, it may be possible to devise an acceptable theory based on fracture mechanics which could lead to the obtaining of a significant relationship between inherent and measurable mechanical properties of steels.

Compact tension specimens were made with thermally simulated microstructures similar to those found in weld heat-affected zones. These were given a fatigue precrack and then tested at elevated temperatures (550-675 C) under conditions of stress relaxation. The times to fracture initiation were measured at different initial stress intensity factors. Metallographic studies were made and related to the fracture mechanics results. Elevated temperature (550-675 C) tensile tests were made in order to provide data for use in fracture mechanics expressions and also to provide some notion of the tensile ductility. It was hoped that the test method developed in this investigation would be generally applicable to many types of materials.

Materials

The composition of the three ferritic creep resisting steels which have been studied are given in Table 1. The 2¼Cr-1Mo and ½Cr-¼Mo steels were obtained in the form of blocks of 40 × 8½ × 6 in. (1016 × 216 × 152 mm) and 30 × 14½ × 5¼ in. (762 × 368 × 133) respectively. The ½CR-½Mo-¼V steel was cut from the inlet stubs steam chest castings of power plant components. The three materials were cut to small blocks which were then rolled to produce plates of ¾ in. (19 mm) thickness and 6 in. (152 mm) width. The blocks of 140 × 44 × 13½ mm were prepared from these plates for thermal cycle simulation of heat-affected zone structures.

Experimental Work and Apparatus

The experimental program can be divided into two major sections, namely (1) the production of a coarsened grain microstructure similar to that found in the weld heat-affected zone of practical welds, and (2) fracture toughness testing at elevated temperatures using a 13 mm thick compact tension specimen.

Measurement of Thermal Cycles in the Weld-HAZ and Simulation of HAZ Microstructure of Steels tested

To measure the heating and cooling cycle in the HAZ of a typical weldment, plates 200 mm long × 150 mm wide × 24 mm thick were prepared with a 90 deg V groove 10 mm deep through the length. Three holes each 2.5 mm diam were drilled on the reverse side of the plate to a depth of 1.5, 1.0 and 0.5 mm below the groove in the center and midway between the center and the edge of the plate. The thermal cycles in the weld HAZ were determined by means of Pt/13% Rh thermocouples, which were spot welded to the bottom of the drilled hole, and connected to a continuous recording millivoltmeter throughout the welding.

After the measurement of the heating and cooling cycle in the weld HAZ, HAZ type microstructures were produced in test pieces large enough to enable preparation of 13 mm thick specimens for fracture toughness tests. For this purpose ac resistance heating was employed. A test arrangement for resistance heating consisting of a specimen holding unit, a two phase transformer with an input variac, a switch contactor and high response single channel chart recorder made it possible to simulate HAZ microstructure in the test piece shown in Fig. 1. From every test piece two of the 33 mm × 32 mm × 13 mm compact tension specimens for stress relaxation tests were machined.

Elevated Temperature Tests

The 13 mm thick fatigue precracked compact tension specimens were held inside the heating chamber (Fig. 2), which was designed for this purpose. A 10000 kg Instron was used.

An electrical potential method was used to detect crack initiation and propagation. This method is based on the fact that when a constant current passes through a precracked specimen the potential across the crack is dependent on the cross-section area beneath the crack and will increase as the crack grows so as to reduce the cross-section. A current (constant) of approximately 40 A was passed through the specimen using a 50 A constant current stabilized power supply unit. To record the potential changes across the crack notch a

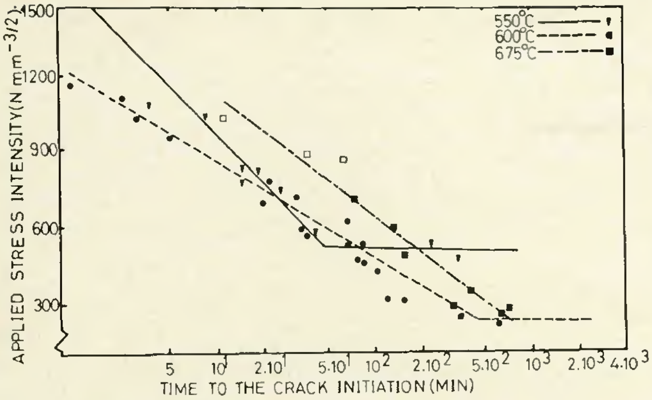

Fig 3 — Stress relaxation tests on 2¼ Cr-1Mo steel

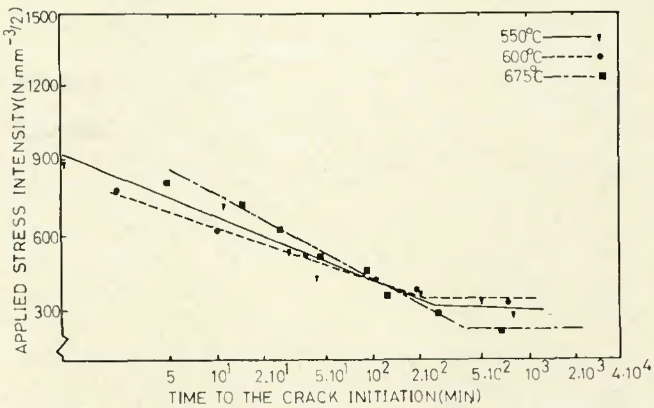

Fig. 5 — Stress relaxation tests on ½Cr-¼Mo steel

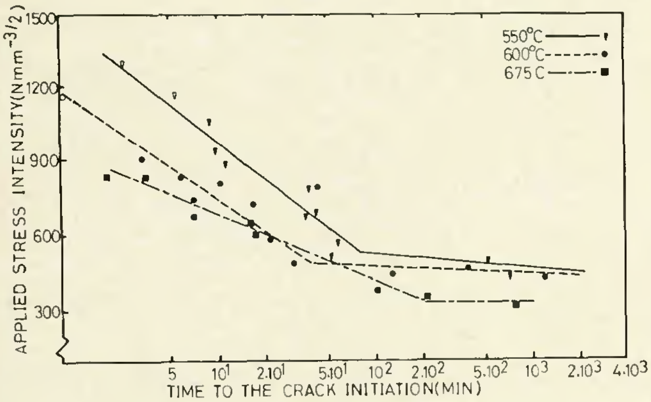

Fig. 4 — Stress relaxation tests on ½Cr-½Mo-¼V steel

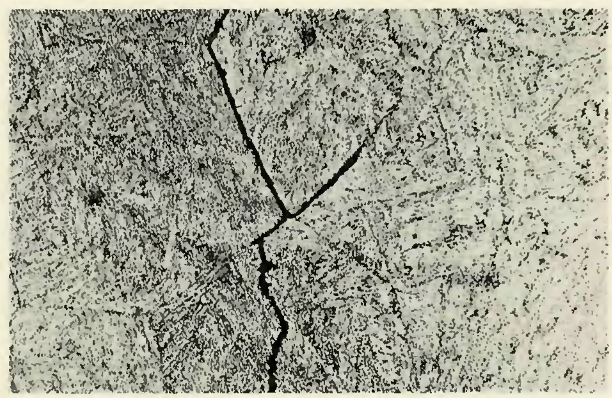

Fig. 6 — Stress relief cracking on 2¼Cr-1Mo steel at 600 C

chart recorder of 0.002 mV/mm sensitivity was used.

The specimens were heated up to the testing temperatures 550, 600 and 675 C while argon gas was passed through the heating chamber. The specimens were always held close to the testing temperature for several hours before applying the test load. It was necessary to provide sufficient time to stabilize the temperature of the specimen and the loading system because of errors arising from the thermal expansion of the load system. The heating of specimens was partially due to the 40 A current which was passing through the specimen for potential drop measurement.

The temperatures of the specimens were measured by a Pt/13% Rh thermocouple via a Cambridge potentiometer. The thermocouple was welded to the surface of the specimen near the fatigue precrack tip as shown in Fig. 2. The temperature was controlled manually to ± 3 C approximately by a variac through which the power was supplied to the heating chamber.

When the temperature was stable a range of stress intensities, calculated from the linear elastic fracture mechanics compliance factor and initial applied load, were applied to the specimens. A cross-head speed of 0.1 cm/min was used to avoid the overshooting of load and also to restrict the stress relaxation that might occur during loading. Stress relaxation to decrease the stress intensity to 90% of its initial value was allowed during the test. Times to crack initiation during stress relaxation were then measured.

A series of elevated temperature tensile tests was also carried out at 550, 600 and 675 C in this investigation. For this purpose the thermally simulated region of the thermal cycle block specimens were machined into modified Hounsfield tensile specimens of 0.15 in. diam. The tensile specimens were tested at a cross-head speed of 0.1 cm/min.

Results and Discussion

Micrographic examination showed that if the heating current of 10,000 A was passed through the thermal cycle block specimen for approximately eight and a half seconds the simulated microstructure produced matched that of the weld coarse grained heat-affected zone microstructure. This was in spite of the fact that the cooling rate of the simulated thermal cycle was slightly faster compared to that of the weld thermal cycle. However, the hardnesses of both the weld and simulated heat-affected zone microstructures were examined frequently using a micro hardness tester and found to be approximately the same.

The results of the elevated temperatures fracture mechanics tests for three steels tested at 550, 600 and 675 C are shown in Figs. 3-5 in terms of the initial applied stress intensity factor against the time to crack initiation.

The ASTM criterion expression 2.5 $(K/\sigma_y)^2$ was calculated from the initial applied stress intensities and from the results of the elevated temperature tensile tests to verify the validity of the plane strain condition. Although this criterion has normally been used for tests at room and lower temperatures it seemed expedient to calculate this for the present work because there is no other criterion for tests at elevated temperatures at the present time. A few tests, where high stress intensities were applied, exceeded the limitation of the ASTM criterion. In these situations the crack initiation occurred after only a few minutes, (indicated with open symbols in the figures). As can be seen from Figs. 3-5 decreasing the initial applied stress intensity leads to an increase in the time to crack initiation.

In addition to the tests at 675 C for 2¼Cr-1Mo, the applied stress intensities for the rest of the tests reached the lowest limit value under which stress relief cracking could not practically initiate. The lowest applied stress intensity at 675 C for 2¼Cr-1Mo was 251 ($Nmm^{-3/2}$). The crack initiated in this case after 723 minutes but did not initiate after 1440 minutes when applied stress intensity was decreased to 233 ($Nmm^{-3/2}$). The stress intensity factor was relaxed to 10% of the original value at the end of the test.

Metallographic examinations were also undertaken to ascertain the correct working of the potential-drop measuring equipment and to make precise observations concerning the crack path. These showed that the crack initiation and propagation in all specimens at all testing temperatures occurred at grain boundaries (Figs. 6-9). From these micrographs it

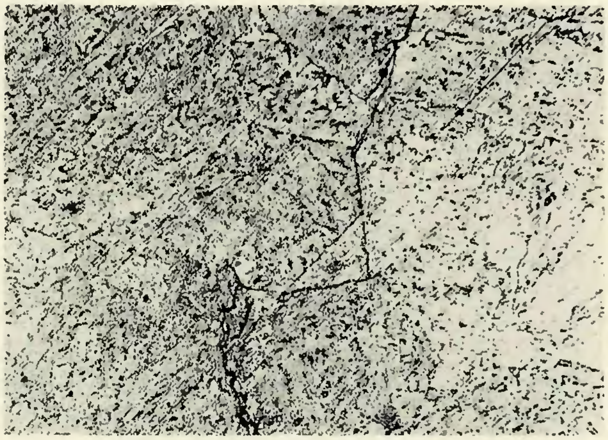

Fig. 7 — Stress relief cracking of ½Cr-½Mo-¼V steel at 600 C

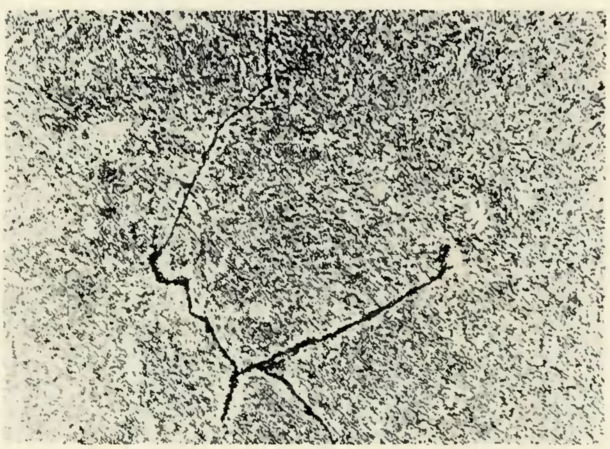

Fig. 8 — Stress relief cracking of ½Cr-¼Mo-0.07V steel at 675 C

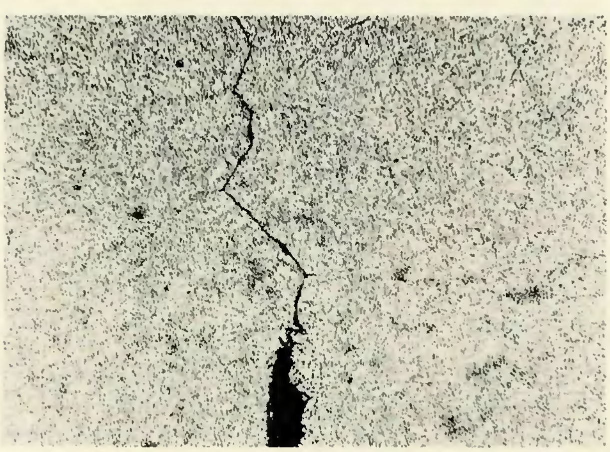

Fig. 9 — Stress relief cracking of 2¼Cr-1 Mo steel at 675 C showing very small plastic deformation in the form of opening of the fatigue precrack

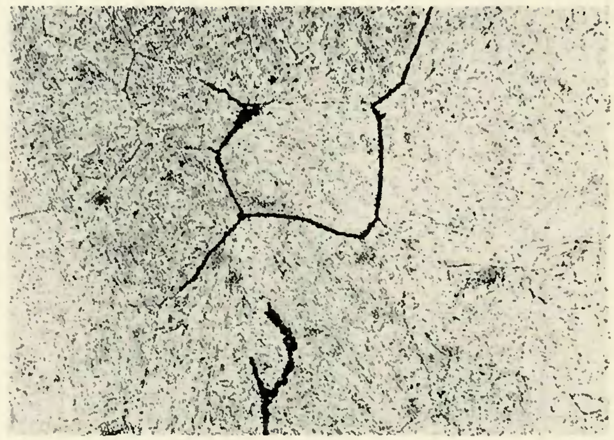

Fig. 10 — Stress relief cracking of 2¼Cr-1Mo steel at 600 C showing crack initiation and propagation

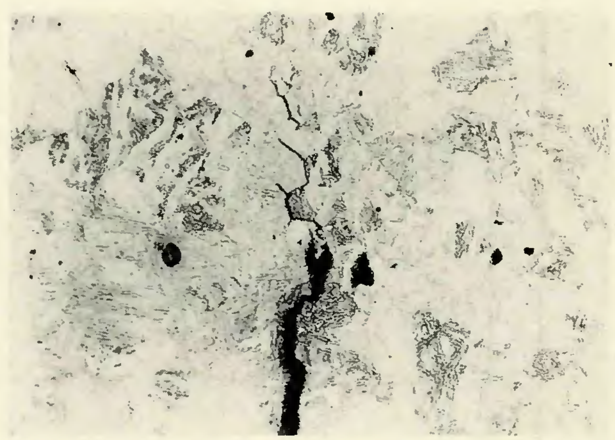

Fig. 11 — Same as Fig. 10, reground and repolished

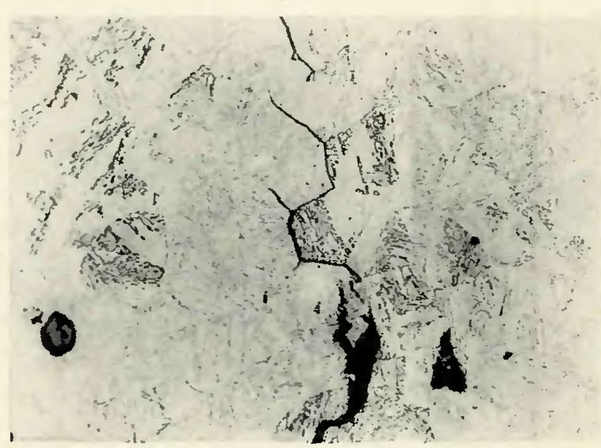

Fig. 12 — Same as Fig. 11 at higher magnification

can be seen that there was no evidence of plastic deformation at the crack tip, except for the specimens of 2¼Cr-1Mo steel at 675 C, which sometimes showed a very small plastic deformation in the form of opening of the fatigue precrack (Fig. 9). In most cases it appeared that the high temperature crack initiated at the end of the fatigue crack. In a very few situations it appeared that the fatigue crack had terminated within a single grain but the high temperature crack had initiated within the adjacent grain boundary (Fig. 10). When the specimens were reground and repolished, it was seen that these cracks also started at grain boundaries like the others (Figs. 11 and 12) but that the initiation was not uniform along the crack front.

Although the test method developed in this investigation differs from previous attempts, the results obtained here compare qualitatively with the results of other workers (Refs. 2-10), and showed that the creep resisting steels tested were sensitive to high temperature cracking.

Conclusion

In the experiments carried out, the residual stresses were simulated by the imposition of loads on compact tension specimens with simulated microstructures similar to those found in the coarsened grain HAZ of the practical welds.

The following points can be generally concluded:

1. It has been possible to simulate the weld heat-affected zone microstructure in 13 mm thick compact tension specimens and then test these specimens for fracture toughness at elevated temperatures using linear elastic fracture mechanics.
2. Apparatus has been developed using the potential-drop technique for detecting the initiation of cracks much shorter than one grain diameter at temperatures in the range 550-675 C.
3. By varying the stress intensities imposed on the compact tension specimens it has been possible to discriminate in terms of time to crack initiation between the susceptibilities to high temperature cracking of 2¼Cr-1Mo, ½Cr-¼Mo and ½Cr-½Mo-¼V steel (simulated weld heat-affected zones).
4. It is concluded that the use of linear elastic fracture mechanics for specimens loaded at elevated temperatures can aid the interpretation of cracking tendencies at high temperature and thus can usefully be related to stress relief cracking problems in welds.
5. Results gained during this investigation indicate that the susceptibilities to stress relief cracking of some ferritic creep resisting steels, in order of increasing susceptibility, is: 2¼Cr-1Mo, ½Cr-¼Mo and ½Cr-½Mo-¼V.

Acknowledgments

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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.

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WRC Bulletin
No. 185
July 1973

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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.

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