Investigation of Hydrogen-Assisted Cracking in FCA Welds on HY-80 Steel

Acidic and basic formulations for flux cored electrodes were evaluated, as well as two methods of hydrogen analyses

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ABSTRACT. Weld metal hydrogen content and hydrogen-assisted cracking in two types of flux cored arc welds on HY-80 were investigated. The hydrogen content analyses were carried out by the RPI silicone-oil extraction method and the IIW method. The results of measurements by both methods show that the hydrogen contents of welds produced with as-received flux cored electrode wires were approximately 2 ppm. Electrode B, a moisture-resistant, fully basic flux cored welding wire, produced welds which had a hydrogen content somewhat less than 2 ppm. Electrode B was also tested after exposure to air at 32°C (90°F) with 100% humidity.

Two variants of the augmented-strain cracking (ASC) tests were used to determine the susceptibility of FCA welds to hydrogen-assisted cracking. Acoustic emission equipment was utilized to record the crack-initiation and propagation processes. The ASC test results show that no cracking occurred in FCA welds subjected to augmented strains of 0.6 and 1.5% when welding with as-received flux cored wires on HY-80 steel. The critical hydrogen content of FCA welds on a single heat of HY-80 was determined to be approximately 4-5 ppm. The hydrogen content in FCA welds was increased by immersing the flux cored electrodes in water for 4, 8 and 12 h, or by exposing the electrodes to 100% humidity at 40°C (104°F) for two weeks. When the hydrogen content of FCA welds on HY-80 reached 9-10 ppm, hydrogen-assisted cracking occurred extensively. The cracking initiated mainly in the coarse-grained or partially melted region of the HAZ and propagated into the weld metal and the base metal.

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Introduction

The flux cored arc welding (FCAW) process is regarded as a low-hydrogen process (Refs. 1, 2), which combines versatility and high productivity for industrial use. In particular, it is generally believed that the use of a basic flux cored wire with Ar/CO_2 shielding produces a lower weld metal hydrogen level than that produced by flux covered electrodes in shielded metal arc welding (SMAW). However, some finite amount of hydrogen remains in welds produced with the FCAW process. Recent investigations have shown that flux cored filler metals can produce weld metal hydrogen contents of 0.9 to 6.6 ppm of deposited metal (Ref. 3). The weld metal hydrogen level that results from FCAW is influenced by many factors (Ref. 4), but the most significant are:

1) Wire lubricant on the external surface of the electrode.

2) Hydrogen content of the flux core ingredients in the electrode.

The low-hydrogen potential of the FCAW process makes it a superior choice for the welding of mild steel. However, the amount of hydrogen necessary to cause cold cracking in steels is inversely related to yield strength. Therefore, high-strength steels, such as the HY-steels, may be susceptible to hydrogen-assisted cracking when welded with the FCAW process.

KEY WORDS

Hydrogen Cracking
FCA Welds on HY-80
Cracking Control
High Yield Strength
Flux Cored Arc Welds
Silicone Oil Extraction
Augmented Strain (AS)
AS Cracking Tests
Acoustic Emission
Crack Susceptibility

Some research has recently been carried out on the properties and diffusible hydrogen contents of weld metal deposited with flux cored wires (Refs. 3, 4). These studies show that a weld metal hydrogen content of 3.0 to 3.6 ppm is allowable when welding high-strength steels, such as A517F and HY-80.

Objectives

The objectives of this investigation were:

1) To determine the hydrogen contents of FCA welds of two types of flux cored wires, using both the RPI silicone-oil extraction method and the IIW mercury-vacuum method.

2) To determine the consistency of the hydrogen analyses measured by the RPI and IIW methods.

3) To evaluate the relative susceptibility to hydrogen-assisted cracking of FCA welds on high-yield-strength steel, HY-80.

4) To investigate the microstructures and the characteristics of hydrogen-assisted cracking in two types of FCA welds on HY-80.

Materials and Procedures

Base Metal

A relatively high-carbon heat of 1½-in. (38-mm) thick HY-80 steel plate was used in this investigation. The chemical composition of this steel is listed in Table 1, along with the nominal compositions of HY-80 material. The mechanical properties of the steel used in this investigation are listed in Table 2. Figures 1 and 2 show the microstructure of the HY-80 base metal, which had been austenitized, water quenched, and tempered in air at 650°C (1200°F) by the producer. The microstructure is tempered martensite and the prior austenite ASTM grain size number is about 7. Figure 1 shows the banding typical of the base metal. The picric acid etch darkens the solute-rich areas, where elongated sulfide inclusions are usually found.

Table 1—Chemical Composition of the HY-80 Base Metal Used in This Investigation

Chemical Analysis (wt-%)									
C	Mn	P	S	Si	Ni	Cr	Mo	V	Ti
0.18	0.32	0.018	0.013	0.20	2.99	1.68	0.41	–	–

Table 2—Mechanical Properties of the HY-80 Base Metal Used in This Investigation

YS, ksi (kg/mm^2)	TS, ksi (kg/mm^2)	% Elong. (1-in. gauge length)	Hardness (HV_{1000})
88 (62)	108 (76)	25	239

Filler Metals

Two types of flux cored wire were used for the tests. Each electrode was 0.063 in. (1.6 mm) in diameter and was designed for welding HY-80 and similar high-yield-strength steels:

1) AWS E91T1-K2 — This electrode is an all-position flux cored wire that contains a somewhat elevated percentage of basic flux components, yet remains within the range of the AWS T-1 classification for acid slag systems. This electrode was developed primarily for the welding of HY-80, and produces high-strength welds with good low-temperature toughness. This electrode will be referred to hereafter as Electrode A, *i.e.*, all-position.

2) AWS E90T5-K2 — This electrode is a fully basic flux cored wire. The basic slag system acts to reduce weld metal inclusion content, resulting in excellent weld metal properties. However, the basic flux produces a fluid slag, making the operability of this electrode poor in out-of-position welding. This electrode will be referred to hereafter as Electrode B, *i.e.*, basic flux.

The chemical composition and AWS classification of Electrodes A and B are listed in Table 3. Typical impact and mechanical properties, taken from the manufacturer's literature (Ref. 5), are listed in Tables 4 and 5.

Specimen Preparation

Hydrogen content analysis specimens were cut from the 1½-in. (38-mm) thick plate and were machined to dimensions of 0.5 × 1 × 0.3 in. (12.7 × 25.4 × 7.6 mm) in compliance with the specifications for IIW specimens. All surfaces were ground flat and polished with 320-grit SiC paper. Run-on and run-off tabs were machined and ground flat to dimensions of 2.25 × 1 × 0.3 in. (57.2 × 25.4 × 7.6 mm). Polished specimens and run-on and run-off tabs were individually degreased with acetone immediately before welding. Following degreasing, they were positioned and loaded into the welding fixture, as illustrated in Fig. 3, and the entire assembly was demagnetized.

The augmented-strain cracking (ASC) test samples were cut from 1½-in.-thick plate, as illustrated in Fig. 4. The specimen was oriented so that the welding direction was perpendicular to the rolling direction and parallel to the plate surface. Samples were machined to dimensions of 0.5 × 2 × 0.3 in. (12.7 × 50.8 × 7.6 mm). The grinding, polishing, degreasing, loading and demagnetizing procedures were identical to those used for hydrogen content analysis specimens.

The welding parameters used for both wires are listed in Table 6. Immediately after welding, the weldment was first quenched in an ice water bath (0°C, 32°F) and then in a bath of dry ice and alcohol at −71°C (−96°F) to minimize the loss of diffusible hydrogen. After cleaning and separating the specimens, they were stored in liquid nitrogen at −196°C (−320°F).

Diffusible Hydrogen Analysis

The diffusible hydrogen contents of FCA welds were determined using both the RPI silicone-oil extraction method and the IIW mercury-vacuum method. The silicone-oil extraction method, developed previously at RPI (Ref. 6), is similar to the JIS glycerin method (Ref. 7). However, the RPI method utilizes silicone oil instead of glycerin in order to facilitate the maintenance of a higher bath temperature — 100°C (212°F) for the RPI method versus 45°C (113°F) for the glycerin test. The elevated bath temperature ensures that 65% of the diffusible hydrogen can be collected from a sample within the first fifteen minutes of the test (Ref. 6).

The mercury-vacuum technique is recognized by the IIW as the standard for diffusible hydrogen measurement. The mercury-vacuum and gas chromatography techniques were recently recommended by the AWS filler metal committee task force group on weld metal diffusible hydrogen as the only acceptable methods for the determination of diffusible hydrogen (Ref. 8). The details of the former method, which involve the evolution of hydrogen in a mercury bath under vacuum, are presented elsewhere (Ref. 9). However, it should be noted that the duration of a single test using the IIW technique is a minimum of three days, and in some cases, hydrogen evolution is not complete for 10 to 15 days (Refs. 10, 11). In the present investigation, the IIW mercury-vacuum hydrogen analyses

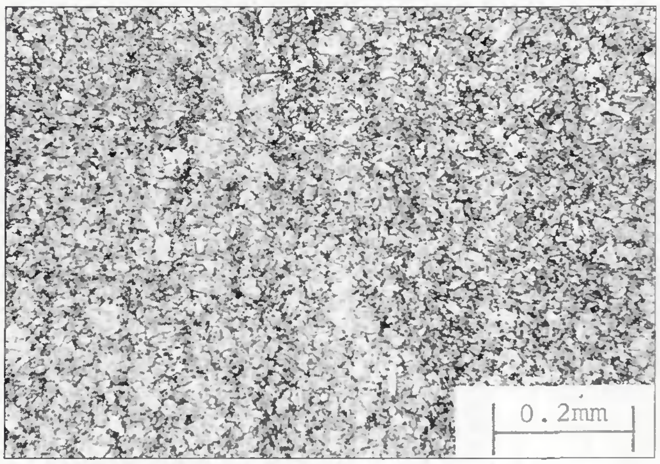

Fig. 1 — Microstructure of HY-80 in the as-received condition, 2% nital, 100X

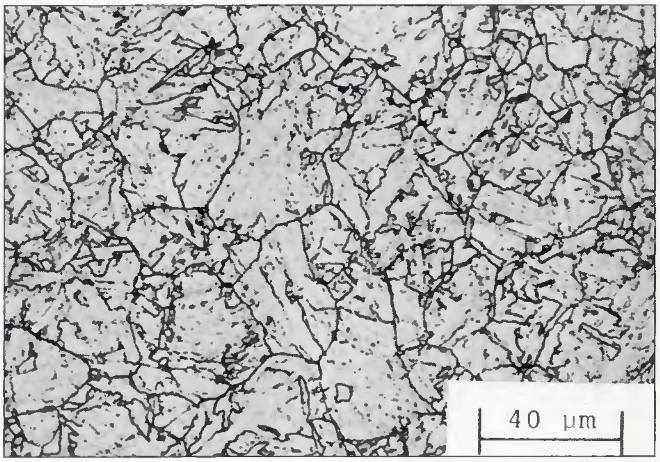

Fig. 2 — Microstructure of HY-80 in the as-received condition, 2% nital, 500X

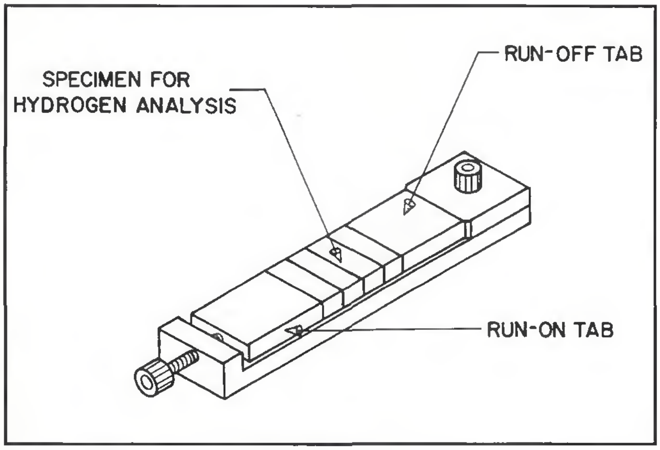

Fig. 3 — Welding fixture for hydrogen analyses and ASC test specimens

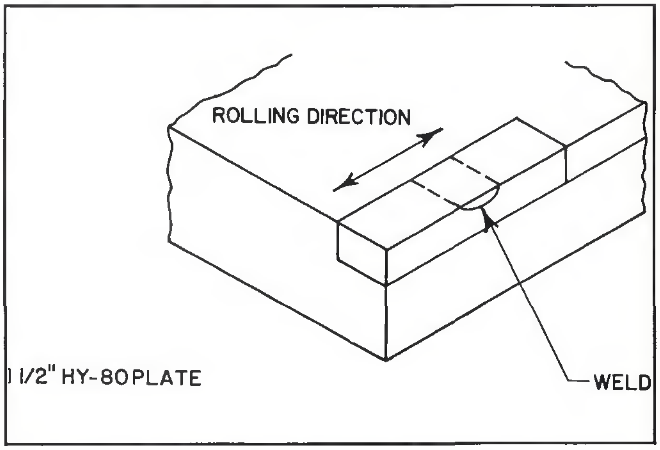

Fig. 4 — Orientation of ASC test specimens removed from base plate

were judged to be complete when no further hydrogen evolved from a test sample in 24 h. The normal duration of these tests, conducted at room temperature, was 8 to 12 days.

The three-step procedure for washing the specimens used for both the silicone-oil and the IIW methods was adopted from the procedure recommended by the BWRA (Ref. 9):

1) Immerse and agitate specimen in pure ethanol for 3-5 s.

2) Immerse and agitate in anhydrous ethyl ether for 3-5 s.

3) Dry with argon gas for 20-30 s.

Hydrogen content on a weld-metal-added basis is computed from the relationship:

$$PPM_d = \frac{\Delta V}{\Delta W} \times \frac{273}{(RT + 273)} \times \frac{AP}{760} \times 90 \qquad (1)$$

where PPM_d = diffusible hydrogen content, parts per million on the basis of deposited metal; ΔV = volume of hydrogen extracted, cc; ΔW = sample weight after welding minus sample weight before welding, gm; AP = atmospheric pressure, mm Hg; RT = room temperature, °C; and 90 = factor to convert from cc/g to PPM.

Hydrogen content on a fused metal or composite-zone basis, PPM_c, is calculated in exactly the same way by substituting the weight of the fused metal in the sample, ΔW_f, for ΔW in Equation 1. The value of ΔW_f for the fused metal is calculated from the equation:

$$\Delta W_f = \frac{A_c W_f}{A_t} \qquad (2)$$

where A_c = cross-sectional area of fusion zone, A_t = total cross-sectional area of the specimen and weld; and W_f = weight of specimen after welding, gm. Area measurements were made with a polar planimeter on photomacrographs of weld samples.

Other investigations (Ref. 3) have shown that the increase in hydrogen content resulting from the exposure of flux cored electrodes to a warm, humid atmosphere (35°C, 90% humidity) is not

Table 3—Typical Undiluted Weld Metal Analyses (Ref. 5)

Electrode	C	Mn	Si	P	S	Mo	Ni	AWS Classification
	Chemical Analyses (wt-%)							
A	0.050	1.50	0.50	0.010	0.018	—	1.75	A5.29, Class E91T1-K2
B	0.060	1.53	0.53	0.009	0.017	0.22	1.66	A5.29, Class E90T5-K2

Table 4—Typical Charpy V-Notch Impact Properties, Electrode A (Ref. 5)

Temperature °F (°C)	As-Welded ft-lb (kg-m)
0 (−17.8)	63 (8.7)
−60 (−51)	30 (4.1)

Table 5—Mechanical Properties of Electrode B (Ref. 5)

	As-Welded	Stress Relieved 1 h at 1150°F (621°C)
Yield strength, ksi (kg/mm^2)	85 (59.8)	77 (54.1)
Tensile strength, ksi (kg/mm^2)	95 (66.8)	90 (63.3)
% Elongation in 2 in. (50.8 mm)	26	28
% Reduction in area	69	69
CVN ft-lb (kg-m) at		
72°F(25°C)	106 (14.7)	119 (16.5)
−20°F(−29°C)	92 (12.7)	101 (14.0)
−60°F(−51°C)	68 (9.4)	63 (8.7)

Table 6—Flux Cored Arc Welding Parameters

Electrode	A	B
Electrode diameter, in. (mm)	1/16 (1.6)	1/16 (1.6)
Welding position	Flat	Flat
Polarity	DCEP	DCEP
Shielding gas	75%Ar-25%CO_2	75%Ar-25%CO_2
Shielding gas flow rate, cfh (L/min)	35-40 (16.5-18.9)	35-40 (16.5-18.9)
Electrode feed speed, ipm (mm/s)	210 (88.9)	380 (160.9)
Welding current, amperes (A)[a]	200	265
Open circuit voltage V	36	36
Arc voltage, V	27	27
Travel speed, ipm (mm/s)	11 (4.7)	15 (6.4)
Heat input, kJ/in. (kJ/mm)	29.5 (1.16)	28.6 (1.13)
Contact tube-to-work distance, in. (mm)	1-1.5 (25-38)	1-1.5 (25-38)

(a) In the middle of the current range recommended by the manufacturer.

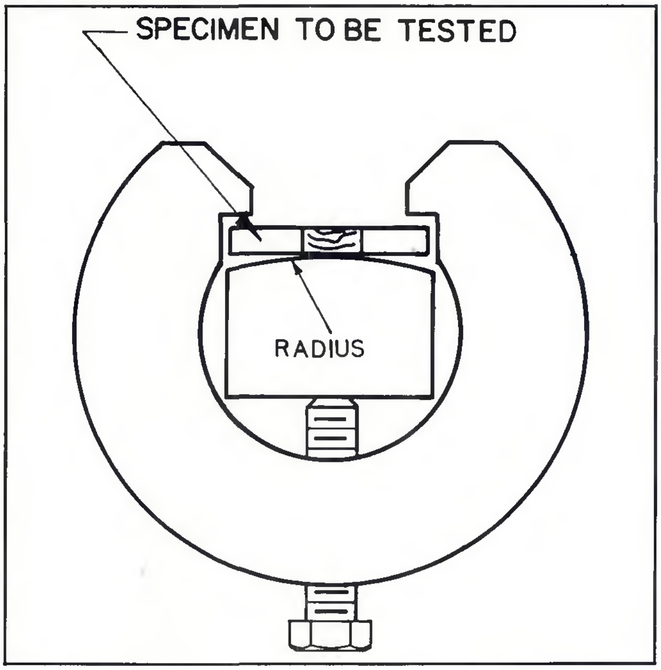

Fig. 5 — Schematic diagram of ASC test with loading parallel to the welding direction

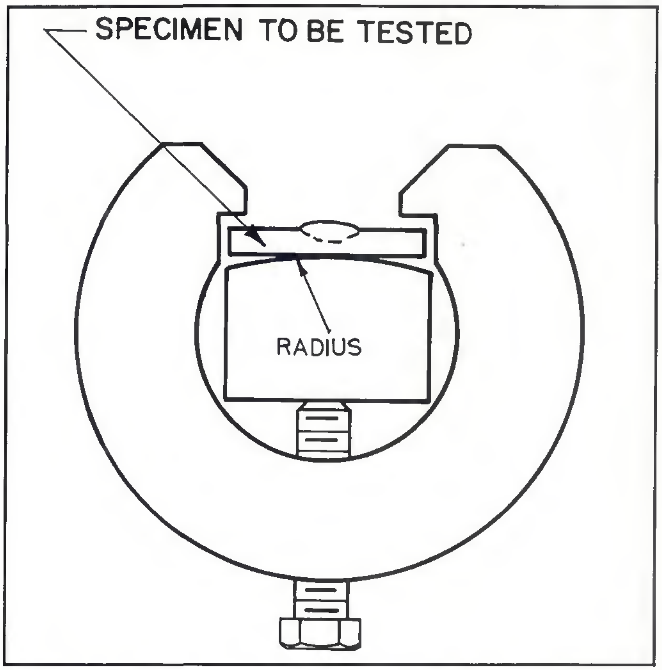

Fig. 6 — Schematic diagram of ASC test with loading perpendicular to the welding direction

large compared to the amounts incorporated in manufacture. In this investigation, it was desired to study the effects of higher hydrogen contents. Therefore, the hydrogen content was varied by immersing the flux cored wires in water for 4, 8 and 12 h at 21°C (70°F) or by exposing the electrodes to 100% humidity at 40°C (104°F) for two weeks in a humidity cabinet. When rusting occurred on the wire surface, it was easily removed by abrasion with fine steel wool.

Augmented-Strain Cracking (ASC) Test and Acoustic-Emission Instrumentation

The ASC test was designed to produce a known reproducible strain in the outer fibers of a weld specimen. The critical diffusible hydrogen content is defined as that amount of diffusible hydrogen which, if present in a steel, in conjunction with critical levels of stress and hardness and at an appropriate temperature, will produce cold cracking. The critical diffusible hydrogen content required to induce cracking in a particular microstructure at a given magnitude of augmented strain can be used as an index of the susceptibility of a steel to hydrogen-assisted cracking. Additional information on the initiation and propagation of hydrogen-assisted cracking can be obtained by measuring acoustic-emission counts versus time. A detailed description of the test procedure appears in an earlier report (Ref. 10).

The two types of ASC test methods used in this investigation are shown schematically in Figs. 5 and 6. One method (Test 1), developed previously at RPI, utilizes loading on a transverse section, parallel to the welding direction — Fig. 5. The second method (Test 2) utilizes loading perpendicular to the welding direction — Fig. 6. In both methods, the HAZ cracking occurs at almost the same location in the ASC specimen — Fig. 7. Although cracking is easier to observe using Test 1, Test 2 is easier to operate and provides a stress system similar to that in a welded joint. Using identical welding parameters, the HAZ cooling rates of the samples will differ somewhat because the effective plate thickness is different, *i.e.,* 0.5 in. (12.7 mm) for the former versus 0.3 in. (7.6 mm) for the latter method. As shown in Fig. 7, HAZ cracking usually occurs perpendicular to the stress direction and under the bead, somewhat removed from the toe on either side of the weld.

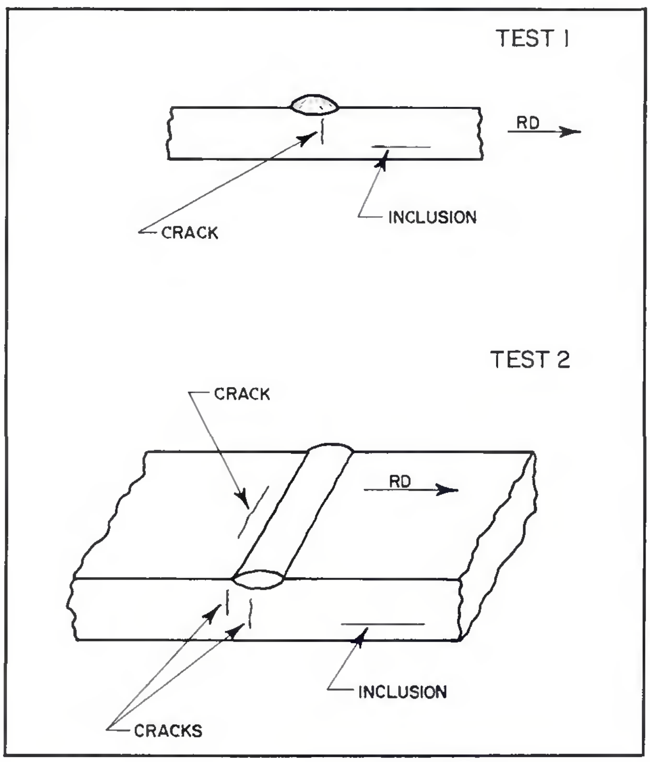

Fig. 7 — Schematic diagram showing relative directions of rolling (RD), welding and cracking in ASC Test 1 and 2 specimens

Metallographic Examination

For metallographic examination, ASC test specimens were repolished and immersion etched at room temperature for 1½ h in a 2% aqueous solution of picric acid mixed with sodium tridecylbenzene sulfonate, a wetting agent. This etchant revealed both the prior austenite grain boundaries and the weld solidification substructure.

Results and Discussion

Diffusible Hydrogen Content Analysis

The hydrogen content analysis results for welds made with Electrodes A and B on HY-80 are shown in Tables 7 and 8, respectively. Table 7 shows that the mean diffusible hydrogen content of welds made with Electrode A in the as-received condition ranges from 1.17 to 1.40 PPM_c. These values are based upon measurements made using the RPI silicone-oil extraction method. A mean diffusible hydrogen content of 1.31 PPM_c was obtained using the IIW method. Table 7 shows that the mean diffusible hydrogen content for welds made with Electrode B in the as-received condition, as measured by the RPI method, ranged from 1.09 to 1.36 PPM_c. A mean diffusible hydrogen content of 1.02 PPM_c was obtained for Electrode B using the IIW method. Although it has been shown that the gas collected over glycerin and silicone oil is not 100% hydrogen (Refs. 13, 14), the data obtained in this investigation indicate that the RPI silicone-oil extraction method is in good agreement with the IIW method. This conclusion supports previous work at RPI (Ref. 6), and it is postulated that the equivalency of volume results from the exchange of gaseous hydrogen and air as the bubble rises through silicone oil in the collection tube. Inspection of Table 7 indicates that the relative deviation for hydrogen contents measured with the RPI method is less than that of the IIW method, within the same weld. This is also in good agreement with data obtained previously at RPI (Ref. 6), shown in Table 9, for welds made with SMAW electrodes.

Hydrogen content analyses were also conducted on welds made with Electrode B which had been exposed to ambient atmosphere (~21°C/70°F) for approximately 6 months and with electrodes that had been subsequently stored in a humidity cabinet at 32°C (90°F), 100% relative humidity (RH) for 1, 3 and 7 days. The results of these tests, shown in Table 10, indicate that Electrode B had high moisture resistance. Welds made with Electrode B stored at ambient atmosphere conditions for about 6 months had a hydrogen content of only 2.33 PPM_d, while the hydrogen content of welds made with the same electrode in the as-received condition was 1.8 PPM_d.

Figure 8 is a graphical comparison of the susceptibility to moisture pickup of FCAW Electrode B and a commercially available SMAW moisture-resistant (MR) electrode. Data for this commercially available SMAW MR electrode were obtained from Ref. 13. These data were converted to appropriate units using a relation between moisture in electrode coatings and weld metal hydrogen content from Graville (Ref. 14).

Welds made with Electrode B, which had been exposed to 32°C, 100% RH for three days, had a hydrogen content of approximately 5.5 PPM_d. Data are available in the literature for welds made with a SMAW E7018 MR electrode humidified for 4 h at equivalent conditions (38°C/100°F, 90% RH), *i.e.*, conditions which produce an equivalent partial pressure of water in the atmosphere to that which occurs at 32°C, 100% RH. These data indicate that welds made with the SMAW electrode typically have hydrogen contents of approximately 10 ppm (Ref. 13). Therefore, the rate of increase in weld hydrogen content with increasing electrode exposure time to moisture is relatively low for Electrode B.

Table 7—Hydrogen Content in HY-80 Weldments with FCAW Electrode A

Test Procedure	Number of Specimens	Hydrogen Content, (PPM_c) Mean	Standard Deviation	Relative Deviation
SO[a]	3	1.17	0.26	22.3%
IIW[b]	2	1.31	0.48	36.6%
SO	5	1.40	0.23	16.7%

(a) Silicone oil.
(b) IIW mercury-vacuum.

Table 8—Hydrogen Content in HY-80 Weldments with FCAW Electrode B

Test Procedure	Number of Specimens	Hydrogen Content, (PPM_c) Mean	Standard Deviation	Relative Deviation
SO	3	1.14	0.08	5.6%
SO	3	1.09	0.11	10.2%
IIW	1	1.02	—	—

Table 9—Hydrogen Content in SMA Weldments (Ref. 6)

Test Procedure	Number of Specimens	Hydrogen Content, (PPM_c) Mean	Standard Deviation	Relative Deviation
SO	3	1.0	0.08	8.2%
IIW	2	1.5	0.20	13.3%
SO	8	6.35	0.69	10.8%
IIW	2	6.40	1.10	17.2%

Augmented Strain Cracking Test and Critical Hydrogen Content Analyses

The results of hydrogen content analyses and ASC tests of FCA welds for Electrodes A and B on HY-80 plate are shown in Tables 11 and 12, respectively. Cracking events are reported on a yes/no basis, based on metallographic observation. For both Electrodes A and B, no cracking occurred in the welds from 0.6% to 1.5% augmented strain when using as-received flux cored electrodes (about 2 ppm hydrogen content). In addition, no cracking occurred when using the flux cored electrodes soaked in water for 4 h (about 3.5 ppm hydrogen content for

Table 10—Hydrogen Content in HY-80 Weldments of Humidified FCAW Electrode B

	Number of Specimens	Hydrogen Content (PPM_c) Mean	Standard Deviation	Relative Deviation
As-received[a]	3	1.82	0.24	13.0%
Stored in atmosphere for 6 months	3	2.33	0.25	10.7%
Exposed to 32°C (90°F), 100% humidity for 1 day	3	3.65	0.53	14.6%
Exposed to 32°C (90°F), 100% humidity for 3 days	3	5.53	1.19	21.6%
Exposed to 32°C (90°F), 100% humidity for 7 days	3	7.15	1.25	17.4%
Exposed to 40°C (104°F), 100% humidity for 14 days	3	9.40	0.55	5.9%

(a) Electrode B was received in a sealed plastic container which acted as a moisture barrier.

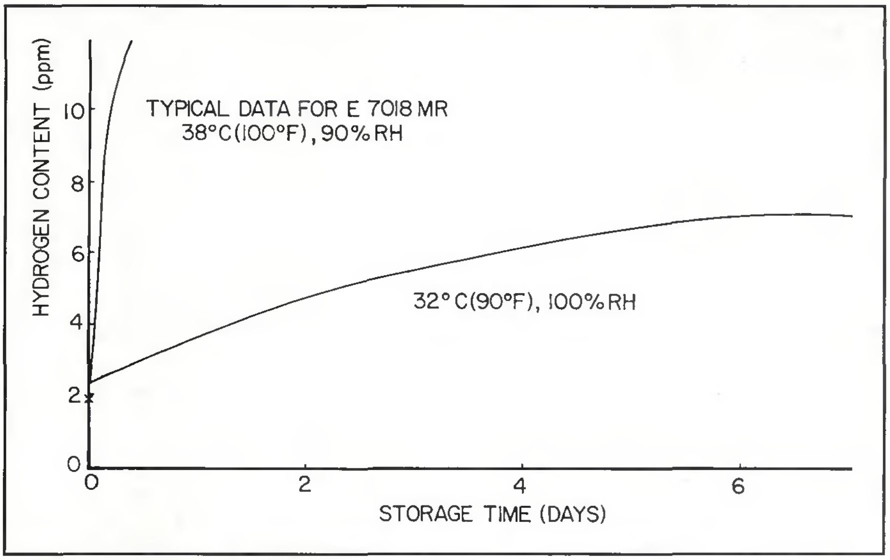

Fig. 8 — The relationship between weld metal hydrogen content and storage time for welds made with humidified FCAW Electrode B. Also shown are typical data for an E7018 MR SMAW electrode

Fig. 9 — Initiation of hydrogen-assisted cracking in HAZ at prior austenite grain boundaries. FCAW Electrode A, 0.6% augmented strain, 9.90 ppm hydrogen, picric acid etch, 250X

Table 11—Augmented Strain Cracking Test Results for FCA Welds of Electrode A on HY-80

Electrode Treatment	Hydrogen Content (ppm_d)	Augmented Strain (%)	Relation between Loading and Welding Directions	Cracking Observed
As-received	2.24	0.6	parallel	No
		1.5		No
Soaked in water for 4 h	3.62	0.6	parallel	No
		1.5		No
Soaked in water for 4 h	3.57	0.6	perpendicular	No
		1.5		No
Soaked in water for 8 h	4.37	0.6	parallel	Yes/No
		1.5		Yes
Soaked in water for 8 h	4.53	0.6	perpendicular	No
		1.5		Yes/No
Soaked in water for 12 h	7.50	0.6	parallel	Yes
		1.5		Yes
Soaked in water for 12 h	9.90	0.6	perpendicular	Yes
		1.5		Yes

Table 12—Augmented Strain Cracking Test Results for FCA Welds of Electrode B on HY-80

Electrode Treatment	Hydrogen Content (ppm_c)	Augmented Strain (%)	Relation between Loading and Welding Directions	Cracking Observed
As-received	1.82	0.6	parallel	No
		1.5		No
As-received	1.81	0.6	perpendicular	No
		1.5		No
Soaked in water for 4 h	2.99	0.6	parallel	No
		1.5		No
Soaked in water for 4 h	2.76	0.6	perpendicular	No
		1.5		No
Soaked in water for 8 h	3.75	0.6	parallel	No
		1.5		No
Soaked in water for 8 h	3.94	0.6	perpendicular	No
		1.5		Yes
Exposed to a warm, humid atmosphere (40°C, 100% humidity) for 14 days	9.40	0.63	parallel	Yes
		1.5		Yes

Electrode A and about 3 ppm for Electrode B).

The critical hydrogen content of welds made with both Electrodes A and B was found to be approximately 4–5 ppm. This hydrogen content resulted from immersion of the electrodes in water for 8 h. The augmented strain necessary to cause cracking was 0.6% for Electrode A (about 4.5 ppm hydrogen content) and 1.5% for Electrode B (about 4 ppm hydrogen content). It should be noted that of the six specimens welded with Electrode A that had been soaked in water for 8 h, three exhibited cracking in the ASC test. Of the six specimens welded with Electrode B soaked in water for 8 h, only one exhibited cracking. When the hydrogen content of FCA welds on HY-80 reached 9–10 ppm (Electrode A immersed in water for 12 h and Electrode B exposed to 40°C, 100% RH for 14 days), extensive hydrogen-assisted cracking occurred.

Metallographic Examination

No significant metallographic differences were found between FCA welds made with Electrodes A and B on HY-80. Metallographic examination indicated that the hydrogen-assisted cracking in ASC test specimens initiated mainly in the HAZ at prior austenite grain boundaries (Fig. 9) and propagated into the weld metal and the base metal. It was also observed that, despite the orientation of inclusions parallel to the primary stress directions, inclusions sometimes act as crack initiators. Crack propagation normally occurred in an intergranular manner, along prior austenite grain boundaries — Figs. 10 and 11. However, in sev-

Fig. 10 — Intergranular and transgranular propagation of hydrogen-assisted cracking in HAZ, FCAW Electrode A, 0.8% augmented strain, 9.90 ppm hydrogen, picric acid etch, 250X. 80 μm

Fig. 11 — Primarily intergranular crack propagation in the HAZ and along the fusion line, FCAW Electrode B, 0.8% augmented strain, 3.94 ppm hydrogen, picric acid etch, 100X. 0.2 mm

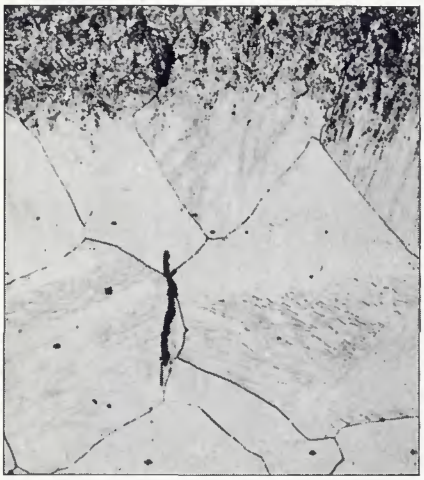

Fig. 12 — Hydrogen-assisted cracking initiated in the partially melted zones of the weld. FCAW Electrode A, 0.8% augmented strain, 9.90 ppm hydrogen picric acid etch, 200X. 100 μm

Fig. 13 — Hydrogen-assisted cracking initiated in the unmixed zone of the weld. FCAW Electrode B, 0.8% augmented strain, 3.94 ppm hydrogen, picric acid etch, 500X. 40 μm

eral specimens, cracks also propagated transgranularly, through prior austenite grains — Figs. 10-12. Occasionally, cracking initiated in the partially melted zone (PMZ) or the unmixed zone — Fig. 13. The maximum hardness values in the HAZ of welds made with Electrodes A and B were approximately equal, *i.e.*, HV 1000 317. This was expected as both welds were made using approximately equal energy inputs of 29 kJ/in. (1.14 kJ/mm).

Conclusions

1) The hydrogen contents of welds on a single heat of HY-80 steel made with acidic and fully basic FCAW electrodes in the as-received condition were approximately 2 ppm. Welds made with a fully basic, moisture-resistant, flux cored wire, Electrode B, had a slightly lower hydrogen content (1.8 ppm) than those made with Electrode A, an all-position flux cored wire (2.1 ppm).

2) The fully basic flux cored wire, Electrode B, was slightly less susceptible to moisture pickup than Electrode A. The hydrogen content of welds made with wire soaked in water for 8 h was about 4 ppm for Electrode B and 4.5 ppm for Electrode A.

3) No cracking occurred in FCA welds with augmented strains of 0.6% and 1.5% using Electrodes A and B in the as-received condition.

4) The critical hydrogen content of FCA welds on the single heat of HY-80 was approximately 4-5 ppm.

5) Welds made with Electrode B were less susceptible to hydrogen-assisted cracking than those made with Electrode A.

6) The hydrogen-assisted cracking of FCA welds on HY-80 initiated mainly in the HAZ at prior austenite grain boundaries. Crack propagation was observed to occur by both intergranular and transgranular mechanisms.

7) The results of hydrogen content analyses made using the RPI silicone-oil extraction method correlated well with those made using the IIW method. The relative deviation for data collected using the RPI method is somewhat less than that for data collected using the IIW method.

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WRC Bulletin 328
November 1987

This bulletin contains two reports covering related studies conducted at The University of Kansas Center for Research, Inc., on the CTOD testing of A36 steel.

Specimen Thickness Effects for Elastic-Plastic CTOD Toughness of an A36 Steel
By G. W. Wellman, W. A. Sorem, R. H. Dodds, Jr., and S. T. Rolfe

This paper describes the results of an experimental and analytical study of the effect of specimen size on the fracture-toughness behavior of A36 steel.

An Analytical and Experimental Comparison of Rectangular and Square CTOD Fracture Specimens of an A36 Steel
By W. A. Sorem, R. H. Dodds, Jr., and S. T. Rolfe

The objective of this study was to compare the CTOD fracture toughness results of square specimens with those of rectangular specimens, using equivalent crack depth ratios.

Publication of these reports was sponsored by the Subcommittee on Failure Modes in Pressure Vessel Materials of the Pressure Vessel Research Committee of the Welding Research Council. The price of WRC Bulletin 328 is $20.00 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Suite 1301, 345 E. 47th St., New York, NY 10017.

WRC Bulletin 330
January 1988

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The Fracture Behavior of A588 Grade A and A572 Grade 50 Weldments
By C. V. Robino, R. Varughese, A. W. Pense and R. C. Dias

An experimental study was conducted on ASTM A588 Grade A and ASTM A572 Grade 50 microalloyed steels submerged arc welded with Linde 40B weld metal to determine the fracture properties of base plates, weld metal and heat-affected zones. The effects of plate orientation, heat treatment, heat input, and postweld heat treatments on heat-affected zone toughness were included in the investigation.

Effects of Long-Time Postweld Heat Treatment on the Properties of Constructional-Steel Weldments
By P. J. Konkol

To aid steel users in the selection of steel grades and fabrication procedures for structures subject to PWHT, seven representative carbon and high-strength low-alloy plate steels were welded by shielded metal arc welding and by submerged arc welding. The weldments were PWHT for various times up to 100 h at 1100°F (593°C) and 1200°F (649°C). The mechanical properties of the weldments were determined by means of base-metal tension tests, transverse-weld tension tests, HAZ hardness tests, and Charpy V-notch (CVN) impact tests of the base metal, HAZ and weld metal.

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