Effects of Welding Parameters and Electrode Atmospheric Exposure on the Diffusible Hydrogen Content of Gas Shielded Flux Cored Arc Welds

A variety of electrodes were subjected to atmospheric exposure tests to determine their susceptibility to moisture absorption

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ABSTRACT. Gas-shielded flux cored arc welding (FCAW-G) has been in use for many years. However, some major issues still exist regarding the ability of the FCAW-G process to deposit sound welds on high-integrity applications, even though it offers significant economies due to its high deposition rate. One of the major issues when welding high-strength steels with FCAW-G is the diffusible hydrogen potential of various electrodes. There have been questions regarding the moisture content of various types and classifications of FCAW-G electrodes, especially after atmospheric exposure. Few studies have been performed to establish the effects of electrode classification, electrode use, moisture absorption from atmospheric exposure and weld parameters on weld metal diffusible hydrogen content. Low-hydrogen shielded metal arc welding (SMAW) electrodes, for example, must be stored at 250°F per ANSI/AWS D1.1 and have a permissible atmospheric exposure up to 9 h before rebaking is required.

The objectives of this investigation were to determine the effects of weld parameters on the results of the diffusible hydrogen test per AWS A4.3-93 for FCAW-G electrodes, develop an atmospheric exposure test procedure and evaluate the atmospheric exposure test procedure on mild steel and Cr-Mo FCAW-G electrodes. The moisture resistance of E71T-1, E70T-1, E71T-5 and ER70S-3 mild steel electrodes and E81T-B2, E91T-B3 and E80C-B2 Cr-Mo electrodes was investigated using the atmospheric exposure test. Three wire feed speeds and three contact tube-to-work distances were used to study the effects of current and electrode extension on the weld diffusible hydrogen content of an E71T-1 mild steel electrode. Weld voltage and travel speed were adjusted to maintain a constant arc length of ¼ in. (6.35 mm) and weld deposit area, respectively. Diffusible hydrogen content of the weld deposit was found to increase almost linearly as the weld current increased for the E71T-1 electrode. The weld diffusible hydrogen content increased from 2.3 mL/100 g at 140 A to approximately 11.6 mL/100 g at 345 A. Contrary to published literature, the effects of electrode extension were small at a constant current and arc length with this electrode. Increased contact tube-to-work distance decreased current and, hence, the weld diffusible hydrogen content at a constant wire feed speed. Diffusible hydrogen content of the weld deposit decreased with increasing time in the electrode extension column. The diffusible hydrogen content was higher in welds made with a longer contact tube-to-work distance when comparing tests that had equal time in the electrode extension column. This was believed to be a result of the higher wire feed speeds, which change the temperature profile in the electrode extension.

The atmospheric exposure test evaluated the moisture resistance of several mild steel and Cr-Mo FCAW-G electrodes from different suppliers. The test used a single layer of FCAW-G electrode that was carefully wound on a painted wire spool. The spool was exposed to moisture inside a forced air humidity cabinet. Diffusible hydrogen tests were performed on welds made with these electrodes in the as-received and after a one-week exposure condition. The atmospheric exposure environment was controlled at 80°F (27°C) and 80% relative humidity. These humidity cabinet parameters were based on the absorbed moisture test described in AWS A5.1-91 sections 16.2 through 16.6 for SMAW electrodes. All weld diffusible hydrogen tests were performed using gas chromatography per AWS A4.3-93. FCAW-G electrodes were found to be susceptible to moisture pickup in a humid environment. For electrodes produced to the same classification, some variability on weld diffusible hydrogen was measured in consumables supplied by different manufacturers. For example, the weld diffusable hydrogen content of E71T-1 electrodes after a one-week exposure increased from 4 to 8 mL/100 g for one electrode and increased from 8 to 27 mL/100 g for another. Based on these results, storage and operating ranges shown by manufacturers to produce low hydrogen weld deposits should be followed carefully when hydrogen-assisted cracking is a risk. The electrode should be used within the current range recommended by the supplier or with lower currents to minimize diffusible hydrogen. Handling guidelines and atmospheric exposure test procedures need to be established to improve the control of hydrogen in high-integrity FCAW-G weldments.

KEY WORDS

Diffusible Hydrogen
Hydrogen Cracking
Flux Cored Electrode
Moisture Resistant
Low Hydrogen
Cr-Mo Electrode
Humidity

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Introduction

The gas-shielded flux cored arc welding (FCAW-G) process has been in use for approximately 40 years (Ref. 1). The process uses a consumable electrode, like the gas metal arc welding (GMAW) process, except the electrode is tubular and filled with flux, in addition to metal powders, instead of being solid. This process is preferred by many for high deposition flat or out-of-position applications. For welding in the flat position, the slag provided by the flux core is usually more basic to increase fluidity, control properties and permit better outgassing. For other welding positions, rutile electrodes are preferred since the slags are stiffer and provide support for the weld pool. Large-diameter rutile electrodes that provide high efficiency and high deposition rates are also used in the flat position. Rutile electrodes are more acidic and typically have lower impact strength than basic electrodes. Caution should be used when using rutile electrodes in the flat welding position since the stiffer slag may inhibit outgassing and promote worm tracking (Ref. 2). Electrode manufacturers continue to develop FCAW-G electrodes that have improved properties and are appropriate for high-integrity applications in all positions.

One of the major issues to consider in thick-section or high-integrity applications is the resistance to hydrogen-assisted cracking (HAC). Hydrogen-assisted cracking can be a problem in higher strength steels used in pressure vessels, pipelines and steel structures (Ref. 1). The susceptibility of a weldment to hydrogen cracking is a function of the hydrogen content, the weld and heat-affected zone (HAZ) microstructure and hardness, service temperature and weld restraint. To prevent hydrogen cracking, many fabricators use low-hydrogen electrodes, preheat the weldment to reduce cooling rate and to promote hydrogen diffusion, and in some cases postweld heat treat (PWHT) to improve microstructure and stabilize the diffusible hydrogen. Weld codes and specifications specify requirements for weld hydrogen control through consumable controls, preheat, interpass temperature and PWHT to reduce the risk of HAC. Of these requirements, control of consumables is critical in the control of diffusible hydrogen below a certain level depending on the welding application. Some codes also specify requirements for weld heat input and maximum weld and HAZ hardness to control microstructure.

This report presents details of a project to evaluate the effects of welding parameters and electrode atmospheric exposure on the diffusible hydrogen content of gas shielded flux cored arc welds. The major objectives of this study can be summarized as follows:

1) Determine the effects of welding parameters on the diffusible hydrogen content of FCAW-G weld deposits.

2) Develop a procedure to assess the effects of FCAW-G electrode atmospheric exposure on the diffusible hydrogen content of FCAW-G weld deposits.

3) Determine the effects of FCAW-G electrode atmospheric exposure on the weld diffusible hydrogen content for a number of mild steel and Cr-Mo FCAW-G electrodes.

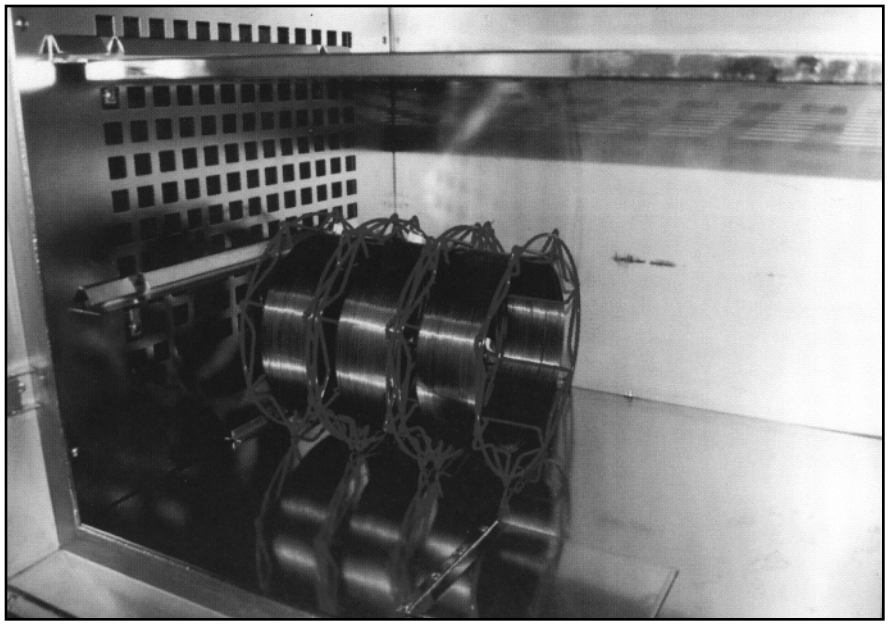

Fig. 1 — Atmospheric exposure FCAW-G electrode samples in humidity cabinet.

Diffusible hydrogen of the weld deposit is typically measured using the procedures outlined in AWS A4.3-93 (Ref. 3). This procedure permits diffusible hydrogen to be measured using either gas chromatography or a mercury collection method. Considerable work has been done within the AWS A5 committees to assure diffusible hydrogen testing repeatability between labs through round-robin testing projects between electrode suppliers and other laboratories (Ref. 4).

Two AWS standards cover FCAW-G electrodes: A5.20, *Specification for Carbon Steel Electrodes for Flux Cored Arc Welding* (Ref. 5), and A5.29, *Specification for Low Alloy Steel Electrodes for Flux Cored Arc Welding* (Ref. 6) (currently being revised). These standards define the requirements for weld properties, shielding gas and welding position. AWS A5.20-95 also includes "hydrogen category designators" as an option to enable manufactures to certify that the electrode is generally capable of achieving the indicated level of diffusible hydrogen under the classification test conditions. The three hydrogen category designations are H4 = 4 mLH_2/100 g; H8 = 8 mLH_2/100 g; H16 = 16 mLH_2/100 g.

This system has been or is being incorporated into the electrode specifications for shielded metal arc welding (SMAW), FCAW-G, GMAW and submerged arc welding (SAW). These classifications certify that the as-received diffusible hydrogen content of weld deposits made per AWS A4.3-93 will be less than the classification rating. The diffusible hydrogen classification system is based on the linear behavior of weld cracking susceptibility to the logarithm of the diffusible hydrogen content (Ref. 4). Therefore, the H4 classification is an order of magnitude less than the H8 classification with respect to the influence of hydrogen. Manufacturers are now beginning to supply electrodes using these designators (Ref. 7).

The diffusible hydrogen content of the weld deposit made with an FCAW-G welding process is influenced by the as-received moisture content of the electrode, the absorbed moisture due to storage and atmospheric exposure, the shielding gas and the welding parameters (Refs. 8–10). The hydrogen classification in A5.20-95 only addresses the as-received weld hydrogen content. Specifications that permit the use of FCAW-G electrodes lack requirements for the effects of electrode use, exposure to the atmosphere and weld parameters. Atmospheric exposure controls and requirements for the SMAW process have been used for years to assure low hy-

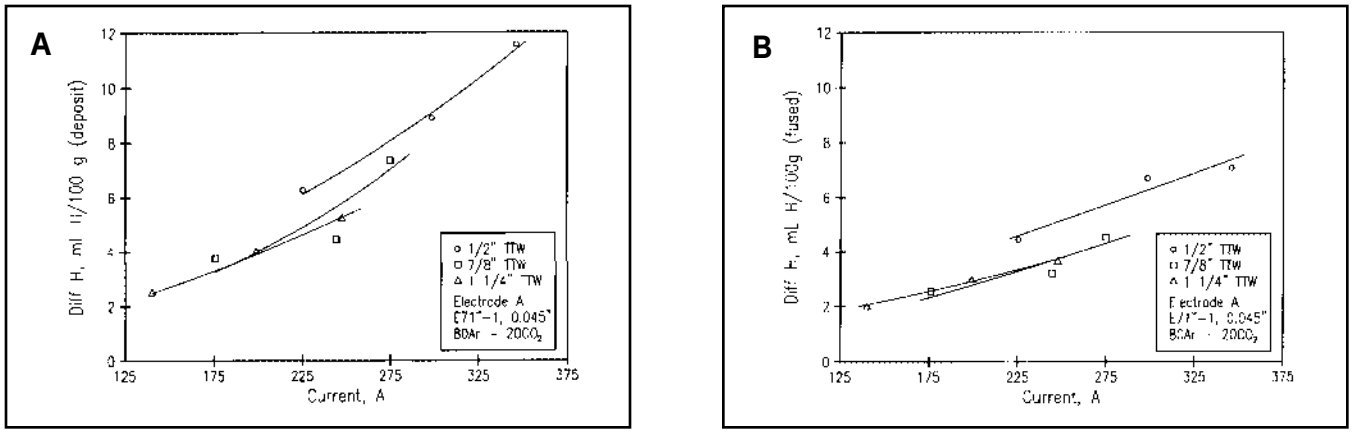

Fig. 2 — Effects of current on diffusible hydrogen for an E71T-1 electrode. A — Diffusible hydrogen (deposited metal); B — diffusible hydrogen (total fused metal).

drogen integrity. For example, an E7018M SMAW electrode must be stored at 250°F (121°C) per AWS D1.1 structural welding code and have a permissible atmospheric exposure of 9 h before rebaking. Most AWS standards do not include requirements for storage of FCAW-G consumables. However, Section 12.6.7 of AWS D1.5-96 bridge welding code does include controls for packaging, electrode storage and electrode drying; and equipment for FCAW-G electrode storage is also now available (Ref. 11). Data is needed for FCAW-G to determine the effects of atmospheric exposure and other key parameters on diffusible hydrogen content of the weld deposit. This data would help support the use of FCAW-G when used for high-integrity applications. It should be noted that the European standard EN758:1992 also distinguishes hydrogen classifications and requires manufacturers to state in their sales literature an envelope of welding conditions for which the claimed class is valid along with storage guidelines (Ref. 12).

FCAW-G electrodes have been reported to absorb moisture from atmospheric exposure (Refs. 8, 13). The initial hydrogen content of the FCAW-G electrode represents the hydrogen level shortly after manufacture. FCAW-G electrodes may absorb moisture from the atmosphere during storage or at the work station after opening the packaging. Some lubricants on the wire sheath can contain moisture, which contributes to hydrogen in the weld. Moisture is absorbed into the flux ingredients through the crevice in the wire sheath. Seamless FCAW-G electrodes are more resistant to moisture absorption in the flux since the flux ingredients are not exposed to the atmosphere after production. Unlike SMAW electrodes, FCAW-G electrodes do not use moisture-sensitive binders in the flux and have a much smaller flux-to-wire volume ratio (Ref. 13). Therefore, FCAW-G electrodes should be more resistant to moisture absorption compared to SMAW. Moisture can also be introduced into the welding arc through the shielding gas and improper shielding (Ref. 14). Atmospheric exposure testing and guidelines and weld parameter guidelines are required for high-integrity FCAW-G applications.

The effects of FCAW-G welding parameters (Refs. 8–10, 14) and atmospheric exposure (Refs. 8, 13) on diffusible hydrogen content of the weld deposit have been investigated by several authors for basic, rutile and metal cored electrodes. In general, the hydrogen content of FCAW-G welds has been reported to increase with increasing current and decreasing tube-to-work distance. At shorter tube-to-work distance and higher currents, there is less time for resistive heating to evaporate hydrogen-containing residuals from the wire surface. Also at higher current, it is believed that the metal drops achieve smaller diameters, which increases the surface-area-to-volume ratio of the drop (Ref. 9). This means hydrogen levels increase faster in fine drops for a given arc environment due to the higher drop surface area.

White, *et al.,* showed that weld diffusible hydrogen levels from using the rutile electrodes, such as E71T-1, were more susceptible to parameter changes than basic electrodes, like E71T-5, and metal cored electrodes (Refs. 9, 10). They compared the diffusible hydrogen content of welds made using different tube-to-work distances and constant current. The tests were designed to maintain constant deposit size and area by changing travel speed. Arc length was not controlled but was believed to be approximately 3 mm (0.118 in.). The hydrogen levels were reported as a function of both deposit and fused metal weight. AWS A4.3 requires hydrogen to be reported in milliliters per 100 grams of weld deposit. For the rutile electrodes, hydrogen level increased with decreasing tube-to-work distance at constant current. Under these test conditions, higher wire feed speeds were required to maintain constant current at the longer tube-to-work distance. The heating time or the time the electrode spends in the electrical extension between the contact tip and arc was longer for the longer tube-to-work-distance tests. Longer heating time was believed to evaporate more hydrogen from the electrode before it entered the arc. Weld diffusible hydrogen measured when using the basic electrode E71T-5 was not affected by tube-to-work distance or current. It was suggested that the fluoride in the E71T-5 flux sublimed and reduced the partial pressure of free hydrogen in the arc. A metal cored electrode, AWS E71T-G, was also tested and found insensitive to tube-to-work distance. Hydrogen content of the metal cored electrode deposit was sensitive to metal transfer mode, where the spray transfer mode produced more weld metal hydrogen than short circuit transfer.

A similar investigation was conducted by Nuhn, *et al.*, where a new E81T1-Ni1, controlled rolled electrode was compared to conventional rutile FCAW-G electrodes (Ref. 8). Both electrodes showed sensitivity to tube-to-work distance and current where the new controlled rolled electrode had lower as-received weld diffusible hydrogen and was more tolerant to change. Atmospheric exposure tests were performed on this FCAW-G electrode by using the absorbed moisture test conditions specified in AWS A5.1-91 for SMAW electrodes (Ref. 15). This absorbed moisture test specifies a testing environment of 80% relative humidity at 80°F (27°C). Electrode exposure

time was from several days to weeks, which was considerably longer than the 9-h test used on SMAW electrodes. The exposed electrodes were then used to make diffusible hydrogen tests similar to the requirements of AWS A4.3. Results from this investigation showed the new control rolled electrode absorbed moisture but at a rate much lower than conventional rutile electrodes.

Siewert (Ref. 13) addressed techniques for controlling moisture in electrodes. The SMAW moisture content of the covering is determined by the increase in weight of an absorption tube filled with anhydrous magnesium perchlorate and is expressed as a percentage of the original weight of the sample covering. The AWS A5.1-91 absorbed moisture test specifies that electrodes be placed in a forced air circulation cabinet that has an environment of 80% relative humidity at 80°F for 9 h. The electrode is considered moisture resistant and can be given an "R" moisture resistant classification if the electrode coating moisture content does not exceed 0.4 wt-%. This moisture content typically represents a weld metal diffusible hydrogen content of 10 mL/100 g (Ref. 4). This method has been used for many years and is easy to perform on SMAW electrodes. For FCAW-G electrodes, Siewert suggested that the electrodes be cut 1 in. (25.4 mm) long to permit moisture weight testing after moisture exposure. Limited data was provided that showed weld deposits made with a rutile FCAW-G electrode were susceptible to moisture pickup from moisture exposure. However, an absorbed moisture or atmospheric exposure test and a moisture-resistant rating does not exist for FCAW-G electrodes to date, although good correlation has been shown between percentage moisture in the wire and diffusible hydrogen in FCAW-G weld metal (Ref. 7).

Experimental Approach

This investigation was performed to develop a preferred procedure for atmospheric exposure testing FCAW-G electrodes and to evaluate the effects of weld parameters on weld metal diffusible hydrogen content. Both mild steel and low- alloy (Cr-Mo) electrodes were evaluated since the latter can be used on high-integrity pressure vessels. An atmospheric exposure test procedure was developed that defines the preferred sample geometry, test conditions (time, temperature and humidity) and documentation. It is hoped this data will assist in the development of handling and weld parameter guidelines, atmospheric exposure limits and an atmospheric exposure testing procedure for FCAW-G electrodes, thereby improving the control of hydrogen in high-integrity weldments.

The effects of weld parameters were evaluated by conducting a series of tests using three wire feed speeds. At each wire feed speed, tests were performed at three contact tube-to-work (TTW) distances. The weld deposit size was held constant by maintaining a constant wire- feed-speed-to-travel-speed ratio. Arc length was also held constant at ¼ in. (6.35 mm). This controlled test matrix was performed to evaluate the significance of current, contact tube-to-work distance and wire feed speed on weld diffusible hydrogen content. Weld metal hydrogen was reported per unit deposit and fused weight to evaluate the effects of weld penetration at higher currents.

Welding was performed on a Lincoln sidebeam station with a Lincoln DC-1000 power supply. The direct current electrode positive polarity was used. The welding gun was gas cooled and mounted in a direct drive setup to minimize wire liner contamination. A mixture of 80%Ar-20%CO_2 was used for the shielding gas. Shielding gas dew point was maintained below –60°C. The welding gun was set at 5 to 10 deg. (0.087 to 0.174 rad.) drag angle to provide better weld pool shielding and help minimize slag buildup at the leading edge of the weld pool. The contact tube-to-work distance (TTW) was set using gauges between the contact tube and the workpiece. Wire feed speed and voltage were controlled by a Lincoln NA-4 controller. A calibration curve was determined between the actual wire feed speed and the set wire feed speed. Calibrated real-time data acquisition was used to measure voltage, current and wire feed speed during the parameter development study — Table 1. An E71T-1, 0.045-in. (1.14-mm) diameter electrode was used to evaluate the effects of welding parameters on the weld diffusible hydrogen content. Three wire feeds speeds (WFS) and three contact tube-to-work distances were used to

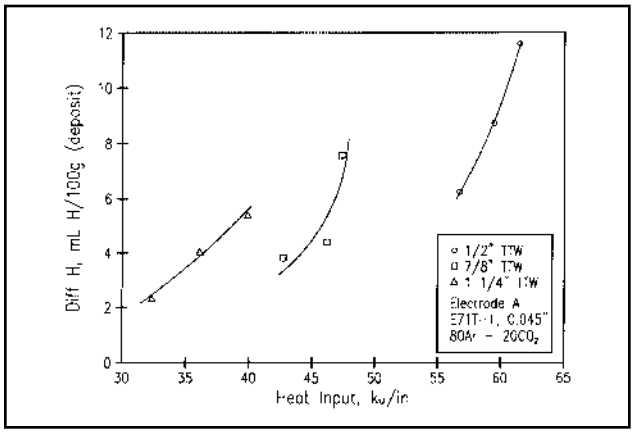

Fig. 3 — Heat input effects on diffusible hydrogen (deposit).

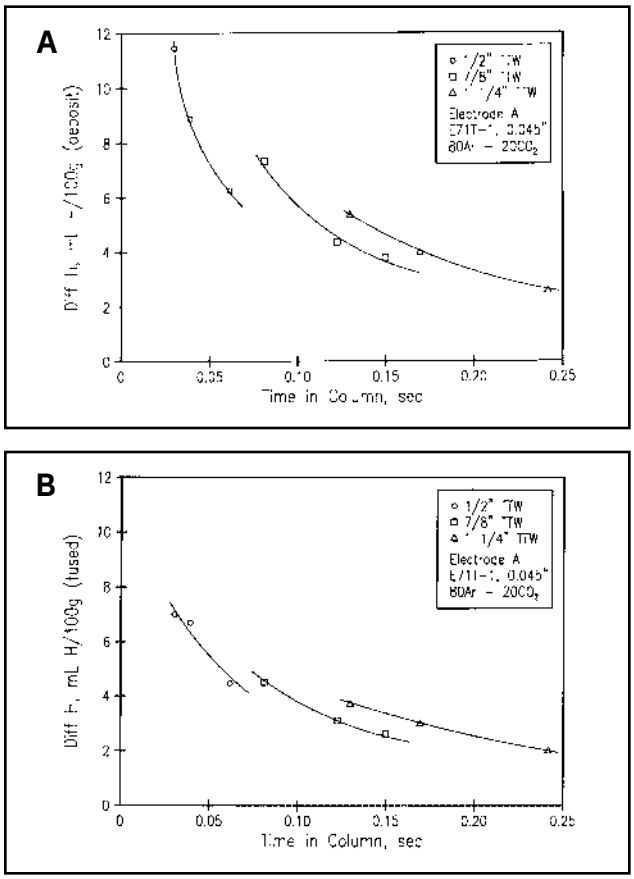

Fig. 4 — Effects of electrode extension time in column on diffusible hydrogen. A — Diffusible hydrogen (deposit); B — diffusible hydrogen (fused).

Table 1 — Weld Parameters for E71T-1 (Electrode A) Diffusible Hydrogen Tests, 1/4-in. (6.35-mm) Arc Length

TTW (in.)	WFS (in./min)	TS (in./min)	Time in Column (s)	Avg. I (A)	Avg. V (V)	Heat Input (kJ/in.)	Avg. Diffusible Hydrogen (mL/100 g)	Fused Area (mm^2)	Deposit Area (mm^2)
1/2	250	7	0.06	226	29.3	56.8	6.2	45	32
1/2	350	10	0.042	293	33.8	59.4	8.8	52	40
1/2	450	13	0.033	345	38.5	61.3	11.6	65	40
7/8	250	7	0.15	179	27.9	42.8	3.8	38	26
7/8	350	10	0.107	240	32.1	46.2	4.3	45	33.5
7/8	450	13	0.083	275	37.2	47.2	7.6	49	30
1 1/4	250	7	0.24	140	27.0	32.4	2.3	38	33
1 1/4	350	10	0.171	200	30.2	36.2	4	43	32
1 1/4	450	13	0.133	247	35	39.9	5.4	47.5	33

Fixed Conditions:
80% Argon-20% CO_2 at 40 ft^3/h
1/4-in. (6.35-mm) arc length
DCEP
10-deg (0.1745-rad.) drag travel angle
3/4-in. (19.05-mm) ID gas nozzle
0.045-in. (1.14-mm) diameter

TTW = Contact Tube to Work
WFS = Wire Feed Speed
TS = Travel Speed
19-g Avg. Deposit Weight

Table 2 — Description of FCAW-G Electrodes Used in Atmospheric Exposure Tests

Material	AWS Classification	Diameter (in.)	Type	Test Code
Mild Steel	E71T-1	0.045	rutile	A
	E70T-1	0.062	rutile	B
	E70T-1	0.062	rutile	C
	E71T-5	0.045	basic	F
	E71T-1	0.062	rutile	I
	E71T-1	0.062	rutile	J
	ER70S-3	0.045	solid	L
Cr-Mo	E91T1-B3	0.045	rutile	D
	E81T1-B2	0.045	rutile	E
	E81T1-B2	0.045	rutile	G
	E80C-B2	0.045	metal-cored	H
	E81T1-B2	0.045	rutile	K

study the effects of current and electrode extension on the diffusible hydrogen content of this mild steel electrode. Electrode extension is the difference between the TTW and arc length and represents the region where I^2R preheating occurs. In the electrode extension, it is believed that hydrogen is evaporated from the wire. A typical TTW is approximately ¾ in. (19.05 mm) for 0.045-in. (1.14-mm) diameter electrodes. Contact tube-to-work distances of ½, ⅞ and 1 ¼ in. (12.7, 22.2 and 28.6 mm) were tested in this investigation. At a constant electrode extension, the time in the column is determined by dividing the electrode extension by the wire feed speed. Higher currents (I) typically produce higher diffusible hydrogen contents because the time in the column decreases. Weld voltage (V) and travel speed (TS) were adjusted to maintain a constant arc length of ¼ in. (6.35 mm) and weld deposit area, respectively. Heat input was calculated by the formula

$$HI = (V \times I \times 60) / TS$$

Diffusible hydrogen tests were performed to the requirements of AWS A4.3-93. The test coupons were made from ½ x 1 x 4-in. (12.7 x 25.4 x 101.6-mm) thick pieces of SA36, plus start and stop tabs. These specimens were prebaked at 1100°F (593°C) for 1 h to remove all residual hydrogen in the base material. The weight of each specimen was measured before and after the diffusible hydrogen weld test. The test specimens were held in water-cooled copper jaws. The weld was made across the 1 x 4-in. (25.4 x 101.6-mm) surface of the specimen, then immediately quenched in water. The slag was wire brushed off the weld deposit and the specimen was then placed in liquid nitrogen to inhibit loss of hydrogen. Diffusible hydrogen was measured using gas chromatography using an Oerlikon-Yanaco hydrogen analyzer. The accuracy of the diffusible hydrogen test using this approach has been reported to be approximately ± 1 mL/100 g (Refs. 4, 16). Four welds were made for each test condition. These four samples were placed in hydrogen-analyzer canisters. Diffusion time and temperature were 302°F (150°C) for 6 h. The results were reported by deposit (DW) and fused (FW) weight. The fused weight was determined by measuring the deposit (DA) and nugget (NA) area on a metallographic cross section and using the following formula:

$$FW = (NA/DA) \times DW$$

A number of carbon and low-alloy steel electrodes were used in the atmospheric exposure tests (Table 2). These electrodes were acquired from several manufacturers to evaluate the susceptibility of FCAW-G electrodes from different sources to atmospheric exposure. Of the mild steel electrodes, several rutile E71T-1 electrodes were compared to a basic, E71T-5 electrode. The low-alloy electrodes were of the Cr-Mo type. Four of the five Cr-Mo electrodes were flux cored and one electrode was metal cored (E80C-B2). In addition, a solid GMAW electrode (ER70S-3) was used as a control since solid wire should not be as susceptible to moisture pick up as FCAW-G electrodes. Atmospheric exposure test specimens were made by carefully winding a single layer of electrode on painted wire baskets. A painted wire basket reel was used to inhibit rusting of the reel and contamination of the electrodes. The atmospheric exposure test specimens from the various wire electrodes were placed inside a Blue M forced air cabinet that controlled the atmosphere to 80% relative humidity at 80°F — Fig. 1. A detailed description of the atmospheric exposure test procedure is provided in Appendix A.

Note that the exposure conditions were modeled after the AWS absorbed moisture test for SMAW electrodes in AWS A5.1, except that weight gain using the absorption tube technique was not performed in this investigation. Instead, the exposed electrodes were directly used to make diffusible hydrogen test welds according to AWS A4.3 using the parameters in Table 3. Note it is difficult to remove the flux from FCAW-G electrodes for weight gain analysis and most low-hydrogen welding applications are engineered based on weld diffusible hydrogen content. The procedure presented in Appendix A is believed to provide a good starting point for developing a standardized atmospheric exposure test procedure for FCAW-G electrodes.

The cored electrodes were placed inside the humidity chamber for one week, which was judged to be a reasonable exposure period for a FCAW-G electrode vs. 9 h for SMAW electrodes. The diffusible hydrogen content of the weld deposit for each FCAW-G electrode was determined in the as-received and exposed condition. It should be noted that two electrodes were tested in August of 1996, then again in August of 1997. Thus, the effects of shelf life was bench-

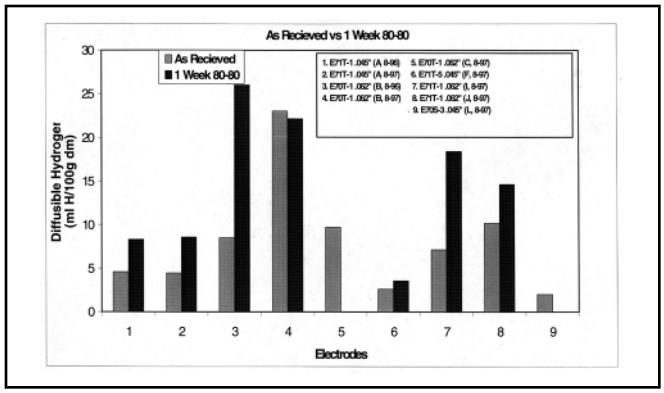

Fig. 5 — Atmospheric exposure test results for mild steel FCAW-G electrodes (note electrode test code and test date in parentheses).

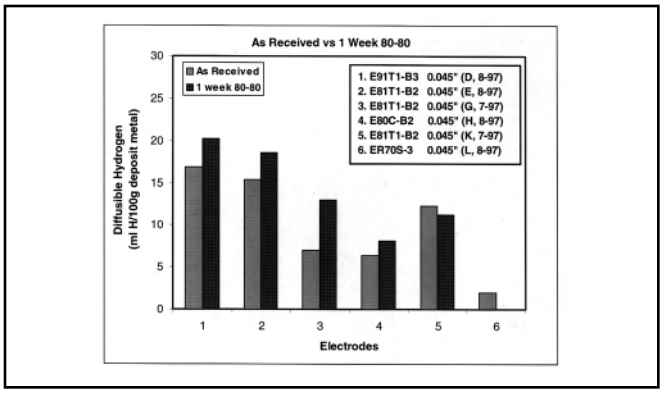

Fig. 6 — Atmospheric exposure test results for Cr-Mo FCAW-G electrodes (note electrode test code and test date in parentheses).

marked for these two electrodes. All electrodes were stored in an air-conditioned room inside metal cans without desiccant. The as-received diffusible hydrogen content was based on the date when the electrode package was opened in the laboratory, not when the electrode was manufactured. Some electrode packages were stored approximately one year before being opened for testing.

Results and Discussion

The effects of welding parameters on weld diffusible hydrogen content was evaluated using only electrode (A), which was an E71T-1 type (Table 1). The diffusible hydrogen content of the weld deposit was correlated to welding current, time in the electrode extension column and heat input. Deposit area was kept fairly constant by maintaining a wire-feed-to-travel-speed ratio of 35. The effects of penetration were evaluated by comparing the diffusible hydrogen content of both the deposit and fused metal. Weld diffusible hydrogen content was found to increase almost linearly as the weld current increased — Fig. 2. However, contrary to published literature, the effects of electrode extension were small at constant current and arc length with the E71T-1 electrode tested here. Increased contact tube-to-work distance decreased current and hence the diffusible hydrogen content at a constant wire feed speed. The weld deposit diffusible hydrogen content varied from 2.3 mL/100 g at 140 A to approximately 11.6 mL/100 g at 345 A. This current range is typical for an electrode this size. The diffusible hydrogen content for the fused metal increased from 2.0 mL/100 g to approximately 7.1 mL/100 g over the same current range. The difference in diffusible hydrogen content between the deposit and fused metal was the greatest at the higher currents due to the increased base metal dilution. This effect is important since higher currents produce slower cooling rates and higher heat inputs in these constant deposit area tests. Higher weld diffusible hydrogen contents can often be tolerated at higher heat inputs because the microstructure may not be as hard and more hydrogen can diffuse out of the weld during a slower cooling rate.

The effects of contact tube-to-work distance were more obvious when the heat input was compared to diffusible hydrogen content of the weld deposit — Fig. 3. Weld diffusible hydrogen content increased with increasing heat input at each contact tube-to-work distance. Longer TTW distances increased the resistive heating, decreased the current and produced lower heat inputs over the wire feed speed range tested. From Table 1, it was apparent the TTW distance must be closely controlled to control heat input of a weldment. Weld diffusible hydrogen content decreased with increasing electrode time in the electrode extension column — Fig. 4. Based on the slope for each TTW condition, the diffusible hydrogen content would be slightly higher in welds made with a longer TTW distance when comparing tests that would have equal time in the column. This trend was believed to be a result of the higher wire feed speeds and a longer distance from the arc, changing the temperature profile in the electrode extension. The more time an electrode spends at higher temperature the more effective should be the hydrogen removal. At constant time in the column, the shorter TTW distances should have a higher temperature profile compared to the longer TTW distance since the shorter TTW distance will receive additional heating from the arc and had a lower current.

The above effects of weld parameters were for one electrode type and size. The behavior of other FCAW-G electrodes can be expected to be different. The relationship between weld parameters and weld diffusible hydrogen contact needs to be established for each type and size of electrode before a FCAW-G diffusible hydrogen classification can be satisfied. For example for the E71T-1 electrode tested here, an H8 classification could be given over a current range from 140 to 275 A, which would cover a range of welding positions. Future work should be performed to develop these relationships.

FCAW-G weld deposits were found to be susceptible to increased diffusible hydrogen levels after the atmospheric exposure test using the 80°F and 80% relative humidity test conditions. All diffusible hydrogen tests were tested from electrode samples, which were removed from storage after one week of exposure inside the forced air humidity cabinet. The welding parameters used on the atmospheric exposure test samples were varied depending on the electrode diameter (Table 3). The diffusible hydrogen content of the weld deposit varied between electrode manufacturer, and some electrodes tended to be more moisture resistant due to their fluxing characteristics. For example, the weld diffusible hydrogen content made with E71T-1 electrodes after one-week exposure increased from 4 to 8 mL/100 g for electrode A and increased from 8 to 27 mL/100 g for electrode B — Fig. 5. These tests were performed in August 1996, a few months after they were received from the manufacturers. These two electrodes were retested in August 1997 and the results for electrode A were the same. However, electrode B was believed to be saturated with moisture in that no difference was observed between the as-stored and one-week-exposed weld diffusible hydrogen content a year later. All the electrodes were stored in metal cans in an air-conditioned room, hence identical conditions. No desiccant was used

inside the cans but, based on these results, should be considered for some electrodes after initial use when the electrode is placed back in storage. Care must be taken to maintain the "dry" condition of the desiccant bags during use and in storage. Two other E71T-1 electrodes (I and J) were tested where the diffusible hydrogen content of the weld deposit increased 10 mL/100 g for electrode I and 4 mL/100 g for electrode J after the atmospheric exposure test. From these results, the susceptibility to increased hydrogen from atmospheric exposure appears to be a function of electrode manufacturer, packaging method, storage time and possibly diameter. Within manufacturers, the conditions that may influence the rate of moisture absorption include factors such as percent fill of electrode, tightness of joint, rolling vs. drawing, fluxing ingredients and lubricant types. There were no direct comparisons made to evaluate the effects of electrode diameter for a given type of electrode from one manufacturer; therefore, no conclusion can be made with respect to diameter.

A basic electrode F, E71T-5, was tested and found to be tolerant to the atmospheric exposure test. This electrode had a weld diffusible hydrogen content of 3 to 4 mL/100 g as-received and after exposure. Whether the electrode absorbed moisture or not was not determined, but could be determined by performing a weight gain moisture test per the procedure recommended by Siewert (Ref. 13). The E71T-5 electrode has a fluoride-base flux system, which was reported to be tolerant to hydrogen by lowering the partial pressure of the hydrogen in the arc environment. The lower the partial pressure of hydrogen, the lower the equilibrium solubility of hydrogen in the weld pool. To benchmark the accuracy of the diffusible hydrogen tests performed in this investigation, a solid electrode (ER70S-3) was used with the GMAW process. This electrode L was in the open shop for several months and had a diffusible hydrogen content of 2 mL/100 g.

Five Cr-Mo electrodes were also evaluated using the atmospheric exposure test — Fig. 6. These electrodes were received with the above rutile electrodes in the spring of 1996. The as-received diffusible hydrogen content of the weld deposit when tested in August of 1997 (*i.e.*, when the electrodes were removed from the manufacturers packaging) varied from 7 to 17 mL/100 g. The latter was considered a high hydrogen level for a Cr-Mo electrode that could be used on high-strength applications. All these electrodes were supplied in the 0.045-in. (1.14-mm) diameter. The electrodes that had the highest weld hydrogen content in the as-received conditions were electrodes D and E. Electrodes D and E did not show a large increase in diffusible hydrogen content of the weld deposit after the atmospheric exposure test probably because of a high initial moisture content. The initial moisture content was probably a result of the plastic bag and cardboard packaging method. Electrodes G and H were supplied in hermetically sealed cans. The weld diffusible hydrogen content of electrode G increased from 7 to 13 mL/100 g after the atmospheric exposure test and showed the highest increase of the Cr-Mo electrodes tested. Electrode H was a metal-cored electrode, which appears to be moisture resistant in that the diffusible hydrogen content of the weld deposit only increased approximately 1 mL/100 g. This was within the standard of deviation of the diffusible hydrogen test. Electrode K had a negligible increase in weld diffusible hydrogen content and appears to be moisture resistant, but this electrode also had a fairly high initial diffusible hydrogen content of approximately 11 mL/100 g.

The results from this project clearly demonstrate that FCAW-G deposits are susceptible to increased diffusible hydrogen levels after atmospheric exposure of the electrodes. Although the project did not address the source and mechanism of diffusion, it is suspected that it is due to moisture pickup. It is possible that the effect is due to a simple absorption mechanism. It is also equally possible that the effect is due to chemical reactions, that occur over time as a result of atmospheric exposure involving the steel surfaces, the lubricants and/or the fill constituents. Basic flux cored, metal cored and solid electrodes appear to be more tolerant to atmospheric exposure than rutile flux cored electrodes. New flux cored electrodes continue to be developed that appear to be moisture resistant. Additional work needs to be performed to fully characterize the effects of flux type, manufacturing method (including the effects of lubricants), electrode diameter, shielding gas and weld parameters. Handling guidelines and an atmospheric exposure test procedure need to be established to improve the control of hydrogen in high-integrity FCAW-G weldments. The atmospheric exposure testing procedure used here in Appendix A is recommended as a starting point.

Conclusions

This project evaluated the effects of welding parameters and electrode atmospheric exposure on the diffusible hydrogen content of a range of FCAW-G weld deposits. The major conclusions that can be drawn from the results of this work are as follows:

1) Weld diffusible hydrogen content was found to increase almost linearly as the weld current increased for the E71T-1 electrode tested here. The contact tube-to-work distance had a small effect on diffusible hydrogen content at constant current.

2) Weld diffusible hydrogen content decreased with increasing time in the electrode extension column. At constant time in the column, the hydrogen content was slightly higher with welds made at higher wire feed speeds and longer contact tube-to-work distances. The temperature profile in the electrode extension may be responsible for this effect.

3) FCAW-G welds are found to be susceptible to increased diffusible hydrogen content after atmospheric exposure of the electrodes. The range of diffusible hydrogen increase varied from 19 mL/100 g to negligible levels depending on the electrode after a one-week exposure at 80% relative humidity at 80°F.

4) FCAW-G electrodes are found to produce welds with higher diffusible hydrogen contents after being stored for one year in metal cans inside an air-conditioned room.

5) Welds made with basic (E71T-5) and metal cored electrodes appear to be more resistant to increased diffusible hydrogen contents after atmospheric exposure of the electrodes.

6) Handling guidelines and an atmospheric exposure test procedure need to be established for FCAW-G electrodes that are intended to be used in high-integrity applications. Based on this work, it is recommended they be purchased in hermitic-sealed containers and stored, and used similarly to the practices for low hydrogen SMAW electrodes.

Table 3 — Weld Test Parameters for Evaluating Effects of Atmospheric Exposure

	Electrode Diameter	
	0.045 in.	0.062 in.
Current (A)	230–240	250–260
Voltage (V)	32–34	34
Travel Speed (in./min)	10–12	12
Tube-to-work (in.)	7/8	7/8
Wire Feed Speed (in./min)	350	225

Fixed Conditions:
80% Argon-20% CO_2 at 40 ft^3/h
1/4-in. (6.35-mm) arc length
DCEP
10-deg (0.1745-rad.) drag travel angle
5/8-in. (15.8-mm) ID gas nozzle

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Appendix A

Test Method for Atmospheric Exposure Testing and Determination of Diffusible Hydrogen Content for Cored Electrodes

Atmospheric Exposure Testing

Sample Preparation

Cored electrodes should be received in the manufacturer's standard package. It is preferred for electrodes to be supplied in sealed metal (moisture resistant) cans to avoid contamination before testing.

Painted wire basket spools shall be used for atmospheric exposure test samples. The spools shall be standard 12-in. spools. A single layer of the electrode shall be wound on the spool so that uniform exposure occurs over the electrode surface.

The manufacturing conditions should be recorded and should include AWS class, diameter, heat/lot no., date of manufacture, baked (conditioning) or nonbaked and time and temperature involved in conditioning.

Atmospheric Exposure Test

The electrode shall be exposed in a suitably calibrated and controlled environmental chamber for one week at 80°F, minus 0, plus 5°F and 80% RH, minus 0, plus 5%.

The environmental chamber shall meet the following design requirements:

1) The apparatus shall be an insulated humidifier that produces the temperature of adiabatic saturation through regenerative evaporation or evaporation of water.

2) The apparatus shall have an average air speed within the envelope of air surrounding the cored electrodes of 100 to 325 ft/min.

3) The apparatus shall have a drip-free area where the electrode(s) can be positioned with the spool axis horizontal and the spool diameter positioned as perpendicular as practical to the general air flow.

4) The apparatus shall have a calibrated means of continuously measuring and recording the dry bulb temperature and either the wet bulb temperature or the differential between the dry bulb and the wet bulb temperature over the period of time required.

5) The apparatus shall have an air speed of at least 900 ft/min over the wet bulb sensor unless the wet bulb sensor can be shown to be insensitive to air speed or has a known correction factor that will provide for an adjusted wet bulb reading equal to the temperature of adiabatic saturation.

6) The apparatus shall have the wet bulb sensor located on the suction side of the fan so that there is an absence of heat radiation on the sensor.

The exposure procedure shall be as follows:

1) The electrode sample(s) shall be heated to temperature, minus 0, plus 10°F above the dew point of the chamber at the time of loading and stored in a desiccator.

2) The electrode sample(s) shall be loaded into the chamber without delay after removed from the desiccator.

3) The electrode sample(s) shall be placed in the chamber with its spool axis horizontal on 6-in. centers, with the diameter of the spool perpendicular as practical to the general air flow.

4) Time, temperature and humidity shall be continuously recorded for a period that the electrodes are in the chamber.

5) Counting of the exposure time shall start when the required temperature and humidity in the chamber are established.

6) At the end of exposure time, the electrodes shall be removed from the chamber and prepared for diffusible hydrogen testing, as specified in Section 2.

The manufacturer shall control other test variables that are not defined, but they must be controlled to ensure a greater consistency of results.

Welding and Preparation for Analysis

Weld Station Setup

The weld station used for making the diffusible hydrogen test samples should be carefully prepared to avoid test errors. A direct drive GMAW gun should be used to minimize wire liner contamination and simplify gun cleaning between test runs. The dew point and composition of the shield gas must be documented by conducting analysis of a sample or procurement of certified gas. Gas lines should be thoroughly purged prior to welding to remove absorbed moisture.

Weld Parameters

The welding gun contact tube should be modified to assure electrical contact at the end of the tube. Contact tube-to-work distance should be within a 1/32-in. tolerance. Weld voltage should be adjusted so that the arc length is approximately 1/8-in. nominal. This will permit better control of the electrical electrode extension. Work angle should be zero. Travel angle should be zero to 10 deg drag (pull).

Weld current for each electrode will be constant as a function of electrode diameter and weld position. These currents need to be established. For example, 280 and 200 A could be used for welding in the flat and vertical position, respectively, with 0.045-in. diameter electrodes.

Prior to welding each diffusible hydrogen sample, 3 ft (0.9 m) of electrode should be ran through the contact tube and cut off to remove wire that may be baked between tests from a warm contact tube. Diffusible hydrogen testing shall be per the section below.

Diffusible Hydrogen Analysis

Diffusible hydrogen tests shall be performed to one of the methods given in ANSI/AWS A4.3, *Standard Method for Determination of the Diffusible Hydrogen Content of Martensitic, Bainitic, and Ferritic Steel Weld Metal Produced by Arc Welding*.