Effects of Moisture Contamination and Welding Parameters on Diffusible Hydrogen

An empirical equation was developed that predicts diffusible hydrogen from FCAW wire hydrogen, welding parameters, and shielding gas dew point

BY J. H. KIEFER

ABSTRACT. Two experiments were conducted on gas-shielded flux cored arc welding. The first one tested the effects of shielding gas moisture contamination and welding parameters on the diffusible hydrogen content. The second compared the hydrogen levels of various unused electrodes with the diffusible hydrogen they produced in the weld.

An empirical equation has been developed that can predict the diffusible hydrogen in weld metal for gas-shielded flux cored arc welding. Estimating diffusible hydrogen is possible using measured welding parameters, shielding gas dew point, and total hydrogen of the consumable. The equation is suitable for small-diameter electrodes and welding parameter ranges commonly used for out-of-position welding.

Introduction

It has been known for more than 50 years that hydrogen could cause or promote cracking and failure in steel and in welds (Ref. 1). Control of cold cracking in welds can be accomplished by controlling hardness and/or reducing hydrogen (Refs. 2, 3). Limiting heat-affected zone (HAZ) hardness is one method of controlling hydrogen cracking. Controlling hardness is accomplished by limiting crack sensitive martensite through slower weld cooling. The higher preheat or heat input needed to slow weld cooling has the additional benefit of promoting diffusion of hydrogen away from the weld zone. Elaborate methods have been devised to find preheat requirements (Ref. 4). Even this is based on some assumptions about the hydrogen levels in the weld, and special preheat and heat input control can have a significant impact on the economics of steel fabrication.

Laboratory tests are required to find the diffusible hydrogen level for the welding process and consumables. Since gas shielded processes depend on the integrity of the gas distribution system, laboratory tests conducted under ideal conditions may not provide an accurate assessment of the weld hydrogen obtained in the field. Field testing for diffusible hydrogen is generally impractical.

Proper handling of welding consumables is necessary to prevent moisture contamination that can be responsible for hydrogen cracking in welds. Hydrogen in welds has also been shown to produce lamellar tears (Ref. 5). Low-hydrogen shielded metal arc (SMAW) electrodes with low-moisture coatings have been available for many years. Electrode handling procedures commonly limit exposure to atmospheric moisture. Storage and baking procedures are required for moisture control of low-hydrogen basic flux-covered SMAW electrodes that are often baked at temperatures over 450°C (842°F) (Ref. 6). An exception to this is cellulosic and rutile electrodes. Baking these to lower the moisture can break down coating, leading to excessive hydrogen pickup and increasing tendency for porosity (Ref. 7). Dry shielding gas and electrodes are necessary to keep hydrogen low for gas-shielded semiautomatic welding such as GMAW and FCAW. It is interesting that an FCAW wire has even been developed where moisture is deliberately added to the flux for welding over coating primer (Ref. 8).

Moisture and air contamination into the shielding gas from leaking hose fittings or bulk gas distribution systems is common, and a potential source of crack-producing hydrogen in the welds. Diffusion through the hose material is also a source of contamination (Ref. 9). In one case, the author measured the relative humidity of shielding gas in shop piping as high as 98%. This moisture contamination, as a source of hydrogen, can cause delayed cold cracking in welds.

Welding gas quality is controlled by specifying the maximum allowable dew point and purity. For carbon steel the dew point is typically required to be at or below −40°C (−40°F) (Ref. 10). One reference recommended a shielding gas purity of at least 99.95% with a dew point better than −30°C (−22°F) (Ref. 11). The AWS D1.1-94, *Structural Welding Code — Steel*, specifies an upper limit of −40°C (Ref. 12). In a related study on a high-

KEY WORDS

FCAW
Moisture Contamination
Welding Parameters
Diffusible Hydrogen
Shielding Gas Dew Point
Steel Weld Metal
Process Control
Predictive Equation

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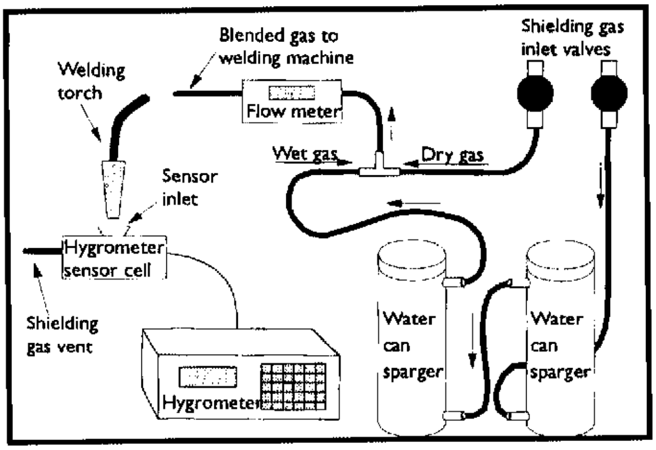

Fig. 1 — Test apparatus for adding moisture to shielding gas.

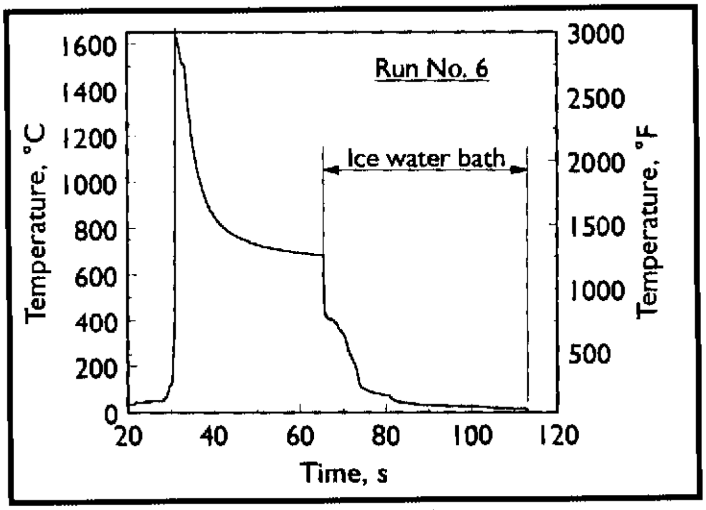

Fig. 2 — Typical diffusible hydrogen test cooling curve.

strength martensitic steel, Mutnansky concluded that the dew point should not be higher than −30°C (Ref. 13).

Gas metal arc (GMAW) and flux cored arc (FCAW) welding are gas-shielded semiautomatic processes widely used for achieving high productivity in steel fabrication. The most economical method for delivering shielding gas to multiple welding machines is through standard carbon steel piping from bulk liquid tanks. Such distribution systems may have trunk lines buried underground with many branch lines and several multiple-valve manifolds. Often these underground lines are not cathodically protected and develop through-wall corrosion. Even for systems without buried pipe, the many small valves that are at the manifold trees often leak and are sources of contamination. An alternative to bulk distribution is to use portable racks of multiple compressed cylinders (e.g., 16–20 cylinders per rack). This is more expensive than bulk distribution. Unless gross welding defects are seen in production, or gas wastage is high, tolerating the leakage of a bulk system is common for fabricators. Since the specified gas quality is often not being achieved in field and shop welding, this study was conducted to quantify the effects of contamination and welding parameters on diffusible hydrogen. FCAW welding was selected because of the popularity of this process for semiautomatic out-of-position welding.

Background

Most studies on diffusible hydrogen have been conducted with either the gas tungsten arc (GTA), or GMA welding processes by doping the shielding gas directly with hydrogen. Only a few have been done where moisture was added to the gas (Refs. 14–17). Salter found that absorption of hydrogen from an argon/water vapor atmosphere closely follows that from an argon/hydrogen atmosphere (Ref. 14). Savage found water vapor added more hydrogen (Ref. 17).

Diffusible hydrogen in weld metal is also influenced by variations in welding parameters. In early research by Howden, voltage was found not to influence the total hydrogen absorbed in pure iron where hydrogen was added to argon in GTAW welds (Ref. 18). Howden found that amperage increased total hydrogen in iron, however, when 2% aluminum was added to the iron, hydrogen decreased with increasing current. This is mentioned because self-shielded FCAW wires contain approximately 1% aluminum, and therefore could absorb hydrogen differently than gas-shielded welding wires in this study that have no intentionally added aluminum.

Salter, using GTAW, suggested that current affects diffusible hydrogen but arc length did not (Ref. 14). Researchers at Kobe Steel studied the effects of welding parameters on FCAW diffusible hydrogen and showed that current, voltage, and electrode extension affected diffusible hydrogen (Ref. 19). Additionally, gas flow rates did not affect diffusible hydrogen when the flow was between 20–35 L/min (9.4–16.6 ft^3/min).

Hart observed that for submerged arc and manual welding, current, voltage, and polarity had a significant increase on total hydrogen as expressed in deposited metal (Ref. 20). When converted to fused metal, the effects on manual welding were insignificant. Deposited metal is the volume of filler metal added during welding, whereas fused metal is the volume of metal added plus the volume of the base metal melted.

Some disagreement exists on whether to calculate diffusible hydrogen as deposited or fused metal. Values based on deposited metal may be more appropriate for multipass groove welds (Ref. 25). AWS A4.3 requires values to be reported as deposited metal (Ref. 21).

To bring together the effects of gas moisture and welding parameters, an experiment was designed with a single type of consumable to include the effects of shielding gas dew point, welding current, voltage, travel speed, and electrode contact tube-to-work distance. To apply the results of this test to other makes of FCAW consumables, a second experiment was conducted to investigate the relationship between the total hydrogen in the unwelded consumable and the diffusible weld metal hydrogen. A variety of wires were tested under otherwise identical welding conditions.

Experimental Procedure

Experiment 1 — Effect of Welding Parameters and Gas Moisture

Two separate experiments were conducted during this investigation. The first experiment examined the effect of five different FCA welding variables on diffusible hydrogen with the same electrode. The variables and ranges tested are given in Table 1. Factor settings were selected to cover a range of parameters typically used for out-of-position welding. A computer program for designing experiments, RS/Discover by BBN Software Products Corp., was used to optimize the number of runs. Twenty-seven factor combinations and five replicate tests were made for a total of 32 runs.

The welds were made with a Lincoln R3S-400 power supply and LN-9 wire

Table 1 — Factors and Range of Settings for Experiment 1

Independent Variables	Variable Settings
Gas dew point, °F (°C)	−50 (−45), 5 (−15), 60 (16)
Current, A	160, 190, 220
Voltage, V	22, 25, 28
Travel speed, in./min (mm/s)	8 (3.4), 11 (4.7), 14 (5.9)
Tube-to-work, in. (mm)	0.375 (9.5), 0.563 (14.3), 0.750 (19)
Fixed Factors	
Ambient conditions, °F (°C)	45 (7) dew point @ 72 (22)
Wire type	Kobe Frontiarc 711
Wire diameter, in. (mm)	0.045 (1.14)
Shielding gas	75%Ar/25%CO_2
Gas flow rate, ft³/hr (L/min)	40 (19)
Tube-to-work, in. (mm)	0.563 (14.3)

feeder. Welding parameters were recorded with a CRC Arc Data Monitor and are given in Table 2. The contact tube-to-work distance was varied by using different lengths of contact tubes. This enabled the distance from the end of the gas nozzle to the workpiece to be held constant at 0.50 in. (12.7 mm) for all runs. Moisture was added to the shielding gas by bubbling it through two columns of water, and blending the saturated gas with dry gas to obtain the desired dew point. The dew point was measured at the welding gun gas nozzle before each test run with a Panametrics System II hygrometer. Figure 1 shows a schematic of the gas moisturizing apparatus.

Diffusible hydrogen samples were prepared and welded following AWS A4.3. Weld cooling thermal histories were recorded by plunging tungsten/tungsten-rhenium thermocouples into the weld pool. In a few tests the thermocouple was left connected to the recorder until the sample was put into the cooling bath. Figure 2 is a graph of one of these tests showing the cooling cycle down to 0°C (−32°F). The cooling time from 800° to 500°C (1408° to 932°F) was measured for all runs. In several instances the run was complete and the sample submerged into the ice water before the sample cooled to 500°C.

AWS A4.3 prescribes that the reported diffusible hydrogen value be based on four replicate tests. The hydrogen values reported for the 32 runs in Experiment 1 are from a single weld and not averages of four runs. However, five replicates were conducted at the experimental center point (*i.e.*, 190 A, 25 V, 11 in./min, 0.563 in. tube-to-work distance, and 5°F gas dew point) to determine experimental error.

Hydrogen determination was done by the hot extraction method using a Leco Model DH102 at an extraction temperature of 400°C (752°F). The Leco instrument, modified for large samples, operates with a nitrogen carrier gas, and measures thermal conductivity differences. A calibration was done by gas dosing with known volumes of prepurified hydrogen gas according to the equipment specifications. Reproducibility of hot extraction was reported by Laycock to be ±0.095 mL/100 g at the 4 mL/100 g level (Ref. 22). This is much smaller than the variations expected from other factors in the diffusion hydrogen test

Total diffusible hydrogen values were based on an evolution period of 2000 seconds inclusive of heating time. A typical hydrogen evolution curve is shown in Fig. 3. For the hydrogen levels in this study, this was sufficient time to allow for diffusion. Coe reported that hydrogen evolution could take one hour at 650°C (1202°F) (Ref. 23). For processes that produce a larger weld bead or yield higher

Table 2 — Experiment 1 Test Data and Results

Run No.	Current, A	Voltage, V	Travel speed, in./min (mm/s)	Tube-to-Work Distance, in. (mm)	Dew Point, °F	(°C)	t8/5, s[a]	Weld Deposit, grams	Diffusible Hydrogen, mL/100g
1	156	22	8.0 (3.4)	0.375 (9.5)	49	9	25.4[b]	11.7	7.5
2	158	22	14.0 (5.9)	0.750 (19.1)	52	11	3.6	8.7	6.0
3	218	22	8.2 (3.5)	0.750 (19.1)	52	11	25.4[b]	22.8	6.4
4	219	22	14.2 (6.0)	0.375 (9.5)	52	11	8.2	9.6	9.4
5	196	25	11.5 (4.9)	0.563 (14.3)	54	12	17.9	10.8	10.3
6	215	28	8.0 (3.4)	0.375 (9.5)	50	10	23.1[b]	17.4	14.5
7	158	28	14.0 (5.9)	0.375 (9.5)	52	11	4.4	6.7	12.1
8	219	28	13.9 (5.9)	0.750 (19.1)	52	11	26.1[b]	14.0	11.0
9	158	28	8.1 (3.4)	0.750 (19.1)	54	12	36.8[b]	14.7	9.5
10	186	23	11.1 (4.7)	0.563 (14.3)	7	−14	10.2	11.1	3.7
11	220	25	11.5 (4.9)	0.563 (14.3)	7	−14	28.5[b]	13.0	7.0
12	191	25	13.8 (5.8)	0.563 (14.3)	8	−13	7.3	9.7	5.3
13	191	25	11.6 (4.9)	0.375 (9.5)	7	−14	18.9	10.2	7.0
14	185	25	11.5 (4.9)	0.563 (14.3)	7	−14	18.8	12.3	5.4
15	189	25	11.4 (4.8)	0.563 (14.3)	7	−14	21.1	12.4	4.9
16	186	25	11.4 (4.8)	0.563 (14.3)	7	−14	16.5	12.5	5.2
17	158	25	11.3 (4.8)	0.563 (14.3)	7	−14	7.3	9.3	4.8
18	185	25	11.6 (4.9)	0.750 (19.1)	6	−14	17.8	13.3	3.9
19	188	25	11.4 (4.8)	0.563 (14.3)	7	−14	14.2	12.0	4.3
20	186	25	11.4 (4.8)	0.563 (14.3)	7	−14	12.6	11.0	4.6
21	186	25	8.0 (3.4)	0.563 (14.3)	7	−14	35.8[b]	15.2	5.2
22	186	25	8.0 (3.4)	0.563 (14.3)	7	−14	31.5[b]	15.2	5.1
23	184	28	11.4 (4.8)	0.563 (14.3)	7	−14	21.0	10.0	6.7
24	221	23	7.9 (3.3)	0.375 (9.5)	−50	−46	29.2[b]	16.8	6.9
25	157	22	13.9 (5.9)	0.375 (9.5)	−51	−46	3.1	6.6	5.0
26	220	23	13.9 (5.9)	0.750 (19.1)	−50	−46	9.0	13.7	4.2
27	163	22	8.0 (3.4)	0.750 (19.1)	−50	−46	24.3	13.6	3.2
28	187	25	11.5 (4.9)	0.563 (14.3)	−50	−46	13.5	9.8	3.8
29	218	28	14.0 (5.9)	0.375 (9.5)	−50	−46	20.2	9.1	8.2
30	165	28	14.0 (5.9)	0.750 (19.1)	−50	−46	5.2	7.0	6.0
31	221	28	8.0 (3.4)	0.750 (19.1)	−50	−46	37.9[b]	19.4	7.8
32	158	28	8.2 (3.5)	0.375 (9.5)	−49	−45	20.7[b]	9.8	5.2

(a) Thermocouple measurement of weld bead cooling time from 800–500°C.
(b) Natural cooling to 500°C was not reached before quenching.

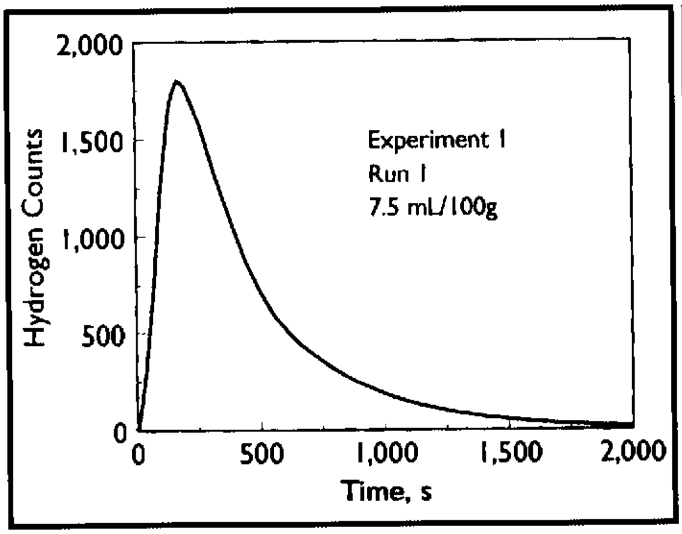

Fig. 3 — Typical hydrogen evolution curve.

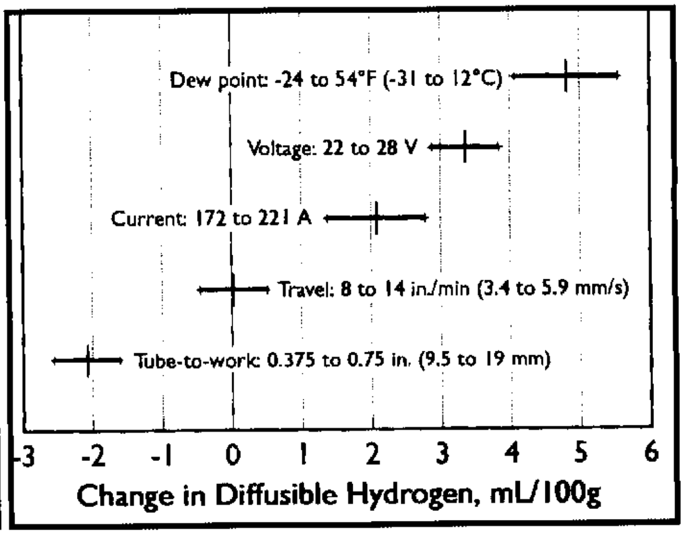

Fig. 4 — Main effects of independent variables on diffusible hydrogen throughout the ranges noted.

hydrogen, a longer diffusion time could be necessary.

Work by Doody showed that sample contamination, either water or alcohol, could cause the formation of "secondary" hydrogen due to surface reactions or decomposition at higher furnace temperatures (Ref. 24). Some initial tests were run at 900°C (1652°F) because of the capability of the Leco DH102 analyzer. It was determined that at 400°C (752°F) this was not a problem. Boniszewski suggested that an extraction temperature of 400°C could be readily correlated to the mercury method (Ref. 25). Subsequent work at TWI showed that for a wide range of hydrogen-controlled processes and consumables, the use of elevated temperatures up to 400°C could be satisfactorily used for extraction of diffusible hydrogen (Ref. 26).

Experiment 2 — Effect of Hydrogen in Welding Wire

The second experiment was conducted on eight different electrodes from six different manufacturers using the same welding conditions. One wire was a solid gas metal arc wire, and the remaining seven were flux cored arc welding wires. Each weld was made with the same welding parameters under ideal conditions to evaluate differences in diffusible hydrogen from different consumable sources. A shorter contact tube-to-work distance of 0.375 in. (9.5 mm) was used to provide compatible conditions for the GMAW run. Shielding gas with a dew point of –52°C was used. The nominal welding parameters for these tests are given in Table 3.

After each weld, a length of wire was fed from the end of the welding gun to obtain a representative sample for analysis (including the internal flux material). These samples were analyzed for total hydrogen with a Leco RH-404 Hydrogen Determinator. The analyzer was calibrated with metal standards at approximately the same level as the samples. Each wire result is based on the average of four tests at 0.10 g per test These results, along with the welding parameters and diffusible hydrogen, are given in Table 4.

Results and Discussion

Experiment 1 — Effect of Welding Parameters and Gas Moisture

The test samples were examined visually, metallographically, and radiographically for signs of porosity caused by moisture contamination. Four samples showed signs of shallow elongated surface depressions sometimes called "worm tracks." This only occurred on the samples with a combination of high dew point and high arc voltage. The remaining 28 samples, including five with high dew points, showed no signs of porosity. No sign of internal porosity or cracking was found in any of the metallographic samples or radiographs. These results suggest that severe gas contamination can exist without any obvious indications.

The statistical analysis features of RS/Discover were used to interpret the diffusible hydrogen results. The main effects each input variable had on the diffusible hydrogen of the deposited metal (H_{dm}) are shown in Fig. 4. This shows the change in hydrogen expected from each individual parameter if increased independently (all others held constant) through the range noted next to the bar. The width of the bar represents a 95% confidence interval based on the variability obtained from the five replicate tests. In addition to gas moisture, all welding parameters except travel speed had a significant influence on the diffusible hydrogen. Some effect of travel speed was expected because of its influence on weld pool size, and the slower travel was expected to allow more hydrogen to diffuse before quenching. This result, however, confirms the study by Kobe Steel that also reported no effect of travel speed (Ref. 19).

The refined model generated by RS/Discover for predicting results is a 13-term polynomial equation. Although the polynomial equation is valid within the envelope of the experiment, there are two drawbacks. The number of terms makes the equation cumbersome, and predictions narrowly outside the experimental envelope are unusable. An equation based on a power law format was, therefore, developed. It is less complicated and can be useful with input variables somewhat outside the test envelope. A form of the power law equation was selected that included the same first and second order interaction terms as prescribed by the RS/Discover polynomial. A multiple regression fit was done to obtain the various coefficients and constant terms. The resulting empirical formula, given in Equation 1, predicts the diffusible hydrogen of FCAW welds from the welding parameters and shielding gas dew point. Interaction effects are seen where welding parameter variables are included within the exponent terms. Since travel speed had no significant influence on diffusible hydrogen, it was excluded. In the first version of the equation, a primary term for voltage was used since it is one of the main influencing variables. It was found, however, that a separate term was not necessary. The formula could be simplified, without reducing accuracy, by eliminating voltage as a main term and accounting for its effects in the dew point exponent

$$H_{dm} = \frac{DP^{(1.86+0.014V-0.036d)}\,A^{(0.612+0.013d)}}{731\,d^{1.15}} \quad (1)$$

Where DP= dew point; K (K = °C + 273;) V = arc voltage, V; d = Contact tube-to-work distance, mm; A = welding current, A.

The terms in Equation 1 seem to display rational physical behaviors. No variable appeared to have an exclusive affect on the results. Interaction effects were found to exist between several welding parameters. These can be seen in Equation 1 where independent variables appear in the exponent. For example, the influence of dew point was affected by welding voltage and contact tube-to-work distance. The effect of current on diffusible hydrogen was also influenced by contact tube-to-work distance. Higher voltage produces a longer arc that exposes more hydrogen available from the shielding gas, so the interaction between dew point and voltage is understandable.

Interaction between contact tube-to-work distance (d) and dew point (DP) and amperage (A) is difficult to explain. As seen in the numerator, increasing contact tube-to-work distance raises the exponents for dew point and welding current. However, counteracting this effect, the exponent for the main contact tube-to-work distance term in the denominator is very large. The net result of increasing contact tube-to-work distance is to reduce the diffusible hydrogen. In practice, increasing the contact tube-to-work distance while maintaining the welding current would require a higher wire speed that tends to produce a larger, wider weld pool that could absorb more hydrogen. However, the predominant effect may be that the longer contact tube-to-work distance allows more preheating of the electrode flux and "burning off" of drawing lubricant or other surface contamination. This supports Asnis' conclusion that the main source of hydrogen is the drawing lubricant on the wire surface, and found lower hydrogen with increasing contact tube-to-work distance (Ref. 27). Figure 5 shows the prediction characteristics of Equation 1. Formula predictions, based on the actual welding conditions measured during the test runs, are compared with the measured hydrogen values.

One way to illustrate the practical implications of these changes on diffusible hydrogen is to plot the effects with a typical variation in welding parameters using Equation 1. The solid curve in Fig. 6 shows the predicted diffusible hydrogen (for the electrode in Experiment 1) with a range of shielding gas dew points. The dashed curve represents a typical increase in arc energy for gas shielded FCAW. Variations in amperage and voltage are limited by some national standards such as AWS D1. 1-94 (*e.g.*, ±10% current, ±7% voltage). Tube-to-work distance is difficult to control to tight tolerances in semiautomatic operations, but can have a major influence on hydrogen. Few, if any, codes or standards mandate tube-to-work or electrode extension limits. Some limit only heat input. It can be seen in Fig. 6 that even for the same heat input, changes in welding parameters can increase hydrogen by over 3 mL/100g even with dry gas. Contaminated shielding gas can add an additional 3 to 6 mL/100 g depending on the welding parameters. Savage reported an increase of 8 ppm (7.2 mL/100 g) when 1.2 vol-% of H_2O (+10°C dew point) was added to GMAW shielding gas (Ref. 17). Voznesenskaya reported an increase of 5.0 to 9.5 mL/100 g for GTA welds in 410 stainless steel when the shielding dew point was increased from −52° to 5°C (Ref. 15).

Experiment 2 — Effect of Hydrogen in Weld Wire

The results of the second experiment using different wires with the same welding conditions show a correlation between the amount of total hydrogen in the welding wire, and the diffusible hydrogen in the deposited weld metal — Fig. 7. Total wire hydrogen measured for the eight FCAW wires ranged from 47 to 140 ppm by weight. The GMAW wire was tested at 22 ppm. In a study by Lathabai, up to 50 ppm of hydrogen was reported for unused FCAW wires.

Sievert's law, Equation 2, is often used to express the relationship between dissolved hydrogen and hydrogen in the atmosphere of the arc (Ref. 28). That is, the dissolved gas is proportional to the square root of the gas pressure.

$$C_g = k\sqrt{p} \quad (2)$$

Where C_g = solubility of dissolved gas; k = constant; p = gas pressure.

Assuming the partial pressure of hydrogen in the arc is related to the total wire hydrogen, the relationship between the diffusible hydrogen and the various amounts of hydrogen in the different wires was checked to see if it would follow Sievert's law. A linear regression of the square root of the total hydrogen for all wire tests gives a coefficient of 0.87 for the following equation:

$$H_{dm} = 0.87\sqrt{H_{wt}} \quad (3)$$

Where H_{dm} = diffusible hydrogen, mL/100 g; H_{wt} = total wire hydrogen, ppm.

Equation 3 is plotted in Fig. 7 for comparison with the experimental results. Except for one of the eight wires, the diffusible hydrogen tends to follow a square root relationship with the total wire hydrogen. By including the square root of the total wire hydrogen in Equation 1, a single equation is obtained that predicts the diffusible hydrogen for any wire

Table 3 — Nominal Welding Conditions for Experiment 2, Total Wire Hydrogen Tests

Gas dew point	−52°F (−47°C)
Current	190 A
Voltage	25 V
Travel	11 in./min (4.7 mm/s)
Tube-to-work	0.375 in. (9.5 mm)
Electrode diameter	0.045 in. (1.1 mm)

Table 4 — Experiment 2 Test Data and Results

Wire ID	Wire type	Average Welding Parameters[a] Current, A	Voltage, V	Travel Speed, in./min (mm/s)	Tube-to-Work, (mm)	Shield Gas Dew Point, °F (°C)	Deposit Weight, grams	Total Wire Hydrogen, ppm	Diffusible Hydrogen, mL/100g
A	E71T-1	190	24.8	11.3 (4.8)	0.375 (9.5)	−51 (−46)	7.75	62	11.0
B	ER70S-6	193	24.7	11.3 (4.8)	0.375 (9.5)	−51 (−46)	8.80	22	4.0
C	E91T1-K2	190	24.8	11.2 (4.8)	0.375 (9.5)	−51 (−46)	8.40	59	6.5
D(b)	E71T-1	192	24.8	11.3 (4.8)	0.375 (9.5)	−52 (−47)	8.78	47	5.7
E	E71T-1	190	24.9	11.3 (4.8)	0.375 (9.5)	−52 (−47)	8.10	140	9.8
F	E81T1-Ni1	192	24.8	11.2 (4.8)	0.375 (9.5)	−55 (−48)	8.33	92	8.9
G	E71T-1	191	24.9	11.2 (4.8)	0.375 (9.5)	−52 (−47)	8.70	54	4.9
H	E91T1-K2	190	24.9	11.2 (4.7)	0.375 (9.5)	−53 (−47)	7.65	65	6.6

(a) All values are the average of four runs each.
(b) Same electrode as used for Experiment 1 as shown in Table 1.

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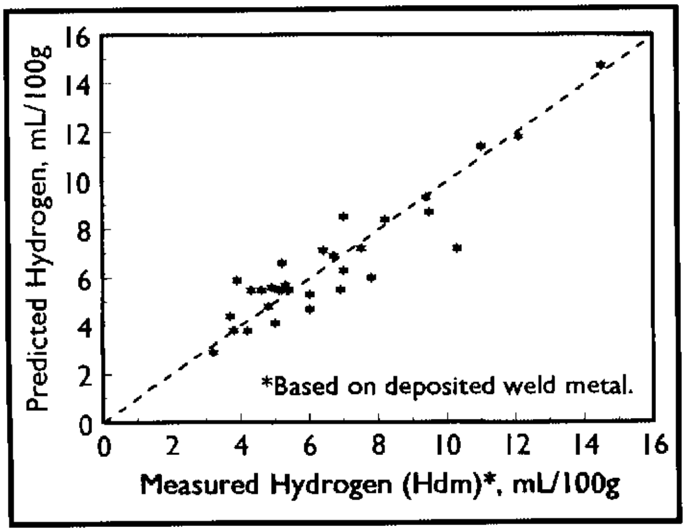

Fig. 5 — Equation 1 prediction vs. measured diffusible hydrogen.

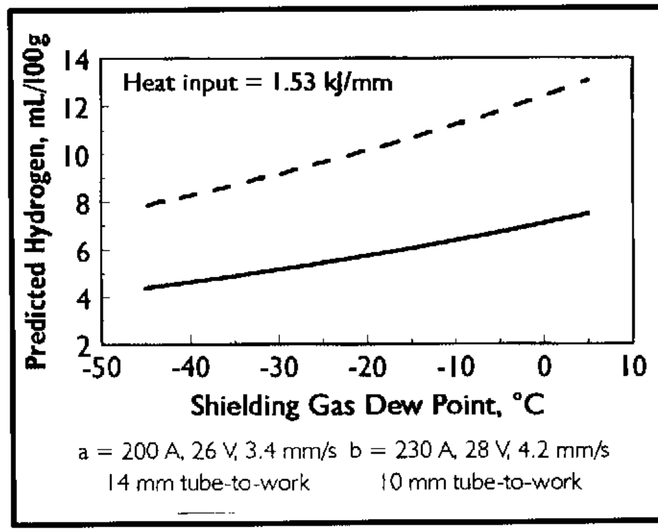

Fig. 6 — Effect of shielding gas dew point on diffusible hydrogen for two arc energies and tube-to-work distances.

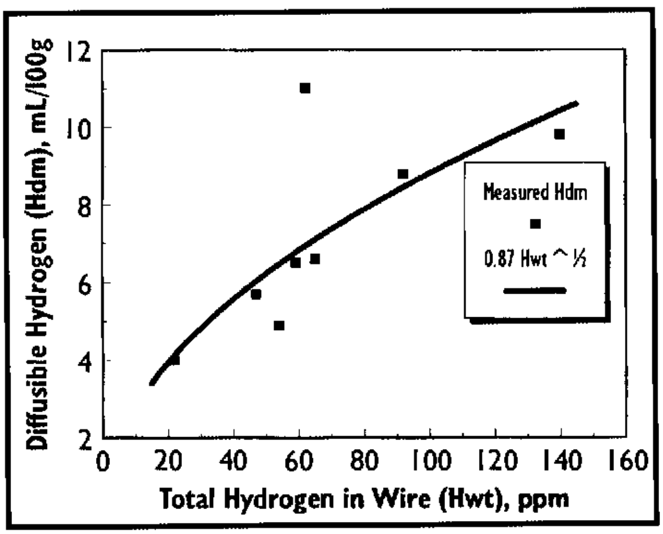

Fig. 7 — Diffusible hydrogen of various consumables as a function of total wire hydrogen.

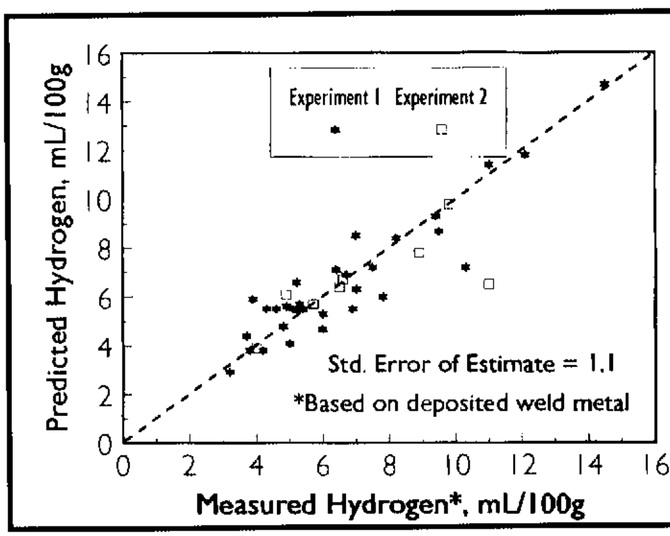

Fig. 8 — Prediction characteristics of Equation 4.

given the total wire hydrogen, gas dew point, and welding parameters. Since Equation 1 was developed with wire type D in Table 4, the matching test conditions are used to calibrate the constant term. Substituting the wire D welding parameters from Table 4, measured diffusible hydrogen, and total wire hydrogen from Experiment 2, a new constant term 5045 is obtained. The following empirical formula is therefore proposed for predicting diffusible hydrogen in FCA welds:

$$H_{dm} = \frac{\sqrt{H_{wt}}\, DP^{(.186+0.014V+0.036d)} A^{(0.612+0.013d)}}{5045\ d^{4.13}} \quad (4)$$

From Equation 4, predictions from the test conditions of both Experiment 1 and 2 can be plotted against the measured weld hydrogen. The results are shown in Fig. 8 and give a standard error of estimate of 1.1 mL/100 g.

Other Factors That Influence Dissolved Hydrogen

Many other factors influence dissolved hydrogen. Weld metal chemistry can influence absorbed hydrogen (Ref. 29). Gas mixtures can affect the weld hydrogen. For example, Gedeon found that, in steel, hydrogen is even more efficiently absorbed if oxygen is added to the shielding gas (Refs. 30, 31). Rabkin found that, when welding commercially pure aluminum, the introduction of oxygen into the shielding argon reduces the hydrogen entering the weld, and the number of pores in the weld (Ref. 32). Salter showed that hydrogen absorption in steel can increase with the quantity of slag on the bead surface (Ref. 14). Wire diameter and arc transfer mode may also influence the diffusible hydrogen.

Another significant contributor to the weld metal diffusible hydrogen is moisture in the atmosphere around the arc (Ref. 14). Dickehut showed a relationship between weld hydrogen and seasonal variations, and developed an elaborate nomograph for SMAW (Ref. 33). Salter showed hydrogen can increase approximately 3 mL/100 g when relative humidity goes from 25 to 72% (Ref. 14). Levchenko reported increases for manual welding up to 7–8 mL/100 g when the absolute humidity in the atmosphere is increased from 5 to 75 g/m³ (0° to 45°C dew point) (Ref. 34). Semiautomatic CO_2 welding in the Levchenko tests was less affected, showing increases up to 2 mL/100g with humidity increasing from 5 to 30 g/m³ (0° to 28°C dew point).

Higher atmospheric humidity did not increase the diffusible hydrogen for CO_2 welding.

Considering the variety of the factors that contribute to diffusible hydrogen, it is unlikely that any single formula will give an absolute prediction. For a given set of conditions, however, it is felt that Equation 4 provides a means of comparing the relative behavior of the individual welding parameters. It can also provide a means of adjusting laboratory tests to field conditions, and approximating absolute values where field tests are impractical.

Conclusions and Recommendations

An empirical formula was developed for estimating the diffusible hydrogen in field welds made with the gas-shielded FCAW process. The formula takes into account the effect of welding parameters and the initial total hydrogen in the consumable. The following are some specific conclusions drawn from the results of this study:

1) Shielding gas moisture contamination can increase diffusible hydrogen by approximately 5 mL/100 g. Diffusible hydrogen also increases with increasing welding current and voltage, but travel speed has no significant influence. Contact tube-to-work distance can significantly decrease diffusible hydrogen with increasing length.

2) Interaction effects were found to exist. Welding voltage and contact tube-to-work distance both influence the effect that dew point changes have on diffusible hydrogen. The effect on diffusible hydrogen from changes in welding current is influenced by contact tube-to-work distance.

3) Diffusible hydrogen is dependent on the total hydrogen of the as-received welding consumable.

4) Elongated surface depressions, often called "worm tracks," appear when moisture contamination and high arc voltage occur in combination. No internal porosity was found for any of the cases with high gas moisture.

5) Gas-shielded FCAW is tolerant to hydrogen pickup shielding gas moisture contamination. When very low hydrogen is required, the shielding gas dew point should be checked in production to ensure no moisture contamination.

6) Parameter variations such as those allowed for structural welding procedures by AWS D1.1 (e.g., ±10% current, ±7% voltage, no control on contact tube-to-work distance) can cause a change in hydrogen of 3 mL/100 g even with dry gas.

7) Atmospheric humidity may be a significant contributor to diffusible weld hydrogen. Additional work is needed to find an appropriate term for inclusion in the hydrogen prediction formula.

Acknowledgments

The author gratefully acknowledges the Conoco management for their support and permission to publish this work, and the laboratory assistance by George Stuever and Dave Krottinger.

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