How to Control Hydrogen Level in (Super) Duplex Stainless Steel Weldments Using the GTAW or GMAW Process

Welding parameters seem to be the determining factor for controlling hydrogen levels even when high shielding gas moisture, high ferrite level and high restraint conditions were induced

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ABSTRACT. In this investigation, an attempt is made to further the understanding of factors influencing the hydrogen content in duplex stainless steel gas tungsten arc (GTA) and gas metal arc (GMA) welds as well as to what extent it affects hydrogen-induced cracking susceptibility.

Hydrogen content in GTA and GMA welds was determined using standard 22%Cr duplex and 25%Cr super duplex consumables. Gas tungsten arc welds were made using 2.4-mm-diameter consumables, argon and argon + 30%helium shielding gases and heat inputs varying from 0.9 to 2.6 kJ/mm.

Gas metal arc welds were made with 1.2-mm-diameter welding wire, argon + 2%oxygen and argon + 2%carbon dioxide shielding gases, and heat inputs ranging from 0.8 to 1.3 kJ/mm.

The shielding gas moisture content was varied from less than 10 ppm up to 1000 ppm. Hydrogen content was analyzed by encapsulating the specimen in an evacuated quartz-glass capsule, heating for 72 h at 400°C and measuring the content at ambient temperature using a gas chromatograph. An additional hydrogen determination at 900°C was performed also.

Susceptibility to hydrogen cracking was determined using a three-point bend test for 24 h, maintaining a 12% strain in specimens welded under conditions rated as most critical: high ferrite, high shielding gas moisture (1000 ppm), low heat input, high hydrogen level and a high restraint level.

The results indicated that susceptibility to hydrogen cracking using the GTA or GMA process appears to be limited. In practice, maintaining a moisture level below 10 ppm in the shielding gas is of less importance than the choice of welding parameters. Even a moisture level of 1000 ppm in the shielding gas, in combination with the correct welding parameters, will result in a sufficient low hydrogen content in the weld. Similarly, a moisture level in the shielding gas below 10 ppm does not necessarily result in low hydrogen content in the weld metal. Although very high ferrite levels were combined with high restrain and high hydrogen content, none of the GMA and GTA welds cracked. Susceptibility to hydrogen cracking is concluded to be limited.

Introduction

Duplex and super duplex stainless steels are applied in a variety of industries. It has been demonstrated in practice that hydrogen cracking in duplex stainless steel weldments may occur where hydrogen content and ferrite level are relatively high and sufficient stress is applied. However, it remains process and consumable dependent. In earlier investigations (Refs. 1, 2), authors have reported on the sensitivity for hydrogen cracking using shielded metal arc welding (SMAW), submerged arc welding (SAW), flux cored arc welding (FCAW) and GTAW consumables. The GTAW process, for instance, showed high hydrogen levels could be found in the weld metal despite the low ,hydrogen content of the consumables. Hydrogen cracking was observed in GTA welds that had over 100 FN and 25–30 mL H_2/100 g. Process variables and shielding gas conditions were indicated to be appropriate for further investigation.

Among others, Lundin (Ref. 3), Shinozaki (Ref. 4) and Ogawa (Ref. 5) reported on hydrogen cracking in duplex stainless steel but did not include these variables. An attempt to contribute to the understanding of factors influencing the hydrogen content in duplex stainless steel GTA and GMA weldments, as well as to what extent it affects the hydrogen-induced cracking susceptibility, was the goal of this investigation. A specific question that needs to be answered is whether an elevated moisture level in the shielding gas will increase hydrogen cracking susceptibility and/or hydrogen level in the weld metal. In addition, the hydrogen determination method was evaluated.

KEY WORDS

(Super) Duplex Stainless Steel
GTAW
GMAW
Shielding Gas
Hydrogen
Moisture
Cracking

Shielding Gas

One of the potential sources for weld

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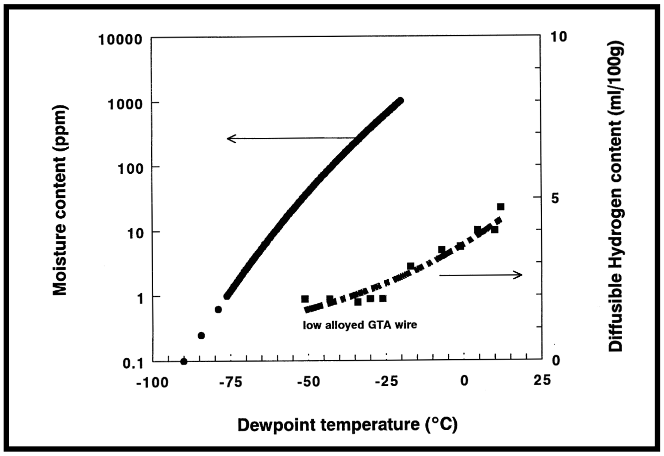

Fig. 1 — Relationship of the shielding gas moisture content, dew point temperature and diffusible hydrogen content.

metal hydrogen is moisture in the shielding gas. As most welding procedures prescribe limits for moisture level in the shielding gas, many of the shielding gases for arc welding are supplied with a guaranteed maximum moisture level of 10 ppm. In Fig. 1, the relationship of moisture content and dew point temperature of gases is plotted. The moisture content of a gas is usually expressed as dew point temperature. This dew point temperature is the temperature where water in the gas starts to condensate. Results from an investigation by Gandy and Findlan (Ref. 6) on the influence of moisture in the shielding gas process on diffusible hydrogen content of GTA-welded, low-alloyed weld metal are also plotted in Fig. 1. This figure, however, shows that an increase in shielding gas moisture from 10 ppm (–60°C dew point) to 1000 ppm (–20°C dew point) will have a marginal effect on the diffusible hydrogen content.

For the gas supplier, the specified moisture level is "as delivered" in cylinders or in liquid form, which may vary substantially from the one measured at the gas cup of the welding torch. Contamination, due to leakage at regulators and/or fittings, but mainly hoses, is a well-known phenomena as published by Farish (Ref. 7) and Brodén (Ref. 8); however, it is not always recognized in practice.

In case the partial pressure of a gas (*e.g.*, water vapor) outside of the gas hose is higher than on the inside, the gas will, depending of the hose material, diffuse through the hose wall and contaminate the shielding gas. Enrichment of the shielding gas in this way was prevented by using special gas hoses, almost non-permeable to moisture. As in practice all types of hoses can be used, and usually no flushing times are specified, a range up to 1000 ppm H_2O in the shielding gas was used in this investigation.

The AGA shielding gases with certified moisture content used for this investigation are in Table 1.

For purging the gas supply system in between and prior to the various tests, dry nitrogen with a 4-ppm moisture level was used. In addition to the "as delivered" condition of the shielding gas, moisture levels of 500 and 1000 ppm, controlled and measured during the experiments, were investigated. These levels were created by bubbling part of the shielding gas through a water container. Moisture level was measured using a calibrated hygrometer with a sensor suitable for a –75°/20°C dew point temperature range and controlled by adjusting the flow of dry and moistened gas. The system for controlling the moisture level in the gas is illustrated in Fig. 2. During all tests, climatological conditions were monitored.

Fig. 2 — System for controlling the moisture level in the shielding gas.

Table 1 — Shielding Gases with Certified Moisture Content Used for this Investigation

Shielding Gas	Certified by AGA, Verified by Authors
Argon 4.0	3 ppm H_2O
70% Argon + 30% Helium (Helon 30)	4 ppm H_2O
Argon + 2% Oxygen (MOX2)	4 ppm H_2O
Argon + 2% Carbon dioxide (MIX2)	not certified

Consumables

In order to produce welds with a wider range of ferrite levels, both duplex and super duplex grades were tested. In Table 2, the chemical composition of the base metal and weld metal is stated. For the GTA process, 2.4-mm-diameter 25%Cr super duplex (Z100M) and 22%Cr duplex (4462) filler metals were used. For the GMA process, welding wires of 1.2-mm-diameter 25%Cr super duplex (Z100M) and 22%Cr duplex (4462) were chosen.

The total hydrogen content in the consumables and base metal used, as measured using a Ströhlein H2500 analyzer, is stated in Table 3.

Welding Variables

Welds were made under varying conditions to evaluate their susceptibility to hydrogen-induced cracking.

Welding parameters for the GTA welds were 150 A, 15 V, direct current electrode negative (DCEN) and 8 L/min gas flow. The heat input was varied by

Table 2 — Consumable, Weld Metal and Base Metal Chemical Composition

Element	GTAW Process				GMAW Process				
	25% Cr Super Duplex (Zeron 100M)		22%Cr Duplex (4462)		25%Cr Super Duplex (Zeron 100 M)		22% Cr Duplex (4462)		AISI 1.4462
	Wire	Weld Metal	Wire	Weld Metal	Wire	Weld Metal	Wire	Weld Metal	Base Metal
%C	0.020	0.017	0.018	0.023	0.020	0.017	0.018	0.018	0.034
%Mn	0.055	0.53	1.70	1.71	0.055	0.52	1.70	1.78	1.49
%Si	0.15	0.20	0.53	0.61	0.15	0.24	0.53	0.63	0.49
%P	0.018	0.019	0.019	0.018	0.018	0.021	0.019	0.020	0.033
%S	0.005	<0.005	<0.005	<0.005	0.005	<0.005	<0.005	<0.005	<0.005
%Cr	25.8	25.9	22.5	22.7	25.8	25.6	22.5	22.7	22.0
%Ni	7.4	7.9	8.64	8.4	7.4	7.3	8.64	8.7	5.1
%Mo	3.65	3.61	3.32	3.17	3.65	3.66	3.32	3.21	2.75
%Nb	n.d.	0.011	n.d.	0.018	n.d.	0.011	n.d.	0.022	<0.005
%Cu	0.69	0.74	0.13	0.16	0.69	0.63	0.13	0.17	0.18
%Ti	n.d.	0.012	n.d.	0.009	n.d.	0.008	n.d.	0.009	0.008
%W	0.66	0.72	n.d.	0.04	0.66	0.70	n.d.	0.04	<0.005
%N	0.22	0.194	0.17	0.181	0.22	0.236	0.17	0.17	—

using different travel speeds. For the GMA welds, welding parameters were 180–260 A, 26–31 V, direct current electrode positive (DCEP), 38 cm/min welding speed and 15 L/min gas flow. All three levels of moisture in the shielding gas (as supplied, 500 ppm and 1000 ppm) were used. The system was purged with dry nitrogen during intervening periods.

During welding, atmospheric conditions were monitored and were within the 16–19°C temperature and 40–60% relative humidity range. All welding was manual.

For GTA welding, a water-cooled torch was used with a 11.5-mm-diameter gas cup, with provisions for a laminar gas flow. The GMA gun had a 16-mm-diameter conic gas cup.

Test Program

In order to be able to study the relationship between process variables and hydrogen content, specimens were welded according to ISO 3690/IIW II-1155-91 standards with the exception that all welds were made on 22%Cr duplex base metal. The AWS or ISO standards for ferritic mild steel are not appropriate for measuring the hydrogen content in (super) duplex stainless steel weldments, as can be explained from phase transformations of duplex stainless steels (Ref. 10).

Based on previous experiments by the authors (Refs. 1, 2), Fekken (Ref. 9) and Lundin (Ref. 3), an extraction in a quartz capsule for 72 h at 400°C was applied initially for determination of hydrogen content in (super) duplex stainless steel. A recent group-sponsored project at TWI (Ref. 11) indicated that significant levels of hydrogen might remain in the sample after encapsulation; therefore, all samples were analyzed at 900°C after hydrogen extraction for 72 h at 400°C.

Hydrogen content in GTA and GMA welds was determined using both duplex and super duplex consumables. Gas tungsten arc filler metal of a 2.4-mm diameter was used with argon 4.0 and argon + 30% helium shielding gas. Two different welding speeds resulted in heat inputs varying from 0.8 to 2.6 kJ/mm. For 1.2-mm-diameter GMA welding wires, argon + 2% oxygen and argon + 2% carbon dioxide were used as shielding gases, and welding was performed with heat inputs ranging from 0.8 through 1.3 kJ/mm.

The weld metal ferrite content was determined for both hydrogen test samples and the restrained welding specimen using Magne Gage according to ANSI/AWS 4.2-91.

The eight most severe conditions (as indicated in Table 5) were tested for cracking susceptibility using a three-point bend test as shown in Fig. 3. Here a longitudinal bead-on-plate weld was made on a 16-mm duplex stainless steel base plate, which, immediately after cooling in air, was placed in the bend test unit for 24 h, where it was bent to a 20-deg angle using a 50-mm former diameter. This configuration results in approximately 12% strain on the top surface of the weld (calculated), which was maintained for 24 h.

After this load, the specimens were examined using the liquid penetrant technique. When no cracks were identified, a further bend of the specimen to 90 deg, which is equivalent to approximately 27% (calculated) strain on the top surface of the weld, was applied. The test welds were inspected microscopically for the presence of cracks. Figure 4 illustrates a rutile SMA welded specimen bent to 90 deg.

Table 3 — Total Hydrogen Content of Consumables and Base Material

	Base Material	22% Cr Duplex GMAW 4462	22% Cr Duplex GTAW 4462	25% Cr Super Duplex GMAW Zeron 100M	25% Cr Super Duplex GTAW Zeron 100M
Total hydrogen content (mL/100 g)	2.6	5.5	10.1	3.5	1.7

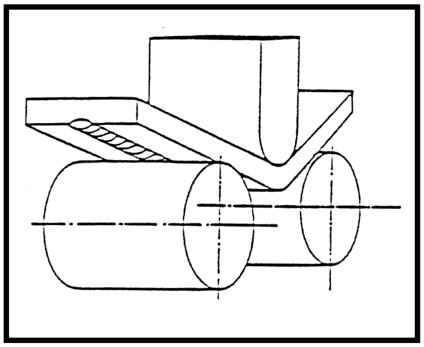

Fig. 3 — Schematic bend test setup with position former, support and weld bead.

Results

In an earlier program (Ref. 2), where test conditions were identical to this investigation, cracking data were presented for shielded metal arc, flux cored arc, gas tungsten arc and submerged arc welds as shown in Fig. 5. In that investi-

Fig. 4 — Rutile-coated SMAW specimen bent to 90 deg.

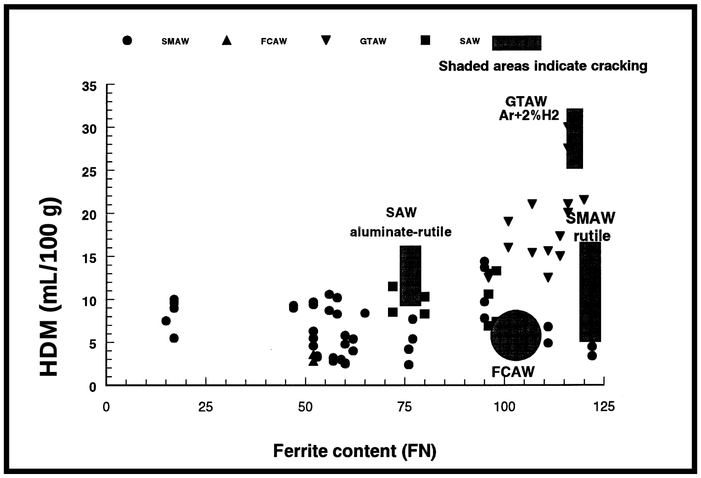

Fig. 5 — Cracking data with several processes from previous investigations (Refs. 1, 2).

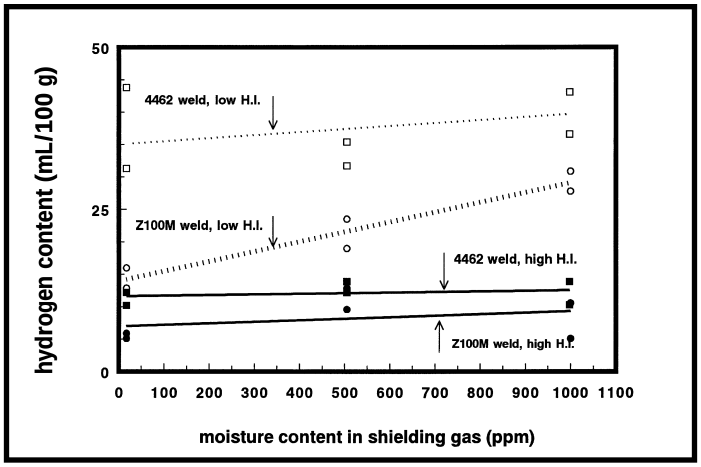

Fig. 6 — Effect of moisture content in Ar 4.0 shielding gas on hydrogen content for GTA welds.

gation, particular high hydrogen levels were measured in GTA duplex weld metal, which in combination with high ferrite levels resulted in cracking. A summary of results showing hydrogen cracking were indicated by shaded areas. Hydrogen cracking using Ar + 2%H$_2$ as a shielding gas was the basis for the investigation reported here.

Results of hydrogen measurements for duplex and super duplex stainless steel weldments, using GTA and GMA consumables and shielding gas moisture levels up to 1000 ppm, are listed in Table 4, along with weld metal ferrite level and applicable heat input.

In Figures 6 and 7, the effect of moisture content in the shielding gas on hydrogen level in weld metal is illustrated for GTA welds with duplex and super duplex consumables using argon 4.0 and argon + 30% helium gas mixtures. The numbers plotted are the total of 400°C and 900°C measurements. It appears that, in general, there is no significant difference in weld metal hydrogen levels despite an increased moisture level in the shielding gas up to 1000 ppm for most of the trials. Only the welding wire (25%Cr super duplex) used with the low heat input showed a significant increase in hydrogen level.

The data in this study showed more variation for hydrogen measurements than mild steel weldments. This is believed to be caused mainly by welding parameters. The influence of welding speed (heat input) on hydrogen level is illustrated in Figs. 8 and 9. A longer arc time for the same weld length, which is reflected in a higher heat input, showed a significant reduction in weld metal hydrogen.

Gas metal arc weldments were made using duplex and super duplex consumables, Ar + 2%O$_2$ and Ar + 2%CO$_2$ shielding gases and different current levels. The moisture content of the shielding gas was found to affect the weld metal hydrogen level only slightly, as illustrated in Figs. 10 and 11. Increased hydrogen levels were found to be associated with lower current levels — Figs. 12, 13. The hydrogen level was found to be a function of heat input (through welding speed and current) for both the GTA and GMA welds made in this study. The practical significance of these numbers should be interpreted in comparison to standard welding conditions being 1.0–2.5 kJ/mm for 1.2-mm GMA wire and 0.8–2.0 kJ/mm for 2.4-mm GTA filler metal.

Susceptibility to cracking was determined for a set of conditions believed to be most susceptible, which were high ferrite, high shielding gas moisture (approximately 1000 ppm), low current (GMAW), high welding speed/low heat input (GTAW), high deposited hydrogen level and an increased restraint level.

Table 4 — Results on Hydrogen (400°C) and Ferrite for Duplex and Super Duplex Stainless Steel Weldments using GTA and GMA Wires with Different Moisture Levels up to 1000 ppm in the Shielding Gas

Grade	Heat Input (kJ/mm)	Arc Time (s)	Hydrogen Content in mL/100 g Shielding Gas Moisture Level			Weld Metal Ferrite (FN)
			20 ppm	500 ppm	1000 ppm	
GTAW with Argon 4.0						
Zeron 100M	1.13-1.45	50–63	14.4 [0.0]	18.2 [3.0]	26.6 [2.8]	120–127
	1.62–2.05	72–91	5.5 [0.0]	9.8 [1.4]	6.6 [1.3]	116–122
4462	0.95–1.31	42–58	33.4 [4.0]	29.4 [4.2]	30.8 [9.1]	103–114
	1.62–1.87	72–83	11.2 [0.0]	11.6 [1.5]	10.3 [1.8]	87–102
GTAW with Ar+30% He						
Zeron 100M	1.22–1.49	54–66	21.0 [1.4]	16.0[1.8]	18.6 [2.7]	125–135
	1.80–2.18	80–97	9.0 [0.2]	7.2 [0.9]	6.6 [2.3]	119–131
4462	0.84–1.58	56–70	12.4 [0.0]	21.3 [2.3]	20.5 [2.6]	112–126
	1.82–2.59	81–115	7.8 [0.7]	7.2 [1.2]	10.6 [1.9]	101–109

Grade	Heat Input (kJ/mm)	Current (A)	Hydrogen Content in mL/100 g Shielding Gas Moisture Level			Weld Metal Ferrite (FN)
			20 ppm	500 ppm	1000 ppm	
GMAW with Ar+2% O_2						
Zeron 100M	0.82	190	8.0 [1.4]	9.5 [1.6]	9.8 [2.0]	102–108
	1.29	260	5.6 [0.8]	7.6 [1.1]	7.4 [1.2]	102–105
4462	0.75	180	9.2 [2.2]	11.6 [1.8}	12.8 [0.9]	86–89
	1.25	260	8.2 [1.2]	7.8 [1.3]	7.8 [1.1]	81–88
GMAW with Ar+2% CO_2						
Zeron 100	0.93	200	13.0 [0.9]	14.4 [1.4]	13.4 [1.4]	101–106
	1.33	260	8.0 [0.9]	9.2 [1.1]	10.0 [0.9]	102–107
4462	0.81	180	12.1 [1.3]	13.8 [1.7]	12.8 [1.9]	80–86
	1.25	260	6.7 [0.9]	7.2 [1.1]	7.6 [0.9]	72–84

Table 5 shows a summary of these variables. None of the investigated welds showed any (micro) cracks, even after bending the specimen to a 90-deg angle, which is equivalent to approximately 27% plastic strain at the top surface in the weld. An overview of the results is illustrated in Figs. 14 and 15.

Discussion

Comparison tests, performed in several laboratories over the last years, demonstrated a good relationship between vacuum hot extraction (VHE) and the encapsulation technique in quartz, followed by an extraction for 72 h at 400°C.

A recent publication out of a group-sponsored project at TWI (Ref. 11), however, indicated that not all hydrogen in the weld metal might evolve using the encapsulation technique. In that publication, an additional hot extraction method at 900°C, following the encapsulation test method, gave an extra volume of hydrogen. The hydrogen release from a sample in a capsule was concluded to be hindered by the development of a positive hydrogen partial pressure within the capsule.

Since the encapsulation technique has been used in a number of investigations and is the basis for several publications worldwide, this project used the encapsulation technique, followed by hot extraction at 900°C.

Hydrogen present in the base metal and the welding consumables previously was identified as the first potential source for weld metal hydrogen. This hydrogen level in consumables may vary from one heat to another. However, the initial hydrogen level of the consumable appeared to be of less importance. Both GTA and GMA weldments, regardless of

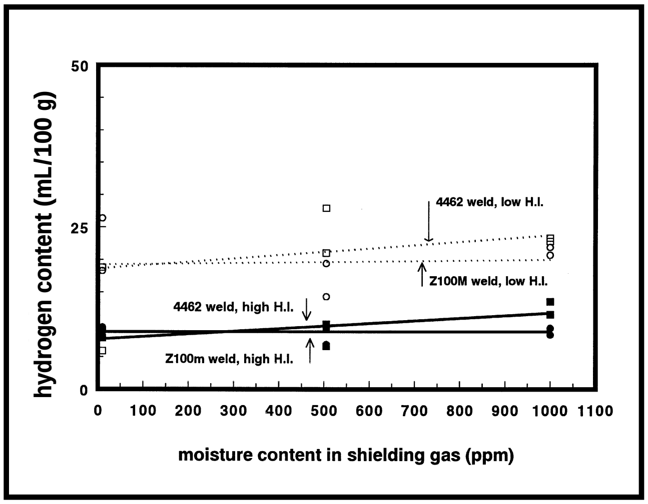

Fig. 7 — Effect of moisture content in Ar + 30%He shielding gas on hydrogen content for GTA welds.

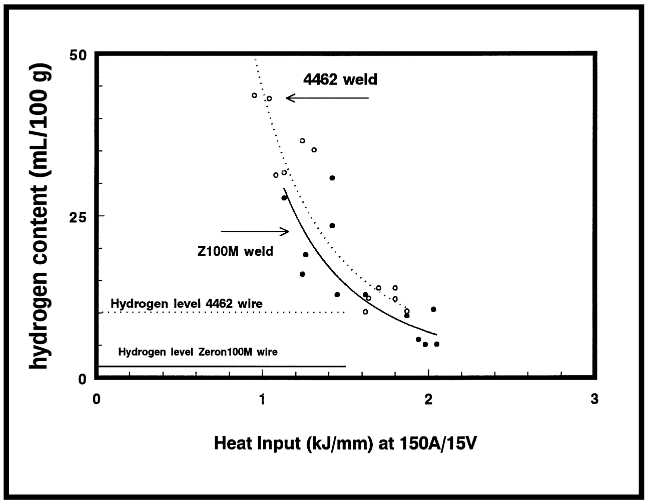

Fig. 8 — Effect of heat input (welding speed) on hydrogen content for GTAW with Ar 4.0.

Table 5—Variables and Results of Cracking Test

Grade	Heat Input (kJ/mm)	Arc Time (s)	Weld Metal Ferrite (FN)	Strain after Bending 20° (%)	Strain after Bending 90° (%)	Cracking (Y/N)
GTAW welded with Argon 4.0 shielding gas containing 1000 ppm H_2O						
Zeron 100M	0.96	47	126–133	11	25	No
4462	1.23–1.26	60–62	91–119	11	28	No
GTAW welded with Ar+30% He shielding gas containing 1000 ppm H_2O						
Zeron 100 M	1.00–1.18	49-58	135	13	25	No
4462	0.98–1.06	48–52	104–114	12	27	No

Grade	Heat Input (kJ/mm)	Current (A)	Weld Metal Ferrite (FN)	Strain after Bending 20° (%)	Strain after Bending 90° (%)	Cracking (Y/N)
GMAW welded with Ar+2% O_2 shielding gas containing 1000 ppm H_2O						
Zeron 100M	0.78–0.82	195–197	106	10	21	No
4462	0.53–0.58	140–150	81	11	25	No
GMAW welded with Ar+2% CO_2 shielding gas containing 1000 ppm H_2O						
Zeron 100M	0.68	170	105–106	13	28	No
4462	0.60–0.64	150–160	82	12	27	No

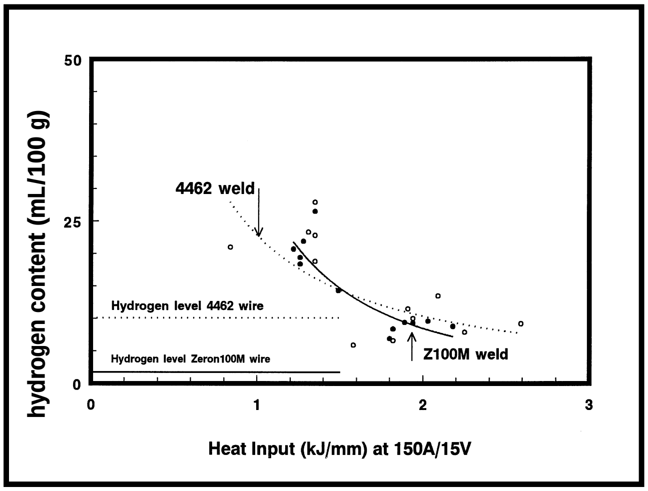

Fig. 9 — Effect of heat input (welding speed) on hydrogen content for GTAW with Ar + 30%He.

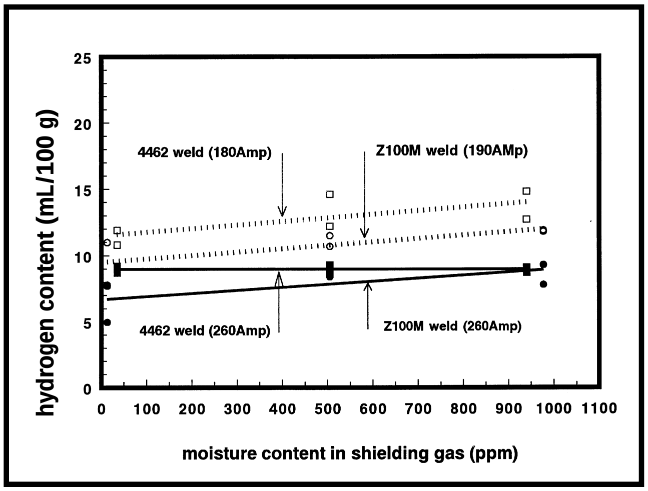

Fig. 10 — Effect of moisture content in Ar + 2%O_2 shielding gas on hydrogen content for GMA welds.

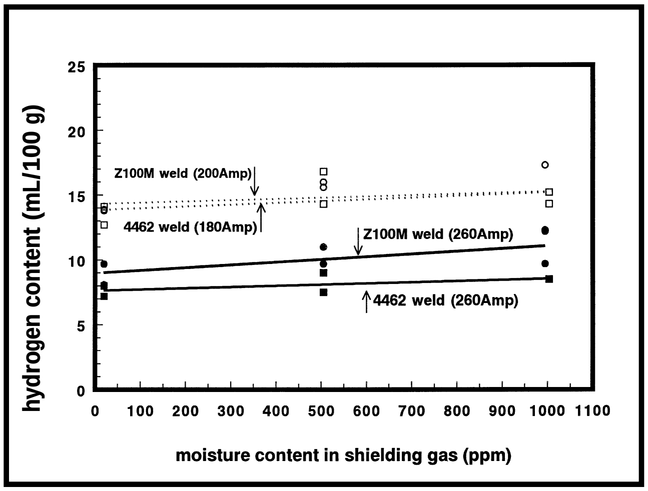

Fig. 11 — Effect of moisture content in Ar + 2%CO_2 shielding gas on hydrogen content for GMA welds.

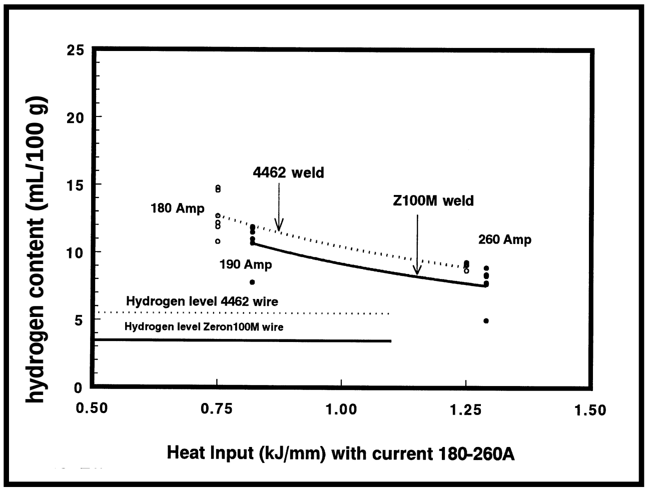

Fig. 12 — Effect of heat input on hydrogen content for GMAW in Ar + 2%O_2.

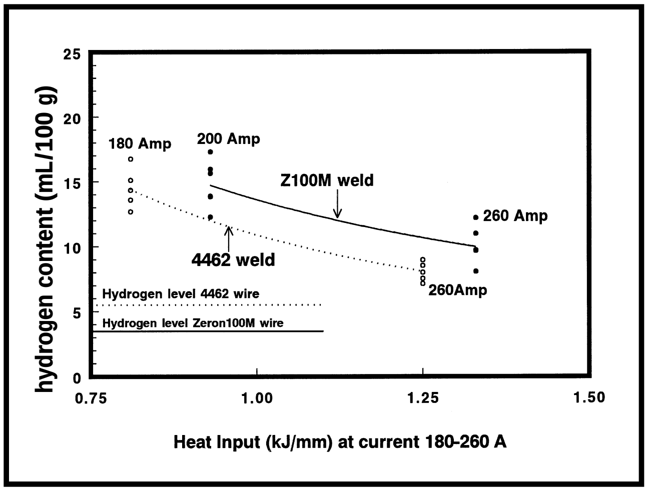

Fig. 13 — Effect of heat input on hydrogen content for GMAW in Ar + 2%CO_2.

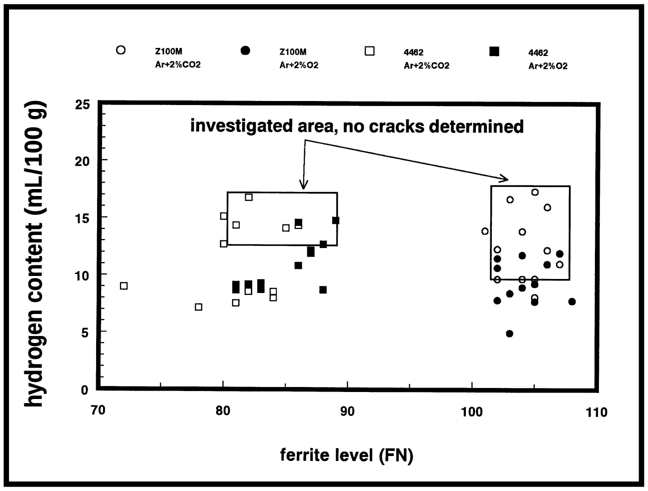

Fig. 14 — Cracking susceptibility for GMA welds.

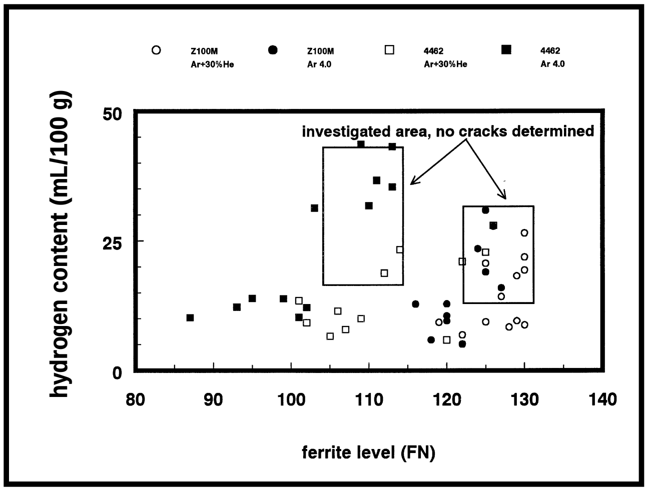

Fig. 15 — Cracking susceptibility for GTA welds.

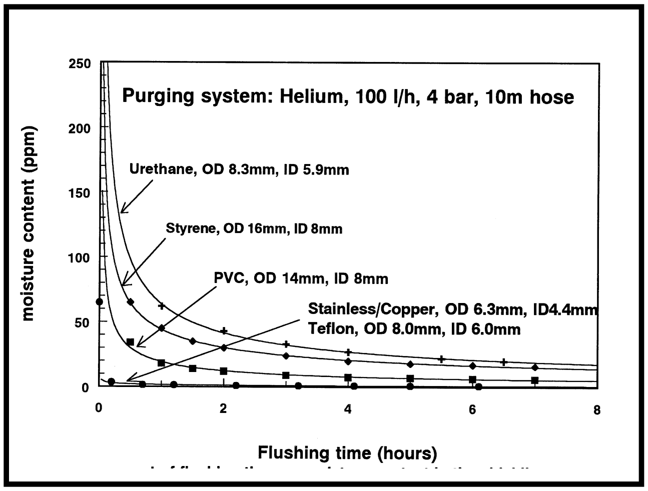

Fig. 16 — Effect of flushing time on moisture content in the shielding gas.

type of consumable or shielding gas, tended to go to a 5–10 mL H_2/100 g level with appropriate welding procedures.

One of the objectives was to determine the effect of elevated moisture levels in the shielding gas. Today, in most procedures, the maximum allowable moisture content in shielding gas is 10 ppm.

In real life, however, moisture content of the gas leaving the gas cup at the time of welding has measured up to 50–100 ppm. Should gas purging not be sufficient, or if moisture diffusion through the hoses has occurred, 375 ppm H_2O in the shielding gas is not rare, as reported by Farish (Ref. 7) and AGA (Ref. 12), illustrated in Fig. 16. That is why, in this study, moisture levels in the shielding gas up to 1000 ppm were applied. It appeared however that the hydrogen content did not significantly increase with increased shielding gas moisture.

This investigation also examined the effect of welding process parameters on weld metal hydrogen content. It was found that parameter selection had a significant effect on hydrogen content. It was found in this investigation that minimum heat inputs of 2 kJ/mm for the 2.4-mm GTA filler metal and 1.3 kJ/mm (250 A) for the 1.2-mm GMA welding wires achieved hydrogen levels not exceeding 10 mL/100 g in the weld metal.

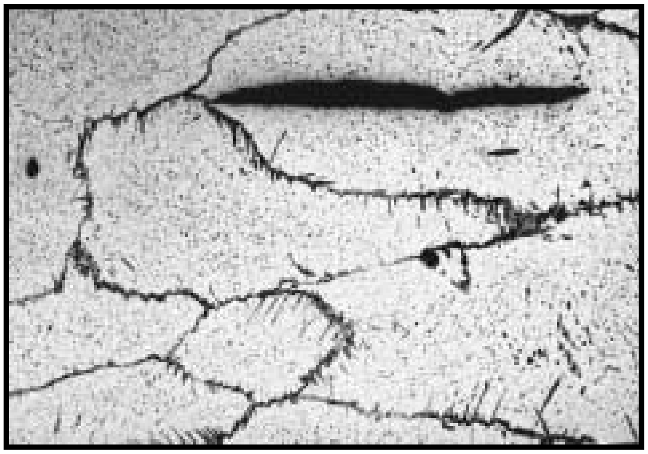

Fig. 17 — Hydrogen cracks in ferrite crystals at 200X in duplex stainless steel weldments (122 FN).

Sensitivity for cracking in duplex stainless steel weldments using the bend test has been proven in earlier investigations by the authors (Refs. 1, 2) and Fekken (Ref. 9). These investigations reported cracks for GTA welds using Ar + 2%H_2 shielding gas, SA welds with aluminate-rutile fluxes, FCA welds with rutile flux cored wires and SMA welds with rutile-coated electrodes. An overview has been given in Fig. 5. A typical example of cracks in weld metal after deformation (bend specimen) from the previously mentioned reports is in Fig. 17. This figure shows hydrogen cracks in the ferritic crystals at a magnification of 200X in duplex stainless steel weld metal with 122 FN.

Microstructure and hydrogen content of the weld metal are important for cracking susceptibility. When the ferrite content in duplex stainless steel increases, hydrogen-assisted cracking becomes more relevant. Austenitic-ferritic duplex stainless steels solidify from liquid as ferrite. When temperature decreases, this ferrite becomes unstable relative to other phases. Desirable ferrite transforms partly to austenite but intermetallic compounds can be formed as well. Depending on composition and cooling rate, carbides and nitrides may precipitate in the ferrite phase. During arc welding, cooling rates from the fully ferritic high temperatures are relatively rapid, so equilibrium is not fully reached and more ferrite than desired will be formed. Hydrogen-induced cracking has occurred in practice with high ferrite levels in the weld metal (Ref. 13). In duplex stainless steels, austenite and ferrite have diffusion coefficients for mono-atomic hydrogen that differs about 2 or 3 orders of magnitude, being the lowest in austenite. The austenite in a duplex structure acts as a barrier to hydrogen escape (Ref. 10). As austenite forms first at the grain boundaries of the original ferrite and envelopes the primary ferrite, the hydrogen present is trapped within the ferrite and hydrogen diffusion is limited. When plastic deformation occurs in this situation, active hydrogen at the deformed austenite/ferrite interface may cause hydrogen cracking.

The lower hydrogen levels, measured with higher heat input, might be due to a longer time for the weld metal being in the delta ferrite phase, giving the hydrogen time to diffuse out of the weld metal. In the past, hydrogen cracking has been noticed in cases where hydrogen was added to the shielding gas (Ref. 14) and both restraint intensity and weld-metal ferrite level were high. However, the addition of hydrogen to the shielding gas for improved welding efficiency or better weld appearance through increase of arc energy density is currently not common practice in welding (super) duplex stainless steels.

As shown in Fig. 14, high hydrogen levels over 15 mL/100 g deposited weld metal were present in GMA weldments with high ferrite. Ferrite numbers of 81 and 82 for duplex and 105 and 106 for super duplex did not result in cracking when a strain ranging from 21 to 28% was applied. For GTA weldments (Fig. 15), hydrogen levels up to 40 mL/100 g deposited weld metal and ferrite numbers of 91–114 for duplex and 126–135 for super duplex gave no cracks, even with a strain ranging from 25 to 28%. Theoretically, 140 FN (being 100% ferrite) is the maximum one can measure. Based upon welding procedure and consumables, the measured ferrite numbers are not rare. They are, however, severe for hydrogen cracking susceptibility. For these severe test conditions, the shielding gas moisture level was 1000 ppm.

Conclusions

Susceptibility to hydrogen cracking, using the GTA or GMA process with standard duplex and super duplex welding consumables appears to be limited. Although very high ferrite levels were combined with high restraint and high hydrogen content, none of the GMA and GTA welds cracked.

In practice, a guaranteed moisture level below 10 ppm in the shielding gas is of less importance than applied welding parameters for these conditions. Even a moisture level of 1000 ppm in the shielding gas, in combination with correct welding parameters, will result in low hydrogen content. A maximum of 10 ppm moisture in shielding gas, however, will not necessarily result in low weld-metal hydrogen content.

Hydrogen in the weld metal appeared to be more dependent on welding procedure rather than moisture content of the shielding gases investigated, or by hydrogen initially present in GTA or GMA consumables.

For the GTA process, a minimum heat input of 2 kJ/mm was preferred for 2.4-mm filler metal to get low-deposited hydrogen in the weld metal. For the GMA process, a 1.2-mm welding wire at 250 A and a heat input of 1.3 kJ/mm gave the same low hydrogen result.

The lower hydrogen levels measured at the higher heat inputs might be due to a longer time the weld metal was in the delta-ferrite phase, giving the hydrogen time to diffuse. The main reason for a difference in hydrogen level was the heat input, which was a result of changing welding speed for GTA welds and current level for GMA welds.

The type of shielding gas, which influences the arc temperature, did not significantly affect the hydrogen level in the weld metal.

The encapsulation technique for measurement of hydrogen content in super duplex stainless weldments appeared to be inadequate without a subsequent hot extraction at 900°C. On average, another 12% was measured with an additional hot extraction cycle at 900°C.

Acknowledgment

The authors would like to recognize J. de Ruiter for his dedicated work on hydrogen analysis.

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