A Study of Hydrogen Cracking in Underwater Steel Welds

A yield strength of 50 ksi appears to be the limit beyond which hydrogen cracking occurs frequently in underwater welding of structural steels

BY H. OZAKI, J. NAIMAN AND K. MASUBUCHI

ABSTRACT. This project was undertaken to investigate hydrogen cracking in underwater ("wet") welds. Several kinds of structural steel specimens were used, including those made of mild steel, 50 ksi (yield strength) class steels, and HY-80 steel.

The Y-slit restraint test was used because the testing conditions of this method can be related to actual fabricating conditions. Several types of electrode were used in the welding of mild steel, and the effects of the different electrode coatings examined. Low hydrogen electrodes were used in the welding of both high tensile strength steel and mild steel (E7018), and 25Cr-20Ni stainless steel electrodes (E310-16) in the welding of HY-80 steel. This enabled an examination of the effects of undermatching, and an examination of austenitic electrodes.

The same materials were also used to make air welds so that comparisons could be made between underwater and air welds.

The hydrogen content in underwater welds was determined using the glycerine method. The carbon-equivalent formulas and the critical cooling time (from 800 to 500 C (1472 to 932 F) to produce a fully martensitic structure) are used in the discussion of hydrogen-cracking susceptibility. It was found that, whatever the electrode-type used, no observable hydrogen cracks resulted from the underwater welding of mild steel. But hydrogen cracks did result from the underwater welding of high strength steels. The use of undermatching techniques or austenitic electrodes did not improve the weld integrity.

Introduction

The increasing use of offshore structures such as platforms, storage tanks and pipelines has created a demand for the development of underwater welding techniques that can be used in their construction and repair.

In order to obtain high quality underwater welds and to develop more reliable processes, the weldability of various structural steels must be investigated.

Because of the high quenching rate caused by the water environment and because large quantities of hydrogen are present, hydrogen cracking is one of the most severe problems in the underwater welding of steel. A number of reports on this subject are available, but the results tend to be inconsistent.

Grubbs and Seth[1] contend that the hydrogen cracking problem in carbon steel welds is minor unless the carbon equivalent exceeds 0.4. Also, extensive cracking was not found in tee and lap joints of HY-80 steel, a material known to be crack-sensitive in air welding.[2] However, England's Welding Institute has reported that extensive hydrogen cracking does occur in underwater welds made in normal carbon steels with 0.3 to 0.42 carbon equivalent.[3] In addition, it has been reported that due to the martensitic structure, the maximum hardness in the heat-affected zone of underwater welds in mild steel (carbon equivalent: 0.33) was about 600 Hv.[4] Both the hardness measurement and the microscopic observation indicate that even in mild steel hydrogen cracking can occur.

The objective of this study is to systematically obtain experimental data on the hydrogen-cracking susceptibility of underwater welds in various structural steels.

The presence of hydrogen, the presence of a susceptible microstructure and the presence of tensile stress or strain are the causative factors in the hydrogen cracking of steel welds. All three factors can be represented by three engineering indexes: the diffusible hydrogen content, the carbon equivalent and the intensity of restraint.[5] In the present study, the underwater hydrogen potential of various types of electrode was determined using the glycerine method. The cracking tests were carried out using a Y-slit restraint test such that the intensity of restraint could be related to actual fabricating conditions.

Austenitic electrodes have a large hydrogen solubility and tend to keep hydrogen away from the crack-sensitive base metal. Because of this, they reduce hydrogen cracking in underwater steel welds when the carbon equivalent exceeds 0.40.[1] Recently, it was reported that several different types of austenitic electrode have been observed to produce underwater welds containing martensitic structures along the fusion boundaries; this

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Table 1—Chemical Composition of Materials Used, Wt-%

	C	Si	Mn	P	S	Ni	Cr	Mo	V	Nb	C.E.[a]	P_{CM}[b]
Mild steel	0.20	0.02	0.53	0.03	0.04						0.29	0.23
ST52	0.19	0.34	1.14	0.02	0.03						0.38	0.26
A537A	0.16	0.30	1.20	0.02	0.03	0.20	0.20	0.06	0.06	0.02	0.45	0.26
HY-80	0.18	0.20	0.32	0.02	0.03	2.99	1.68	0.41			0.85	0.36

[a] Carbon Equivalent $= C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$

[b] $P_{CM} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + \frac{Cu}{20} + 5B$

is due to the high base metal dilution and the high quenching rate caused by the water environment which in turn results in weld metal hydrogen cracking.[6]

It has been demonstrated that the use of undermatched electrodes (the weld metal strength being lower than that of the base metal) effectively reduces hydrogen cracking.[7]

This study examines how the use of an austenitic electrode and an undermatched electrode affects the welding of HY-80 steel.

Experimental Procedure

Materials

Several commercially available steels including mild steel (ABS grade A), 50 ksi (yield strength) class steels (A537A and ST 52), and HY-80 steel were used in the evaluation of the hydrogen cracking susceptibility of underwater welds—Table 1. The specimens were 1/2 in. (12.5 mm) thick. In Table 1, the carbon equivalent values (C.E.) and the P_{CM}[5] values of these steels are shown. The following equations were used to calculate these values:

$$C.E. = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \text{ (Current spec.)}$$

$$P_{CM} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B \text{ (Ito and Bessyo}^{5}\text{)}$$

For the experiment on mild steel, three types of electrodes—including titania-iron powder type (E7014), iron powder-iron oxide type (E6027) and low hydrogen type (E7018)—were used.

The titania-iron powder type reportedly has good running characteristics.[8] The iron powder-iron oxide type has been demonstrated to reduce the hydrogen-cracking susceptibility of underwater welds.[6]

Low hydrogen electrodes (E8018) were used for A537A steel and ST52 steel. For HY-80 steel, three types of electrode including low hydrogen electrodes with different strengths (E11018 and E7018) and austenitic electrodes [E310-16 (25Cr-20Ni)] were used. E7018 electrodes and E310-16 electrodes were used to determine exactly how an undermatched electrode and an austenitic electrode affect the hydrogen-cracking susceptibility of underwater welds in HY-80 steel. All of these electrodes were 5/32 in. (4 mm) in diameter.

Hydrogen Cracking Tests

Hydrogen-cracking susceptibility was evaluated using a Y-slit self-restrained cracking test—Fig. 1. The measure of the hydrogen-cracking susceptibility of a steel is the cracking ratio—Fig. 2. This is a ratio of the height from the root to the tip of the crack versus the height from the root to the surface of the weld metal.

The restraint intensity involved in this test corresponds to the upper limits of the restraint intensity of an actual welded joint. Because of this,

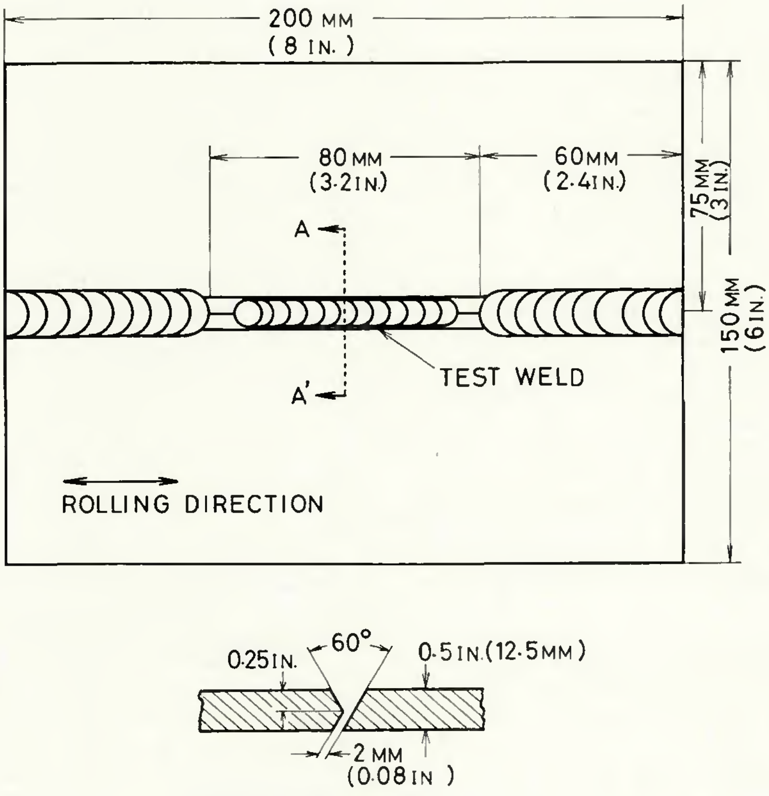

Fig. 1—The Y-slit type test specimen

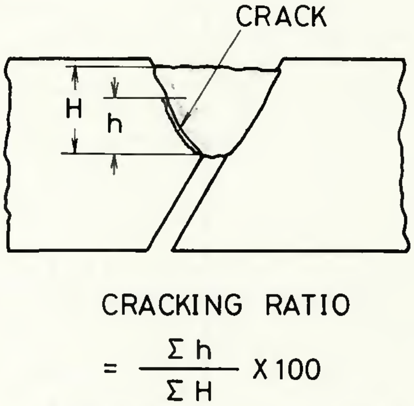

Fig. 2—Determination of a cracking ratio

the test results are a reasonably accurate indicator of hydrogen-cracking susceptibility.

Testing Procedure

The Y-slit specimens were cut from the plates in such a way that their longitudinal dimension was parallel to the rolling direction of the plates. The restraint welds were made in the usual manner.

The specimens were put in a tank 10 × 16 × 12 in. (250 × 400 × 300 mm) deep. Water was pumped in up to a level 1.2 in. (30 mm) above the top of the plate. The electrodes, which had been kept dry, were taken from the holding oven and waterproofed with an enamel spray prior to welding. The welding was done using 200 A, 25 V DCRP and an average welding speed of 8 ipm (20 cm/min), resulting in an average heat input of 38 kJ/in. (1500 kJ/m).

The welded specimens were submerged in a container of water at 70 F (21.5 C) for 48 hours and then sectioned to expose the cracking.

The cracking ratio of each plate-electrode combination was determined by averaging the cracking ratio values observed in four different sectionings.

Air welds were made using the same welding conditions as the underwater welds.

Metallographic Examination and Hardness

Measurement

In the metallographic examination, the specimens were polished and etched using 1% nital or aqueous picric acid and observed microscopically.

The hardness was measured using a Knoop hardness testing machine set at a 500 g load. The results were converted to the DPH (10 kg) scale. The hardness measurements were taken 1 mm (0.04 in.) above the root level in each case.

Measurement of Diffusible Hydrogen Content

Diffusible hydrogen content evolved from underwater welds was measured using the glycerine method (the procedure proposed by the Japan Industrial Standard was employed).[9]

These results can be related to those obtained by the IIW method using the following equation:[10]

$$H_{IIW} = 1.27\ H_G + 2.2$$

where H_{IIW} = hydrogen content by IIW method; H_G = hydrogen content by glycerine method.

How the type of waterproof medium and the length of time the electrode is in the water before it is used affects the diffusible hydrogen content was also investigated. The waterproof mediums investigated were paraffin wax, epoxy resin, and enamel.

Table 2—Summary of the Cracking Tests

Steel	Electrode	Cracking ratio, % Air	Cracking ratio, % Underwater
Mild steel	E7014	0	0
	E7018	0	0
	E6024	0	0
ST52	E8018	2	30
A537A	E8018	21	26
HY-80	E11018	95	100
	E7018	18	100
	E310-16	1	80

Experimental Results

Cracking Tests

Table 2 summarizes the results of the cracking tests. No cracks were found in the mild steel specimens either in the underwater welds or in the air welds. Figure 3 shows the cross-section of an underwater weld made with an E7018 electrode. Figure 4 shows the microstructure of the weld; the bottom left side of Fig. 4 is the weld metal and the balance is the HAZ where the Widmanstätten structure can be seen.

Unlike mild steel, the high strength steels are likely to crack. The cracking ratio of A537A steel was 26% and the microstructure of the HAZ was bainitic—Fig 5.

The cracking ratio of ST52 steel was 30%, close to that of A537 steel. The real differences in the cracking ratios are evident in the air welds: 2% for ST52 steel and 21% for A537 steel. Although A537A steel is more susceptible than ST52 steel in air welding, both steels have approximately the same underwater hydrogen-cracking susceptibility.

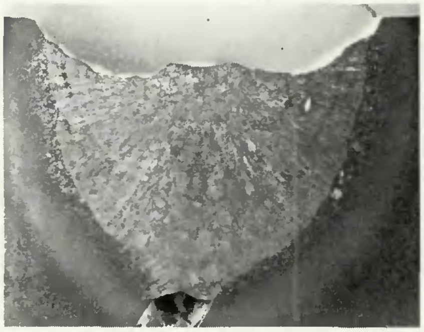

Fig. 3—An underwater weld made with E7018 electrode in mild steel. Nital etch, ×10 (reduced 59% on reproduction)

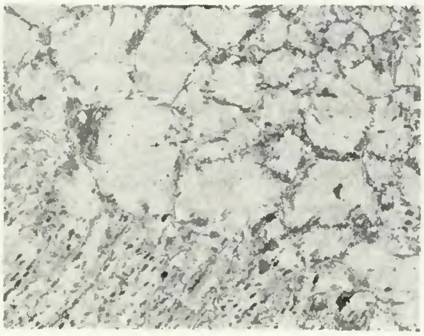

Fig. 4—Microstructure of an underwater weld made with E7014 electrode in mild steel. Aqueous picric acid, ×128 (reduced 50% on reproduction)

Fig. 5—Cracks in the underwater weld made with E8018 electrode in A637A steel. Nital etch, ×128 (reduced 50% on reproduction)

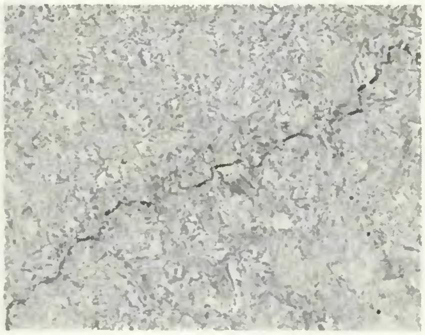

Fig. 6—The microstructure of an underwater weld made with E7018 electrode in ST52 steel; cracks can be seen in the coarse grained region in the HAZ. Nital etch, ×128 (reduced 40% on reproduction)

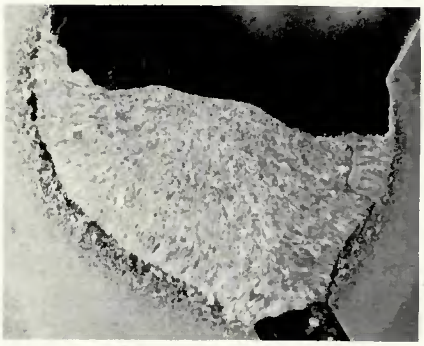

Fig. 7—An underwater weld made with E11018 electrode in HY-80 steel. Nital etch, ×12.5 (reduced 57% on reproduction)

Fig. 8—Cracks in an underwater weld made with E11018 electrode in HY-80 steel. Nital etch, ×128 (reduced 35% on reproduction)

Figure 6 shows the underwater ST52 steel weld microstructure, with cracks in the HAZ where the martensitic structure is present.

In the HY-80 steel welds, extensive cracks are evident in both the underwater welds and the air welds, except in the case of those made using E310-16 electrodes.

The cracking ratios of underwater welds made with E11018 and E7018 electrodes are as high as 100%. The cracking ratios of the air welds are 95% for E11018 and 18% for E7018. Note that the undermatched E7018 electrodes reduced the cracking ratio of the air welds, but not of the underwater welds.

Figure 7 shows the cross-section of an underwater HY-80 steel weld made with an E11018 electrode. Figure 7 shows that the crack initiated at the root and mostly followed the fusion line to the surface, penetrating 100% of the height.

The crack shown in Fig. 8 propagated along the prior austenite grain-boundaries in the HAZ, where the martensitic structure was present.

Table 3—Summary of Diffusible Hydrogen Content of Underwater Welds

Type of electrode	Amount of diffusible hydrogen, cc/100 g
E7014	49 (53.5)[a]
E7018	31
E6027	(24)[a]
E8018	31
E11018	32
E310-16	38
E312-15	(40)[a]

[a] Data from Stalker, Hart and Salter.[6]

The cracking ratio of the HY-80 steel welds made with E310-16 electrodes was 21% for underwater and 1% for air. These numbers are considerably smaller than those associated with the other types of electrode in both underwater and air welds.

It can be said that the use of an austenitic electrode can reduce the hydrogen cracking susceptibility of underwater welds. Further investigation, however, has shown that the use of an austenitic electrode cannot reduce the cracking problem in underwater welds. This is discussed in more detail further in the paper.

Diffusible Hydrogen Content of Underwater Welds

Table 3 summarizes the diffusible hydrogen content of the underwater welds; data provided by The Welding Institute are included. As mentioned under Experimental Procedure, the data in this experiment were obtained using the glycerine method and converted to the IIW scale. On the other hand, the data of The Welding Institute were actually obtained using the IIW method.

Fairly good agreement can be seen between the two bodies of data as they relate to E7014 electrodes. Among the electrodes, E6027 appears to give the lowest diffusible hydrogen content (24 cc/100 g) and E7014 appears to give the highest (49–53.5 cc/100 g). The amount of diffusible hydrogen with the low hydrogen type electrodes—including E7018, E8018 and E11018—is approximately 31 cc/100 g and is the value that falls in between those associated with E7014 and E6027 electrodes.

Because austenite has a high hydrogen-solubility, the amounts of diffusible hydrogen present in the welds made with austenite electrodes are fairly high (38 cc/100 g for E310-16 and 40 cc/100 g for E312-15).

Figure 9 shows how the amount of time the electrodes are in the water (with and without three different waterproof mediums) affects the diffusible hydrogen content in underwater welds. An E7014 electrode was used. The experimental data fall between 41 and 53 cc/100 g and are independent of the immersion time and the waterproof medium.

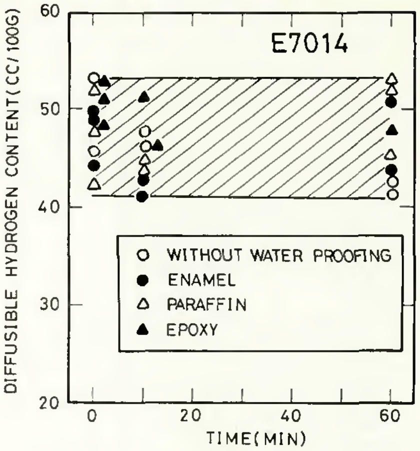

Fig. 9—Effect of immersing time of electrodes in water on the diffusible hydrogen content of underwater welds

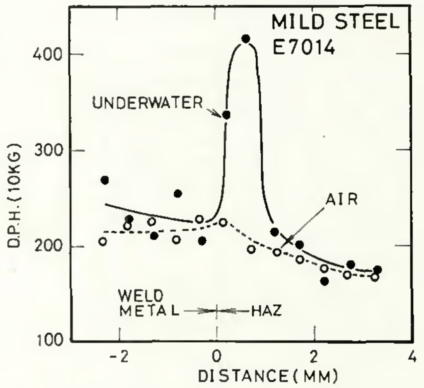

Fig. 10—Hardness distribution within the welds made with E7014 electrode in mild steel

The results indicate that neither waterproofing nor immersion time before welding affects the diffusible hydrogen content of underwater welds. It can therefore be stated that, unlike air welding, the absorption of water by the coating flux does not affect the diffusible hydrogen content.

Hardness Distribution within Underwater Welds

Figures 10 and 11 illustrate the hardness distribution within underwater welds on mild steel and HY-80 steel, respectively. Electrodes used were E7014 for mild steel and E11018 for HY-80 steel. Table 4 tabulates the maximum hardness in the HAZ and the hardness of the weld metal.

The maximum hardness for an underwater weld in mild steel (400 DPH) is much harder than that for an air weld made in the same material

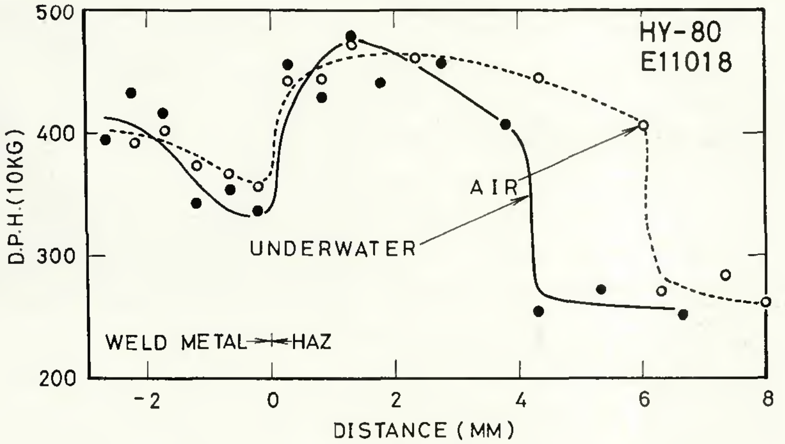

Fig. 11—Hardness distribution within the welds made with E11018 electrode in HY-80 steel

Table 4—Summary of the Hardness Measurement

Steel	Electrode	Maximum hardness in HAZ		Maximum hardness in weld metal	
		Underwater	Air	Underwater	Air
Mild steel	E7014	420	235	240	215
	E7018	400	220	210	220
	E6027	410	220	200	175
A537A	E8018	380	200	210	160
ST52	E8018	430	245	230	200
HY-80	E11018	470	470	400	400
	E7018	460	440	350	290
	E310-16	425	400	190	200

(235 DPH), indicating that the structure is susceptible to hydrogen cracking. Despite these hardness results on mild steel, no hydrogen cracking was observed—Table 3. The type of electrode used did not seem to have a significant effect on the maximum hardness. These results do not agree with those of Hasui and Suga which indicated that the use of an iron oxide type electrode could reduce the maximum hardness.[11]

When A537A steel was welded underwater, the maximum hardness was less than 400 DPH, lower than that of mild steel by 20 to 40 DPH. Despite this, hydrogen cracking occurred—Table 3.

On ST52 steel, the maximum hardness was about 430 DPH, higher than that of mild steel.

The maximum hardness in the underwater welds on HY-80 steel varied from 425 to 470 DPH and was affected by the electrode type. The E11018 produced the hardest HAZ and the E310-16 the softest. Coating type affected the hardness; the underwater weld metal hardness was 400 DPH for E11018, 350 DPH for E7018, and 190 DPH for E310-16.

Unlike mild steel in which there is a large difference between the maximum hardnesses of underwater and air welds, the maximum hardnesses of underwater and air welds in HY-80 steel are nearly the same; also, the air weld hardness is almost as high as the underwater weld hardness.

Discussion: Hydrogen-Cracking Susceptibility in Underwater Welds

According to Grubbs and Seth,[1] under restrained conditions and when underbead cracking was present the carbon equivalent was 0.445; when underbead cracking was not present, it was 0.392. They concluded that steels with a carbon equivalent of up to 0.40% could be welded underwater without hydrogen cracking.

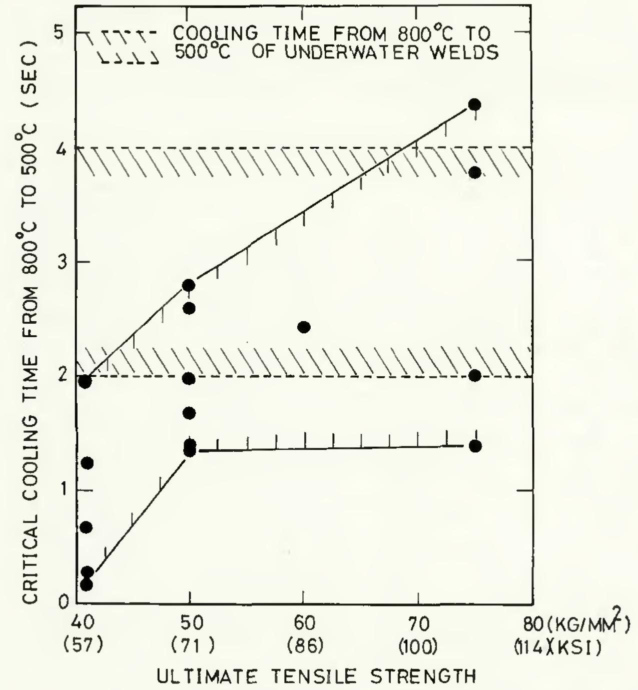

Fig. 12—Relationship between the critical cooling time from 800 to 500 C and the ultimate tensile strength of various structural steels

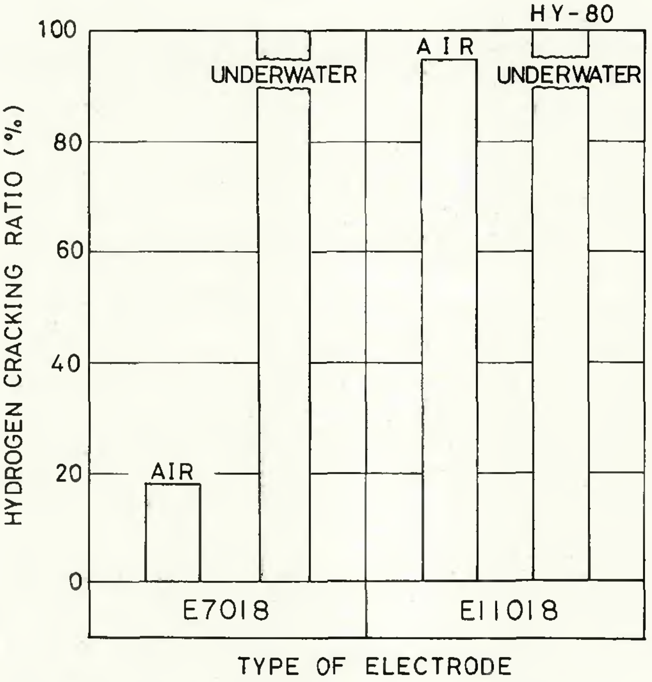

Fig. 13—Effect of an undermatched electrode on the hydrogen cracking susceptibility of HY-80 welds

Table 5—Effect of the Use of Austenitic Electrode on Cracking in Underwater Welds of HY-80 Steel

Type of electrode	Atmosphere	Hydrogen cracking ratio, %	Total cracking ratio, %
E11018	Air	95	100
	Underwater	100	100
E310-16 (25Cr-20Ni)	Air	1	10
	Underwater	21	100

Bouwman and Haverhals[12] carried out controlled thermal severity (CTS) tests on ST37, ST41, and ST52 steels. Among these steels, only ST52 steel cracked spasmodically. The present experimental results indicate that steels having a yield strength of more than 50 ksi (345 MPa) frequently experience hydrogen cracking when they are welded underwater.

As mentioned above, the 50 ksi yield strength class in steels is a critical one in which hydrogen cracking frequently occurs; the critical carbon equivalent (C.E.) is approximately 0.35 and the critical P_{CM} approximately 0.25 (see Table 1). This critical carbon equivalent value is lower than that proposed by Grubbs and Seth.

The critical cooling time (the cooling time necessary to produce a fully martensitic structure in steel welds) is another index useful in the prediction of cracking. Figure 12 illustrates the relationship between the critical cooling time (from 800 to 500 C or 1472 to 932 F) and the strength of various steels. The critical cooling time values were obtained from steels available commercially. In Fig. 12 the typical cooling time from 800 to 500 C of underwater welds is superimposed to be in the range of 2 to 4 seconds.[6,12,13]

In underwater welding, steels with a yield strength of more than 50 ksi (345 MPa) are likely to produce a fully martensitic structure. Only mild steel can be welded underwater without forming a martensitic structure. The tendency of this data agrees with that of cracking susceptibility.

Effect of Undermatched Electrodes

Satoh and Toyoda[7] demonstrated that the use of undermatched welding techniques effectively reduces the hydrogen-cracking susceptibility of air welds. The lower strength weld metal can absorb more strain than the higher strength weld metal, allowing the strain needed to cause cracking to be attenuated.

In addition, since the rapid quenching that takes place in underwater welding hardens the weld metal, it is not always necessary to use overmatched electrodes. Figure 13 shows how undermatched electrodes affect the hydrogen-cracking susceptibility of both air welds and underwater welds in HY-80 steel.

In the air welds, the cracking ratio of the weld metal made with E11018 is considerably higher than that with E7018. The effect of undermatched electrodes can be clearly seen. According to hardness measurements (Table 4) the hardness of the weld metal is approximately 400 DPH with E11018 and 350 DPH with E7018. This hardness difference may be responsible for the cracking ratio difference.

Since the underwater cracking ratio of both E11018 and E7018 is 100%, the use of E7018 is not effective, even though its hardness value is 50 DPH less than that of E11018.

Undermatched electrodes do not significantly affect underwater weld quality, even though they do affect air weld quality.

Effect of Austenitic Electrodes

The Welding Institute studied how austenitic electrodes affect the hydrogen cracking susceptibility of underwater welds.[6] They found that the use of austenitic electrodes reduced the susceptibility. Also, they found that many electrodes that produced austenitic weld metal in air welds produced martensitic weld metal in underwater welds due to the base metal dilution and the high quenching rate caused by the water environment, and hydrogen cracking was the result. It was also observed that all austenitic welds contained bands of hard martensite along the fusion boundaries.

Table 5 compares the hydrogen cracking ratio with the total cracking ratio of the welds made with E11018 and E310-16 electrodes.

The use of austenitic electrodes is apparently effective in reducing hydrogen cracking in both underwater and air welding. For instance, the underwater cracking ratio of E310-16 electrodes is 21%, much lower than that of E11018 electrodes (100%); in air welds the reduction of the cracking ratio is even more significant (from 95% to 1%). But the total cracking ratio value for both electrodes is 100%; the total cracking ratio cannot be reduced using either electrode.

Figure 14 shows a cross-section of a weld made using an austenitic electrode; hot cracking is evident. The use of an austenitic electrode, therefore, does not always minimize the cracking problem in underwater welds.

Fig. 14—Underwater weld made with E310-16 electrode in HY-80 Steel. Nital etch, ×8 (reduced 48% on reproduction)

Conclusions

1. No observable hydrogen cracks were found in either underwater or air welds in mild steel. The coating type did not noticeably affect the weld integrity.
2. Underwater welds in high strength steels cracked.
3. 50 ksi (yield strength) class steel was the border line case as far as hydrogen cracking was concerned.
4. Underwater welds in HY-80 steel cracked extensively.
5. The use of undermatching techniques did not prevent cracking in HY-80 steel.
6. The use of an austenitic electrode (25Cr-20Ni stainless steel) reduced hydrogen cracking but increased hot cracking.

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References

1. Grubbs, C. E., and Seth, O. W., "Multi-

pass All Position Wet Welding—A New Underwater Tool," Fourth Annual Offshore Technology Conference, 1972, Houston, Texas, Paper/Communication OTC 1620.

2. Masubuchi, K., and Meloney, M. B., "Underwater Welding of Low-Carbon and High-Strength (HY-80) Steel," Sixth Annual Offshore Technology Conference, 1974, Houston, Texas, Paper/Communication OTC 1951.

3. The Welding Institute Report, "Fusion Welding Underwater," *Metal Construction*, May 1975, pp. 41-43.

4. Brown, R. T., and Masubuchi, K., "Fundamental Research on Underwater Welding," *Welding Journal*, 54 (6), June 1975, Res. Suppl., pp. 178-s to 188-s.

5. Ito, Y., and Bessyo, K., "Weldability Formula of High Strength Steels Related to Heat-Affected Zone Cracking," IIW Document IX-576-68.

6. Stalker, A. W., Hart, P. H. M., and Salter, G. R., "A Preliminary Study of Underwater Manual Metal Arc Welding," Welding Institute Report No. 3412/5B174.

7. Satoh, K., and Toyoda, M., "Joint Strength of Heavy Plates with Lower Strength Weld Metal," *Welding Journal*, 54 (9), Sept. 1975, Res. Suppl. 311-s to 319-s.

8. Galerne, A., "Underwater Welding and Painting," Symposium on Underwater Welding, Cutting and Hand Tools held at Battelle Memorial Institute, 10-11 October 1967, pp. 43-53.

9. Japanese Industrial Standards, "Method for Measurement of Hydrogen Evolved from Deposited Metal," JIS Z 3113-1975.

10. IIW Document "Weld Metal Hydrogen Levels and the Definition of Hydrogen Controlled Electrodes, IIS/IIW-452-74.

11. Hasui, J., Suga, Y., "On Underwater Gravity Arc Welding (Report 1)," *Journal of the Japan Welding Society*, 43 (8), 1974, pp. 17-25.

12. Bouwman, H. J., and Haverhals, J., "Underwater Welding with Covered Electrodes," *Lastechnic*, 37 (12), 1974, pp. 219-226.

13. Kinugawa, J., Fukushima, T., and Fukushima, S., "Development of Shielding Method with Water Jet and Gas in Underwater Plasma Welding," Transactions of National Research Institute for Metals 16 (5), 1974, pp. 19-29.

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Preventing Hydrogen-Induced Cracking After Welding of Pressure Vessel Steels by Use of Low Temperature Postweld Heat Treatments

by J. S. Caplan and E. Landerman

Hydrogen-induced cracking occurs either in the heat-affected zone microstructure or in weld metal when four factors react simultaneously. These factors have been defined as (1) presence of hydrogen, (2) welding stresses, (3) a susceptible microstructure and (4) a low temperature. Hydrogen can become available during welding from base and welding materials and extraneous contaminating matter. Data are presented to show the effects of preheat and postweld heat treatments. These data are principally concerned with the type of steels used for nuclear pressure vessels.

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Friction Welding

by K. K. Wang

Friction welding has emerged as a reliable process for high-production commercial applications, with significant economic and technical advantages. Professor Wang, in this report prepared for the Interpretive Reports Committee of the Welding Research Council, provides an objective view of operating theory, process characteristics, advantages and limitations. Of particular interest is his comparison of friction welding with two principal types of machines, inertial and continuous drive.

Data are included on the weldability of a variety of similar and dissimilar metals and alloys, which show the importance of frictional characteristics and high-temperature ductility. There is an obvious need for further development work on a number of important metal combinations having marginal weldability.

It is the hope of the Interpretive Reports Committee that this document will stimulate further research and development so that this relatively new welding process will achieve its true potential.

The price of *WRC Bulletin 204* is $6.50. Orders should be sent with payment to the Welding Research Council, United Engineering Center, 345 East 47th Street, New York, NY 10017.