A Prediction Diagram For Preventing Hydrogen-Assisted Cracking in Weld Metal

A new concept—Average Cracking Coefficient—is introduced to help predict safe welding conditions to avoid hydrogen-assisted cracking in weld metal

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ABSTRACT. With the new trend towards heavy sections and higher strength structural steels, the problem of hydrogen-assisted cracking (HAC) or cold cracking has increasingly been transferred to the weld metal from the HAZ and must be eliminated.

Since relevant information on weld metal cracking is insufficient, an investigation was carried out into the controlling factors of cold cracking in high strength steels and weld metals.

A weld root bead deposited in a normal Y-groove Tekken testplate* of 19 mm (0.75 in.) thickness was used to study low carbon-manganese structural steel weld metals with basic covered E7018, E10018 and E13018 electrodes, redried and sealed prior to the weld in order to limit the diffusible hydrogen to less than 5 and 5–10 ml/100g of deposited metal.

The diffusible hydrogen in the weld metal was associated with the susceptibility to cold cracking through the relationship with arc energy (heat input) and the degree of weld metal cracking (average cracking coefficient). As a result, it was possible to devise a cracking prediction diagram for high strength weld metals.

The three operating variables were related to produce a triangular diagram capable of indicating safe welding procedures to avoid HAC in the weld metals. Once the diffusible hydrogen content is known, it is possible to establish the minimum arc energy value for avoiding cold cracking—or alternatively, starting with a convenient arc energy, it is possible to predict the critical diffusible hydrogen level.

Variation of the Lehigh restraint cracking test specimen wherein the Tekken specimen is characterized by an oblique root extending downward from the base of a partial V-groove.

Experimental Procedure

Weld Metal Cracking Test

The phenomenon of hydrogen assisted cracking (HAC) is of such practical importance that numerous tests have been developed to study the factors leading to its occurrence and to determine the optimum welding conditions by which it may be prevented (Refs. 6, 7).

The ideal test has never been devised, but depending on the aspect studied a better test may be applied. Analysis of existing HAC tests found that none of the existing tests as a whole was satisfactory for analyzing the susceptibility of HAC in the weld metal (Ref. 8).

In the same work (Ref. 8) it was found that a modified groove in the Tekken test would be appropriate to produce and direct the cracks through the weld metal. Thus both a slotted type specimen and the experience of root cracks in different grooves (Ref. 9) have produced a (symmetrical) Y-groove Tekken test for testing the weld metal for cold cracking.

The plate material used in the cracking test was a low carbon-manganese pipe steel with the chemical composition shown in Table 1. The plate thickness was 19 mm (0.75 in.), and its microstructure was basically tempered martensite.

The test plates were oxygen cut, smoothed by grinding, degreased and assembled as shown in Fig. 1. All test plates were brushed and degreased once more and then immediately put into an oven in order to be prepared for room temperature tests (20–25°C, *i.e.*, 68–77°F).

Welding Procedure

A weld root bead was produced by the SMAW process using three different 4 mm (0.16 in.) diameter basic covered electrodes: AWS E7018, AWS E10018 and AWS 13018. The typical all-weld-metal mechanical properties, conforming to BS 639 are shown in Table 2, while the all-weld-metal chemical analyses are shown in Table 1. All analyses were undertaken by standard spectroscopy.

The control of hydrogen level to below 5 ml H_2/100 g of deposited metal was obtained by redrying the electrodes at 450°C (842°F) for 60 minutes (min.), while hydrogen levels between 5 to 10 ml H_2/100 g of deposited metal were obtained by redrying the electrodes at 250°C (482°F) for 60 min.

Immediately afterwards, all electrodes were sealed in glass tubes. Then from a series of 5 electrodes, one was taken for diffusible hydrogen analysis, according to the British Welding Institute mercury test (Refs. 2, 10).

Using the combination of two typical current values for 4.0 mm (0.16 in.) diameter electrodes and two welding speeds (operator's normal weld speed and the fastest possible to produce a sound

Paper selected as an alternate for the 64th Annual AWS Convention held in Philadelphia, Pennsylvania, during April 24-29, 1983.

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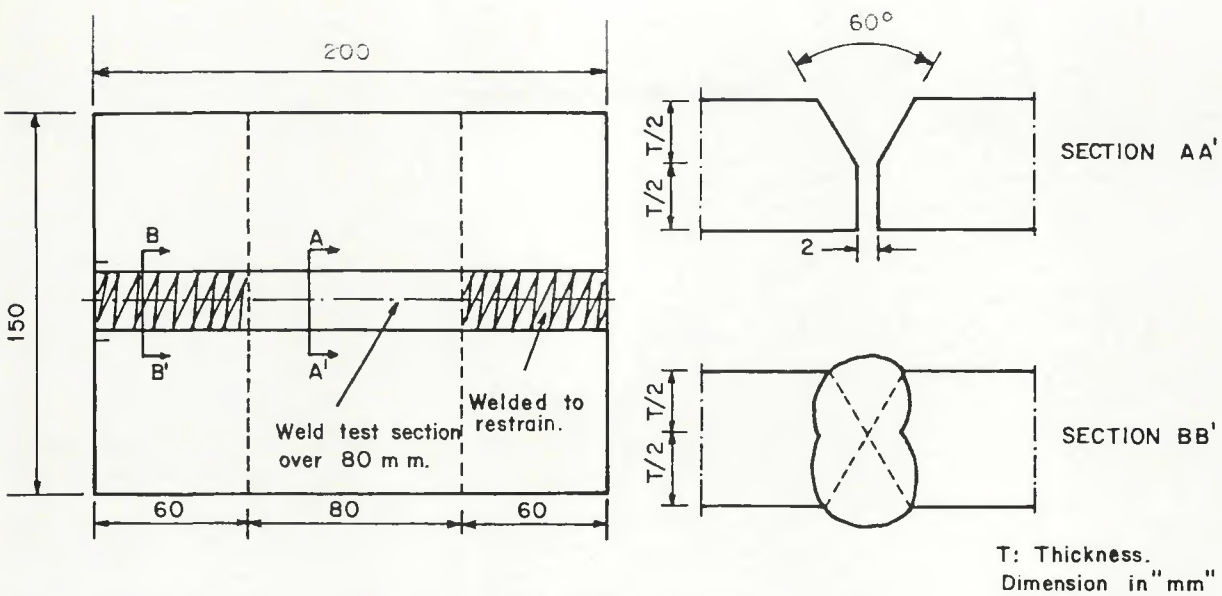

Fig. 1—Diagram of the normal Y-groove Tekken test

weld), each of the E7018, E10018 and E13018 electrodes was tested.

Testing

Experiments with acoustic emission showed that, if HAC occurs in the weld metal, its growth and propagation always occurs within 48 hours (h) in 19 mm (0.75 in.) thick Tekken testplates (Ref. 11). Based on this experience, all sectioning of welds was done after 48 h.

Hardness measurements made with a 5 kg (11 lb) load in a Vickers hardness machine were carried out on sections taken transverse to the weld direction and always facing the section used for metallographic studies. The selected cross sections for testing are shown in Fig. 2.

All cracking and weld metal area measurements were carried out from the magnification of sections taken transverse to the weld direction as shown in Fig. 2. A projection microscope was used to magnify the transverse sections of the weld metal. These sections were recorded on tracing paper at a magnification of ×10. A planimeter was used for weld metal area measurements. The crack length was obtained by careful measuring of a thread which was aligned and pinned along the length of the real crack path as displayed on the tracing.

The degree of cracking susceptibility is usually expressed in terms of cracking percentage as represented in Fig. 3. However, the use of data such as real crack length and weld metal area for a better quantitative approach was found to be preferable. For this purpose the "average cracking coefficient" (ACC) was introduced; this expresses the relationship between real crack length (in mm) and weld metal area (in mm^2), as shown:

$$ACC = \Sigma \frac{\text{crack length}}{\text{weld metal area}} \quad (mm^{-1})$$

Table 1—Base Metal and Electrode All-Weld-Metal Chemical Compositions, Wt-%

	Base metal	E7018	E10018	E13108
C	0.12	0.09	0.06	0.05
S	<0.005	0.008	0.007	0.010
P	0.019	0.016	0.019	0.016
Si	0.21	0.47	0.21	0.14
Mn	1.19	0.87	~2.1	1.54
Ni	0.01	0.02	2.13	2.24
Cr	<0.01	0.03	0.38	0.61
Mo	<0.01	0.01	0.46	0.51
V	0.03	0.02	0.03	0.03
Cu	0.01	0.02	0.02	0.03
B	<0.001	<0.001	<0.001	<0.001
CE[a]	0.33	0.25	0.73	0.69
Pcm[b]	0.19	0.16	0.26	0.24

(a) CE (IIW) = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15 (Ref. 2)
(b) Pcm (Ito-Bessyo) = C + (Mn + Cu + Cr)/20 + Si/30 + Ni/60 + Mo/15 + V/10 + 5B (Ref. 9)

Table 2—Typical All-Weld Metal Mechanical Properties

Mechanical properties	Electrode E7018	E10018	E13018
Yield strength, N/mm^2	463	675	872
Ultimate tensile strength, N/mm^2	510	729	937
Elongation, %	30	–	17
Reduction of area, %	70	–	56
Charpy V-notch at: 20°C, (68°F), J	120	–	46/42/55
50°C, (122°F), J	–	57	44/42/35

Results and Their Interpretation

The Influence of Heat Input

Heat input controls cooling rate, the microstructure, weld hydrogen content, and hence the susceptibility of the weld metal to HAC.

Typical current values suggested by the manufacturer of the E7018, E10018 and E13018 electrodes were 120 to 180 A for the 4.0 mm (0.16 in.) electrode diameter. Thus, 172 A was found to be the closest maximum constant current (CC) in the power supply, while 136 A would be the minimum CC in the power supply to provide real welding current

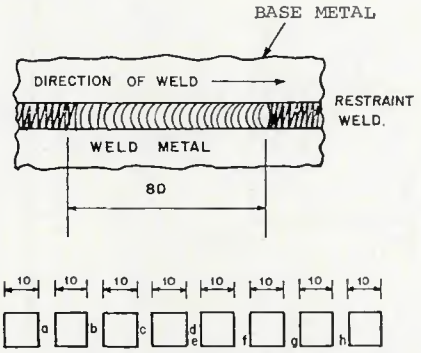

Fig. 2—Selected cross sections for analysis: a, b, c, d, f, g, h—sections for cracking measurements; d—section for Vickers hardness testing; e—section for metallography. Dimensions in mm

values over 120 A.

In order to obtain better accuracy in the reading of current and voltage values, a multichannel ultra-violet (UV) light recorder was used in the welding system for constantly recording welding variables. This was convenient, because it produced current values around 122 and 156 A for the 136 and 172 A set in the power supply. The experimental results for E7018, E10018 and E13018 are presented in Tables 3, 4 and 5, respectively.

With the calculated heat input, two relationships could be obtained. As the heat input increases, the deposited weld bead, which is expressed in terms of average transverse weld metal area, increases for E7018, E10018 and E13018 electrodes as seen in Tables 3, 4 and 5 respectively.

The second relationship with heat input is the degree of weld metal cracking susceptibility; this is expressed in terms of average cracking coefficient. The zero ACC results obtained from E7018 deposits (Table 3) indicate that, at any operational level of heat input, no HAC in the weld metal is formed. However, as the heat input increases when welds are made with E10018 (Table 4) and E13018 (Table 5) electrodes, there is a tendency to decreased ACC values; consequently, the risk of cold cracking decreases as discussed in the following sections.

The Influence of Hydrogen Content

It is well established that one of the basic controlling factors of cold cracking in the weld metal is the hydrogen content. Since the principal source of hydrogen in weld metals is the electrode coating, the manufacturer's recommended redrying temperatures to reduce hydrogen content in basic electrodes were applied. They were 250 and 450°C (482 and 842°F) for 60 min. The results are shown in Table 6.

The ACC results for 4 mm (0.16 in.) diameter E7018 electrodes are presented in Table 3. All results were zero, and no crack was formed at any operational level of heat input, *i.e.,* from 0.5 to 1.7 kJ/mm (12.7 to 43.2 kJ/in.). This result indicates that in 19 mm (0.75 in.) normal Y-groove Tekken test plate with intensity of restraint higher than in fabricated joints, no HAC is produced as the diffusible hydrogen level goes up to 6 ml/100 g of deposited metal.

Extending the experience from other authors (Refs. 2, 9, 12) for predicting safe welding conditions to avoid HAZ cold cracking and also taking into account some subsidiary experiments with as-received E7018 electrodes, it may be concluded that welds made with E7018 electrodes are not susceptible to HAC in the weld metal when the base metal is a low carbon steel.

The E10018 and E13018 electrodes did not present as good a performance, although their crack/noncrack limits

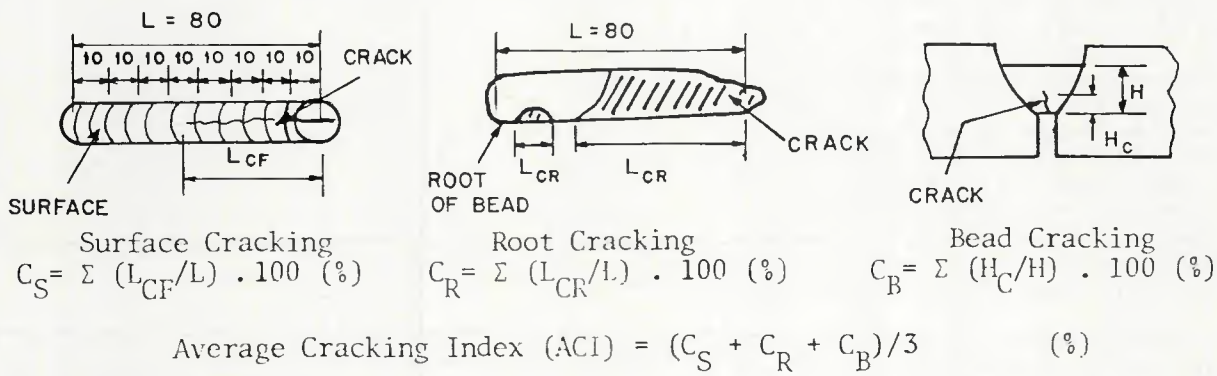

Fig. 3—Weld metal cracking percentage

Table 3—Summary of Results Obtained with E7018 Electrodes

Test number	Condition for 60 min, (°C)	Electric arc characteristics: Current, A	Voltage, V	Welding Speed, mm/s	Heat input, kJ/mm	Microstructures (see Fig. 5), %[a]: F	AF	FC	AC	NA	M	ACI,[b] %	ACC,[c] mm^{-1}
W1.26	250	121	18	4.7	0.5	16.6	54.4	2.8	12.6	13.6	–	0	0
W1.28	250	154	20	4.4	0.7	15.2	61.2	4.1	5.8	13.7	–	0	0
W1.07	250	153	18	2.1	1.3	18.4	41.8	12.8	1.2	25.8	–	0	0
W1.77	250	123	17	1.5	1.4	19.2	51.0	8.2	3.0	18.6	–	0	0
W1.27	450	120	18	3.3	0.7	18.8	50.6	4.4	13.8	12.4	–	0	0
W1.29	450	151	19	3.8	0.8	19.0	50.8	5.2	13.8	11.2	–	0	0
W1.83	450	122	17	1.5	1.3	20.4	48.2	6.8	4.2	20.4	–	0	0
W1.08	450	156	17	1.6	1.7	24.2	38.8	6.2	5.2	25.6	–	0	0

(a) Number of counts—500.
(b) ACI—Average Cracking Index—see text.
(c) ACC—Average Cracking Coefficient—see text.

Table 4—Summary of Results Obtained with E10018 Electrodes

Test number	Condition for 60 min, °C	Electric arc characteristics: Current, A	Voltage, V	Welding Speed, mm/s	Heat input, kJ/mm	Microstructures (see Fig. 5), %[a]: F	AF	FC	AC	NA	M	ACI[b] %	ACC,[c] mm^{-1}
W1.34	250	153	19	4.1	0.7	9.0	–	–	9.6	9.2	72.2	97	0.28
W1.82	250	124	16	1.6	1.3	8.8	–	–	6.8	9.2	75.2	94	0.22
W1.22	250	157	18	1.9	1.5	10.9	–	–	5.6	19.6	64.0	99	0.22
W1.33	450	121	19	3.4	0.7	14.4	–	–	2.0	9.2	74.4	95	0.27
W1.31	450	154	20	3.3	0.9	14.4	–	–	8.4	16.2	61.0	42	0.12
W1.19	450	126	17	1.7	1.2	11.2	–	–	7.4	13.2	68.2	76	0.19
W1.85	450	123	16	1.6	1.3	19.0	–	–	6.8	19.4	54.8	0	0
W1.01	450	161	18	1.5	1.9	14.8	–	–	5.4	24.8	55.0	0	0

(a) Number of counts – 500. (b) ACI – Average Cracking Index – see text. (c) ACC – Average Cracking Coefficient – see text.

could be established. Figure 4A shows the relationship between hydrogen content, arc energy and ACC for E10018 electrodes; Fig. 4B does this for E13018 electrodes.

The Fig. 4 diagrams* were constructed on the assumption that they must be capable of indicating safe weld procedures to avoid HAC in the weld metal. They were constructed using the heat input and ACC values from Tables 4 and 5 for E10018 and E13018 electrodes, respectively; in addition, the corresponding average diffusible hydrogen results from Table 6 were utilized.

The crack/noncrack situation, as known previously from testing, was then indicated as shown.

Once the diffusible hydrogen content is known, it is possible from the diagrams to establish the minimum arc energy value for avoiding HAC. For example, the

**Note: these particular diagrams were obtained for root beads made in a 19 mm (0.75 in.) plate thickness; thus, they may not be completely accurate for other thicknesses.*

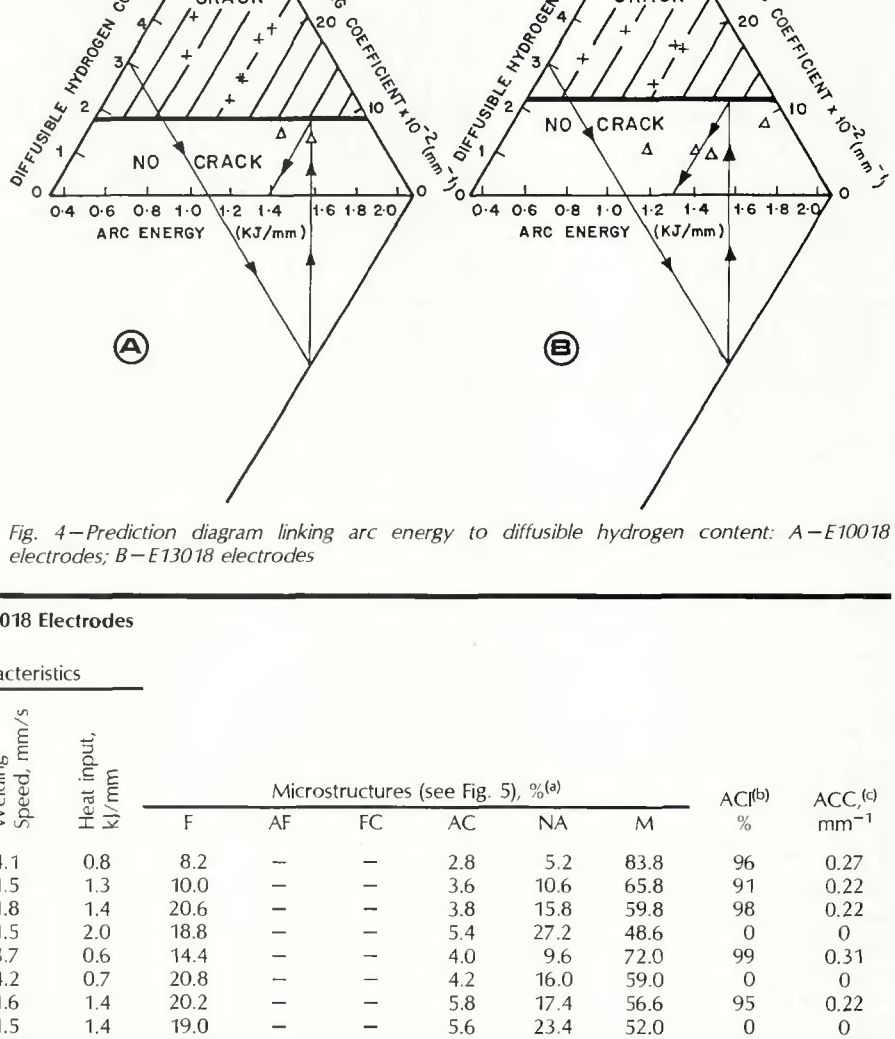

Fig. 4—Prediction diagram linking arc energy to diffusible hydrogen content: A—E10018 electrodes; B—E13018 electrodes

Table 5—Summary of Results Obtained with E13018 Electrodes

Test number	Condition for 60 min, °C	Electric arc characteristics: Current, A	Voltage, V	Welding Speed, mm/s	Heat input, kJ/mm	Microstructures (see Fig. 5), %[a]: F	AF	FC	AC	NA	M	ACI[b] %	ACC,[c] mm^{-1}
W1.38	250	155	20	4.1	0.8	8.2	–	–	2.8	5.2	83.8	96	0.27
W1.81	250	129	16	1.5	1.3	10.0	–	–	3.6	10.6	65.8	91	0.22
W1.23	250	158	17	1.8	1.4	20.6	–	–	3.8	15.8	59.8	98	0.22
W1.96	250	163	18	1.5	2.0	18.8	–	–	5.4	27.2	48.6	0	0
W1.37	450	120	19	3.7	0.6	14.4	–	–	4.0	9.6	72.0	99	0.31
W1.39	450	154	19	4.2	0.7	20.8	–	–	4.2	16.0	59.0	0	0
W1.24	450	129	17	1.6	1.4	20.2	–	–	5.8	17.4	56.6	95	0.22
W1.86	450	121	18	1.5	1.4	19.0	–	–	5.6	23.4	52.0	0	0
W1.02	450	157	18	1.7	1.6	17.4	–	–	8.2	24.8	49.6	0	0

(a) Number of counts – 500.
(b) ACI – Average Cracking Index – see text.
(c) ACC – Average Cracking Coefficient – see text.

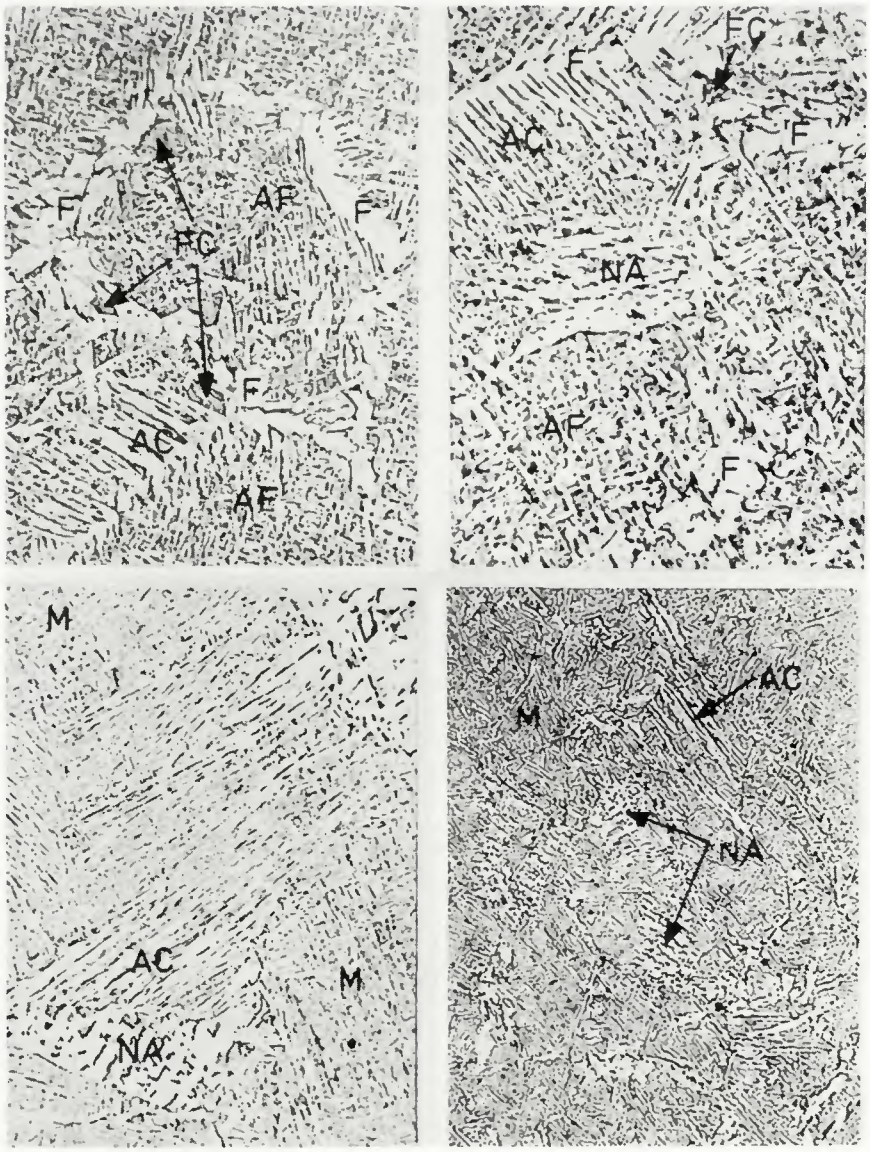

Fig. 5—Proposed as-deposited weld microstructures, showing the classification for various microstructural constituents: F—primary ferrite; AF—acicular ferrite; FC—ferrite-carbide aggregate; AC—ferrite with aligned M-A-C; NA—ferrite with non-aligned M-A-C; M—martensite. 2% nital etch. X500 (reduced 10% on reproduction)

arrows in Fig. 4 show the steps (starting with 3.0 ml/100 g diffusible hydrogen content) that demonstrate that 1.4 and 1.3 kJ/mm (35.6 and 33 kJ/in.) are the minimum arc energies necessary to avoid HAC in the weld metal for welds deposited with E10018 and E13018 electrodes, respectively. The diagrams can, of course, be traversed in the opposite direction, starting with a convenient arc energy and obtaining the critical hydrogen level.

From the diagrams in Fig. 4, it can be concluded that the E10018 electrodes are more prone to HAC than the E13018 electrodes. Moreover, the degree of cracking susceptibility expressed in terms of ACC was found to be much more representative than ACI (see Tables 4 and 5), since the latter describes cracking percentage but does not describe the actual amount of cracking.

The Influence of Microstructures

The weld metal deposit may contain several microstructures that are dependent on the chemical composition of the electrodes and cooling rates of the weld metal.

Six categories of constituents were used to describe the as-deposited weld microstructure, visible under light microscopy, as exemplified in Fig. 5. This convenient scheme is based on the proposals of Davey (Ref. 13) and Abson *et al.* (Ref. 14). These constituents are: primary ferrite, acicular ferrite, ferrite-carbide aggregate, ferrite with M-A-C, (martensite-austenite-carbide), ferrite with non-aligned M-A-C, and martensite.

The quantitative description of these microstructural constituents was determined by the swift point counter; results are shown in Tables 3, 4 and 5 for the E7018, E10018 and E13018 deposits, respectively. Table 3 shows that the major microstructural constituent in E7018 weld metal is acicular ferrite, and that the combinations present do not produce a susceptible microstructure in the weld metal.

Hydrogen content may be correlated with susceptible microstructure in the case of E10018 and E13018 deposits, although no well defined crack/noncrack limit can be established. For the same amount of constituent found in the weld metal, an increase in the amount of diffusible hydrogen induced HAC in the weld metal. This conclusion is achieved by tests W1.23 and W.139 (Table 5) in which the constituents were 21% F + 4% AC + 16% NA + 59% M. Test W1.23 relates to 5.6 ml of diffusible hydrogen per 100 g of deposited metal; here hydrogen cold cracking formed in the weld metal. Meanwhile, a slight decrease in the amount of diffusible hydrogen content to 4.0 ml/100 g (test W1.39) avoided the formation of cold cracking.

The Influence of Composition and Hardness

At the present, there is little information on the optimum alloy combination that will confer good resistance to HAC; this is because the data that exist are often difficult to interpret. The data obtained in the present work do not make it possible to state the influence of a particular element individually; however, increases in Mn, Mo, Cr and Ni and decreases in Si content (see Table 1) were certainly the major alloying changes which increase the risk of cold cracking in the weld metal.

The microstructure produced in any weld deposit is dependent upon the cooling rate and hardenability (Ref. 1), while hardenability is governed by composition, usually expressed in terms of carbon equivalent. Carbon equivalent formulas CE and Pcm, used for HAZ, and extended for weld metals E7018, E10018 and E13018, provided the results shown in Table 1. Remembering that no crack was formed at any welding condition and hydrogen level when deposits were made with E7018 electrodes and that the performance of the E13018 electrodes was slightly better than E10018 electrodes, it may be suggested that in weld metals the risk of HAC declines as the CE and Pcm values are lowered.

It would, of course, be premature to describe which carbon equivalent formula is best, or even if they could be used for an indication of the crack/noncrack

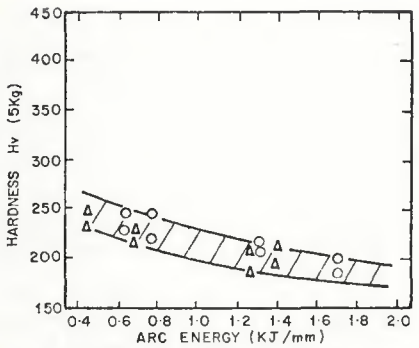

Fig. 6 — Correlation of Vickers hardness in the weld metal with arc energy for E7018 electrodes redried for 60 min at 250 and 450°C (482 and 842°F). Symbols: triangles — 250°C; circles — 450°C; closed symbols — crack; open symbols — no crack

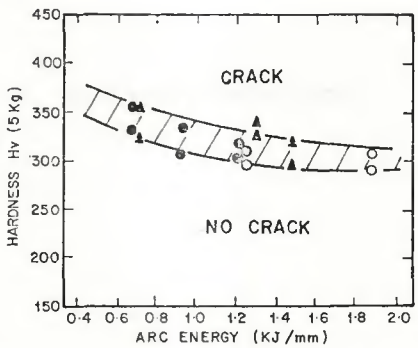

Fig. 7 — Correlation of Vickers hardness in the weld metal with arc energy for E10018 electrodes redried for 60 min at 250 and 450°C (482 and 842°F). Symbols: triangles — 250°C; circles — 450°C; closed symbols — crack; open symbols — no crack

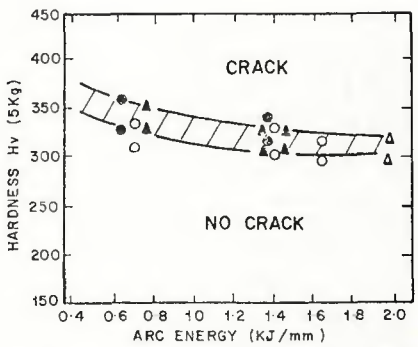

Fig. 8 — Correlation of Vickers hardness in the weld metal with arc energy for E13018 electrodes redried for 60 min at 250 and 450°C (482 and 842°F). Symbols: triangles — 250°C; circles — 450°C; closed symbols — crack; open symbols — no crack

limit in the weld metals (a noncrack situation exists when no cracking was measured in the weld metal or HAZ, and a crack situation exists when even a very small crack was measured). The use of a large number of electrodes with different chemical compositions and CE-Pcm values should be tried and is strongly suggested for further studies on avoidance of HAC in the weld metal.

The susceptibility to cold cracking in the HAZ is very often related to hardness or hardenability, which in turn is frequently used to assess weldability. In general terms, it is accepted that the risk of cold cracking in the HAZ decreases as the hardness and alloy content decreases (Ref. 1).

In the case of weld metals, hardness can be related to the arc energy to assess weldability. This led to construction of the graphs in Figs. 6, 7 and 8 for E7018, E10018 and E13018 deposits, respectively. As shown, there is a tendency for hardness to decrease as the heat input increases.

The decrease in the weld metal hardness deposited with E7018 electrodes may be associated with the increase in the amount of primary ferrite (mainly proeutectoid ferrite), which is very soft and inherently brittle. Meanwhile, the decrease in weld metal hardness deposited with E10018 and E13018 electrodes may be associated mainly with the decrease in the amount of martensite; this is, of course, undesirable when present in large amounts.

The graphs found in Figs. 6-8 can also indicate the critical hardness value for avoiding cracking for different levels of diffusible hydrogen in the weld metal (see Table 6). Although the E10018 electrodes were more prone to cold cracking than the E13018 electrodes, the critical hardness value is approximately the same in both cases and can be defined as 300 Hv. Thus weld metals with diffusible hydrogen contents up to 7 ml/100 g of deposited metal, are likely to have HAC if their hardness goes over 300 Hv (load of 5 kg, *i.e.*, 11 lb).

Conclusions

The effects of hydrogen-assisted cracking on weld metals were evaluated by hydrogen level, hardness, welding process variables and weld cracking index studies. The following conclusions were reached:

1. Heat input can be related to diffusible hydrogen content through the new average cracking coefficient (ACC), which involves a triangular diagram for predicting a safe welding condition to avoid HAC in weld metal.

2. The welds deposited with a type of E7018 electrode were not prone to HAC, providing their diffusible hydrogen content is below 10 ml/100 g of deposited metal; however, welds made with E10018 and E13018 electrodes exhibited cold cracking even at levels below 5 ml/100 g of deposited metal, although their cracking limit is easily obtained from the prediction triangle diagram.

3. From the prediction triangle diagram, it can be shown that the E10018

Table 6—Diffusible Hydrogen Testing Results

Electrode	Welding current, A	Length of electrode used, mm[a]	Time taken to deposit bead s	ml H_2/100 g Weld Metal I	II	Mean
Electrodes redried at 250°C for 60 min:						
E7018	136	100	33.0	5.31	5.34	5.32
E7018	172	110	32.5	4.64	4.28	4.46
E10018	136	140	45.0	5.84	4.87	5.36
E10018	172	140	39.0	8.62	7.63	8.12
E13018	136	145	39.4	4.25	4.43	4.34
E13018	172	145	36.8	5.53	5.59	5.56
Electrodes redried at 450°C for 60 min:						
E7018	136	145	44.2	4.47	4.30	4.38
E7018	172	145	37.4	3.33	3.70	3.52
E10018	136	145	44.8	3.04	3.65	3.34
E10018	172	145	36.2	4.44	6.39	5.42
E13018	136	145	42.0	2.71	2.57	2.64
E13018	172	145	36.2	4.26	3.74	4.00

(a) 1 in. = 25.4 mm.

electrodes used in this diagram are more prone to HAC in the weld metal than the E13018 electrodes.

4. If the E10018 and E13018 weld deposits are described in terms of hardness, 300 Hardness Vickers (load of 5 kg, *i.e.*, 11 lb) is the critical hardness value for avoiding HAC in the weld metal, providing the diffusible hydrogen is below 5 ml/100 g of deposited metal.

5. A significant conclusion of this work is that weld metal HAC is governed by similar rules to those which govern HAZ cold cracking, although new approaches to the avoidance of this problem were obtained.

Acknowledgment

The authors are grateful for the financial support of this work by Federal University of São Carlos, São Paulo, Brazil, and also the Brazilian CNPq-STI/MIC.

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WRC Bulletin 284
April, 1983

The External Pressure Collapse Tests of Tubes

by E. Tschoepe and J. R. Maison

An experimental program was performed to confirm or refute the applicability of Figure UG-31 in Section VIII, Division 1 of the ASME Boiler and Pressure Vessel Code to the design of tubes under external pressure. Commercially available tubes were subjected to external pressure until collapse occurred. The data generated indicates the current ASME design rules for tubes under external pressure are suitable for continued application.

Publication of this report was sponsored by the Subcommittee on Shells of the Pressure Vessel Research Committee of the Welding Research Council.

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WRC Bulletin 287
September, 1983

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