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The Welding of Structural Steels without Preheat

A program was initiated to evaluate whether current guidelines for preheat should apply to low hardenability steels

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ABSTRACT. As a result of recent steel making trends toward low hardenability thermomechanically controlled processed (TMCP) steels and the development of lower hydrogen-potential welding consumables, the possibility of welding even thick-section structural steels without preheat is becoming more feasible. Current British guidelines for very low-hydrogen-potential consumables that deposit less than 5 mL H_2/100 g deposited weld metal (Scale D consumables according to BS 5135) are largely based on cracking data obtained mostly on high-carbon equivalent steels. A program was therefore conducted at TWI to assess the validity of the current guidelines when applied to low hardenability steels.

In general, good agreement was observed between the HAZ cracking behavior and that predicted by the TWI nomograms. Steels of low-carbon equivalent were successfully welded using the shielded metal arc welding (SMAW) and flux cored arc welding (FCAW) processes without the application of preheat using low-hydrogen, Scale D consumables. In most cases, the present TWI nomograms correctly predicted cracking behavior, although the deleterious effect of low sulfur on cracking tendency was noted when welding some steels. The use of very low-hydrogen consumables is to be encouraged since, in conjunction with low-carbon equivalent steels, they can reduce the requirement for preheat to avoid HAZ hydrogen cracking and, therefore, reduce fabrication costs. The TWI nomograms provide a good basis for the derivation of procedures for such consumables.

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Introduction

A comprehensive scheme for predicting statistically based, safe welding procedures for structural steels was first published in 1970 (Ref. 1). Industry is now familiar with the nomograms that were developed from this work and are presented in BS 5135: 1984 (Ref. 2). Such nomograms enable the prediction of suitable safe welding conditions for the avoidance of heat-affected-zone (HAZ) cracking in carbon and C-Mn steels. Based on practical experience, these nomograms have been updated and modified since their first introduction in 1972 (Ref. 3), notably by the introduction of a revised second edition of the TWI publication *Welding Steels without Hydrogen Cracking* (Ref. 4) and the proposed pr EN 1011-2 (Ref. 5). Currently, four hydrogen levels are recognized in BS 5135: 1984 (*viz* Scale A through D). To conform to scale D, which represents the lowest weld metal hydrogen content, the hydrogen potential of a given consumable must be less than 5 mL H_2/100 g deposited weld metal. More recently, however, a fifth Scale E level (<3 mL H_2/100 g deposited weld metal) has been proposed for pr EN 1011-2 (Ref. 5). With the emergence of low hardenability thermomechanically controlled processed (TMCP) steels, and the development of lower hydrogen-potential welding consumables, the possibility of welding even thick joints without preheat has arisen. This would obviously lead to a favorable reduction in fabrication costs in a wide variety of situations and industries.

KEY WORDS

Preheat
TMCP
Low Hardenability
Low Hydrogen
SMAW
FCAW
Nomograms
Diffusible Hydrogen

However, at present, few controlled thermal severity (CTS) test cracking data exist at hydrogen levels below the Scale D limit (5 mL hydrogen/100 g deposited weld metal). Indeed, most of the previous tests were performed on older, high-carbon equivalent steels (Ref. 1) and a need exists to extend the data to lower carbon equivalent steels. Therefore, the principal aim of this work was to define quantitative limits on material composition, hydrogen level and weld thermal cycle that would enable preheat above normal ambient to be avoided without inducing HAZ hydrogen cracking.

In addition, some concern has been raised over the necessity to apply preheat to "dry the plate" and eliminate any adverse effects of water that may be present. Practically, moisture of this nature usu-

Table 1 — Compositions of Steel Plates Used for CTS Testing

Plate Identity	Grade of Steel Plate	Element wt-% C	S	P	Si	Mn	Ni	Cr	Mo	V	Cu	Nb	Ti	Al
18433	50	0.18	0.037	0.018	0.45	1.57	0.04	0.02	0.010	0.002	0.060	0.047	<0.002	0.045
18789	50D	0.19	<0.002	0.021	0.28	1.38	0.01	0.02	<0.005	<0.002	0.005	0.024	<0.002	0.047
18704	55	0.05	<0.002	0.012	0.27	1.39	0.80	0.01	<0.005	<0.002	0.940	0.015	0.011	0.021
18457	50E	0.17	0.015	0.010	0.26	1.17	0.01	0.01	0.005	<0.002	0.010	0.063	0.002	0.030
18485	50E	0.08	0.006	0.014	0.40	1.39	0.22	0.06	0.010	0.060	0.230	0.018	0.009	0.030
18859	50D	0.10	0.003	0.015	0.30	1.35	0.005	0.01	0.005	0.002	0.005	0.002	0.005	0.040
18885	50E	0.06	0.004	0.011	0.26	1.28	0.51	0.01	0.005	0.002	0.005	0.021	0.017	0.038

Plate Identity	Grade of Steel Plate	Element wt-% B	Sn	Co	As	Ca	Pb	Zr	O	N	CE_{IIW}
18433	50	<0.0003	0.005	0.01	—	—	—	—	0.0035	0.0076	0.45
18789	50D	—	—	—	—	—	—	—	0.0004	0.0041	0.43
18704	55	<0.0003	0.010	<0.005	<0.005	<0.0003	<0.002	<0.005	0.0020	0.0074	0.40
18457	50E	<0.0003	<0.005	<0.005	0.023	<0.0003	<0.005	<0.005	0.0024	0.0066	0.37
18485	50E	0.0005	<0.005	0.010	<0.005	<0.0003	<0.005	<0.005	0.0009	0.0091	0.37
18859	50D	<0.0003	<0.005	<0.005	<0.005	<0.0003	<0.005	<0.005	0.00086	0.0028	0.33
18885	50E	<0.0003	<0.005	0.010	<0.005	0.0034	<0.005	<0.005	0.0049	0.0047	0.31

Table 2 — Deposited Weld Metal Diffusable Hydrogen Levels for CTS Test Weld Consumables

Consumable Type/ Specification	Drying Conditions Temperature, °C	Time, (h)	Welding Conditions Current, A	Voltage, V	Diffusible Hydrogen Content mL/100 Deposited Metal Final (21 day)	TWI Analysis No.
Medium alloy highly basic flux cored wire AWS E80T5-G/Argoshield 20 gas (18 L/min) flow rate, 20-mm electrode extension	As-received		364	23.2	1.7	H93/6
Moisture-resistant basic coated low-hydrogen (vacuum packed) BS639 E51558 AWS 5.1 E7018-1	As-received		169	21.6	3.3	H92/23
Basic coated low-hydrogen BS639 1986 E51548 (120 2 6H) AWS 5.1-81 E7018	350	2	162	21.2	4.4	H92/22
Basic coated BS639 1986 E51548 (120 2 6H) AWS 5.1-81 E7018	350	2	162	20.7	3.9	H92/21

ally forms as condensation when a cold plate is brought into a warmer fabrication shop. Therefore, the effects of moisture contamination on the propensity for hydrogen cracking was also briefly assessed using a variety of methods to simulate this phenomenon.

The above objectives were met by generating controlled thermal severity (CTS) test data on a range of steels, using consumables with hydrogen levels that conformed to the Scale D level. Tests were performed at ambient temperature both with and without the application of a contaminant such as water.

Experimental Details

Materials and Consumables

In all, seven steels were studied that were representative of old and new steels, and a brief description of each is provided below in order of carbon equivalent.

1) 0.31 CE_{IIW}, 0.06%C, TMCP steel (Grade 50E), TWI identity No.1B885.

2) 0.33 CE_{IIW}, 0.10%C, TMCP steel (Grade 50D), TWI identity No.1B859.

3) 0.37 CE_{IIW}, 0.17%C, microalloyed, normalized C-Mn-Nb steel (Grade 50E), TWI identity No.1B457.

4) 0.37 CE_{IIW}, 0.08%C, microalloyed, normalized, C-Mn-Ni-Cu-Nb-V-Ti, Ca-treated steel (Grade 50E), TWI identity No.1B485.

5) 0.40 CE_{IIW}, 0.05%C, controlled rolled and aged steel (Grade 55), TWI identity No.1B704.

6) 0.43 CE_{IIW}, 0.19%C, low sulfur C-Mn steel, low oxygen content, Al-treated (Grade 50D), TWI identity No.1B789.

7) 0.45 CE_{IIW}, 0.18%C, high sulfur C-Mn steel (Grade 50), TWI identity No.1B433.

Most of the steels were obtained while the now superseded BS 4360 standard was in existence and have been assigned a grade covered by that standard. The steels designated Grade 50 would have had a minimum yield strength typically of around 350 N/mm^2 (~50 ksi), while the Grade 55 would have had a minimum yield strength of around 450 N/mm^2 (~65 ksi). Grades 50D and 50E would be equivalent to Grades S355J2G3 and S355N in BS EN 10025:1993 and BS EN 10113:1993, respectively, while Grade 55 would be similar to S460N.

All CTS tests were conducted using 50-mm (~2-in.) thick plate. The oxygen and nitrogen contents of the steels were determined by inert gas fusion; all other elements were determined using a direct reading optical spectrometer on remelted samples. Grades and compositions are given in Table 1.

Three shielded metal arc (SMAW) electrodes and one flux cored wire (FCAW) were chosen. Details of the consumables, the drying conditions and diffusible weld metal hydrogen levels are given in Table 2. Procedures given in BS 6693: Parts 3 and 5 were followed to determine the deposited weld metal hy-

drogen levels (Refs. 6, 7). Hydrogen was collected at room temperature over mercury. All four consumables conformed to Scale D hydrogen level as defined in BS 5135: 1984.

Welding

All consumables were used in the same condition as employed for the hydrogen analyses. Shielded metal arc welds were produced using an automatic welding system as described by Pedder and Watkinson (Ref. 8). All welds were produced using 4-mm (5/32-in.) diameter electrodes. Welding current and voltage were held essentially constant, and the travel speed was adjusted so that a range of arc energies could be investigated for each plate/consumable combination. For SMAW, 21–24 V and 160–170 A were used such that arc energies of between 0.8 and 1.45 kJ/mm (approximately 20 and 37 kJ/in., respectively) were obtained.

Flux cored arc welds were deposited automatically by fixing the welding gun to an automatic traverse machine usually used for submerged arc welding (SAW). A wire diameter of 1.6 mm (1/16-in.) was used throughout. Approximately 23 V and 320–375 A were employed such that the arc energy was varied between 0.6 and 1.5 kJ/mm (approximately 15 and 38 kJ/in., respectively).

Controlled Thermal Severity Testing

The self-restrained controlled thermal severity (CTS) test block assembly used during this program is described in BS 7363: 1990 (Ref. 9) and is shown in Fig.1. Single-pass welds were deposited in the flat position across the full width of the block in accordance with BS 7363: 1990 (Ref. 9). In total, six faces were examined metallographically for cracking from each test weld. A Vickers hardness survey of the coarse-grained HAZ was carried out on one face taken from each weld using an indenting load of 5 kg. The face showing maximum cracking was chosen for cracked welds, while a face taken from the midlength was used for uncracked welds.

Controlled Thermal Severity Testing with Moisture Contamination

The procedure outlined above was also performed on test blocks whose surfaces were covered in moisture to simulate condensation as may occur when cold plate is brought into a warmer fabrication shop and no preheat is used. Three methods were employed in order to introduce water onto a clean, degreased test block. First, test blocks were placed in a cold refrigerator at 13°C or 6°C (55°F or 43°F) in order to induce the formation of dew on the test block surface when brought into the laboratory. Second, blocks were placed in a freezer at –2°C (–19°F), which resulted in frost formation on the test block. Finally, blocks were placed in a humidity cabinet at approximately 30°C (86°F) and 87% relative humidity. This induced water droplet formation after approximately 45

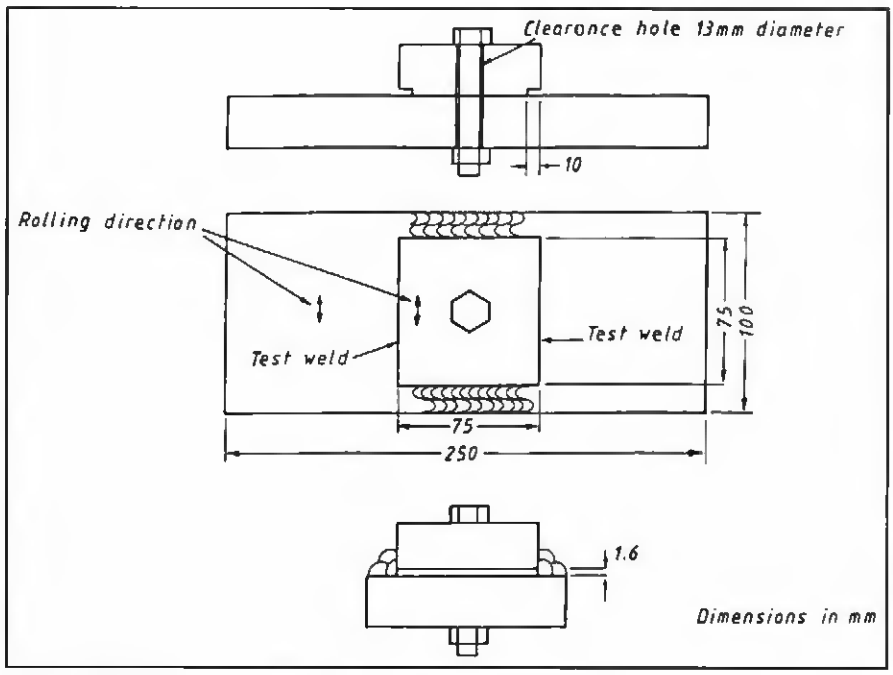

Fig. 1 — Controlled thermal severity (CTS) test block configuration.

Table 3 — Deposited Weld Metal Diffusible Hydrogen Level for Consumable Used for CTS Test Welds with Humidity-Cabinet-Induced Moisture

	Drying Conditions		Welding Conditions		Diffusible Hydrogen Content, mL/100g[a]
Consumable Type/ Specification	Temperature, °C	Time, (h)	Current, A	Voltage, V	Deposited Metal
Basic coated BS639 1986 E5154B (120 2 6 H) AWS 5.1-81 E7018	350	2	165	21.8	5.2, 5.1, 4.3 / 4.9

(a) individual values / mean

Table 4 — CTS Test Weld Data for Plate 1B885 (50-mm thickness, 150-mm combined thickness, $0.31CE_{IIW}$)

		Welding Parameters		Weld Cooling Characteristics			
Weld No.	Diffusible H_2 mL/100 g Deposited Weld Metal	Travel Speed, mm/min	Arc Energy, kJ/mm	$\Delta t_{800-500}$, s	HAZ Hardness HV5[a]	Mean Weld Metal Hardness HV5	HAZ Cracking/No Cracking, C/NC	Proportion of Faces Cracked from a Total of Six
W45	4.4	267	0.83	3.6	239–223 / 233	263	NC	0
W47	4.4	253	0.89	3.2	245–218 / 235	261	NC	0

(a) Presented as max.–min. / average

Table 5 — CTS Test Weld Data for Plate 1B859 (50-mm thickness, 150-mm combined thickness, $0.33CE_{IIW}$)

Weld No.	Diffusible H_2 mL/100 g Deposited Weld Metal	Welding Parameters: Travel Speed, mm/min	Welding Parameters: Arc Energy, kJ/mm	Weld Cooling Characteristics: $\Delta t_{800-500}$, s	HAZ Hardness HV5[a]	Mean Weld Metal Hardness HV5	HAZ Cracking/No Cracking, C/NC	Proportion of Faces Cracked from a Total of Six
W44	4.4	267	0.85	3.1	317–252 / 295	253	NC	0
W46	4.4	240	0.93	--	336 280 / 305	265	NC	0

(a) Presented as max.–min. / average

Table 6 — CTS Test Weld Data for Plate 1B485 (50-mm thickness, 150-mm combined thickness, $0.37CE_{IIW}$)

Weld No.	Diffusible H_2 mL/100 g Deposited Weld Metal	Welding Parameters: Travel Speed, mm/min	Welding Parameters: Arc Energy, kJ/mm	Weld Cooling Characteristics: $\Delta t_{800-500}$, s	HAZ Hardness HV5[a]	Mean Weld Metal Hardness HV5	HAZ Cracking/No Cracking, C/NC	Proportion of Faces Cracked from a Total of Six
W57	4.4	282	0.78	—	362–345 / 350	280	NC	0
W56	4.4	259	0.93	—	367–313 / 347	283	NC	0
W60	1.7	513	0.8	—	362–310 / 340	269	NC	0
W61	1.7	559	0.87	—	358–325 / 340	261	NC	0

(a) Presented as max.–min. / average

Table 7 — CTS Test Weld Data for Plate 1B457 (50-mm thickness, 150-mm combined thickness, $0.37CE_{IIW}$)

Weld No.	Diffusible H_2 mL/100 g Deposited Weld Metal	Welding Parameters: Travel Speed, mm/min	Welding Parameters: Arc Energy, kJ/mm	Weld Cooling Characteristics: $\Delta t_{800-500}$, s	HAZ Hardness HV5[a]	Mean Weld Metal Hardness HV5	HAZ Cracking/No Cracking, C/NC	Proportion of Faces Cracked from a Total of Six
W54	4.4	253	0.9	—	396–325 / 360	291	NC	0
W55	4.4	259	0.9	2.8	376–353 / 364	287	C	4
W63	4.4	246	0.96	2.7	418–349 / 373	291	C	1
W71	4.4	206	1.1	—	391–310 / 369	292	NC	0
W73	4.4	178	1.23	3.3	391–349 / 373	282	C	2
W72	4.4	165	1.32	4.4	412–358 / 385	277	NC	0
W58	1.7	513	0.8	2	396–349 / 370	283	NC	0
W59	1.7	513	0.87	—	401–296 / 350	298	NC	0

(a) Presented as max.–min / average

min of exposure. All test welds were made immediately after the block was removed from the freezer, refrigerator, or humidity cabinet. Two shielded metal arc consumables were used that produced weld metal hydrogen levels of 3.9 mL or 4.4 mL/100 g deposited weld metal when welding was performed under normal, dry conditions (Table 2). A measure of the actual deposited weld metal hydrogen with humidity-cabinet-induced surface moisture was made for the 3.9 mL/100 g deposited weld metal consumable. This was compared to the result obtained under normal, essentially dry, conditions. Two steels were evaluated using this technique, corresponding to 0.45 and 0.33 carbon equivalents.

Results

Hydrogen Levels

The hydrogen levels determined for each consumable are shown in Table 2. All are observed to be within the Scale D level (<5 mL H_2/100 g deposited metal) in BS 5135: 1984.

The diffusible hydrogen present in the weld metal deposited on test blocks covered with humidity-cabinet-induced surface moisture was observed to be 4.9 mL H_2/100 g deposited metal (Table 3). This represents an increase of 1 mL H_2/100 g deposited weld metal in comparison with the previous result obtained under nominally dry conditions. Further assessment and data generation would be required to establish if this is a "real" difference. However, the value of 4.9 mL H_2/100 g still conforms to the Scale D level stipulated in BS 5135: 1984.

CTS Test Data

All CTS test weld results (without moisture contamination) are presented in Tables 4–10 for each individual steel composition. The HAZ cracking behavior is presented in Figs. 2–5. The predicted arc energy for the avoidance of hydrogen cracking, as defined by TWI nomograms for 50-mm (2-in.) thick steel/no preheat/Scale D hydrogen is also shown. (Note that the term "arc energy" describes the energy supplied by the arc, while the term "heat input" refers to the heat input into the steel being welded. The difference between the two terms is accounted for by the "arc efficiency" of the welding process. The arc efficiency of SMAW and FCAW is 80% for the purposes of the TWI scheme). The maximum HAZ hardness is recorded adjacent to each crack/no crack data point.

Cracking was seen to occur in steel 1B789 at a marginally higher arc energy

than that predicted as being safe by the TWI nomogram for a carbon equivalent of 0.43 (Figs. 2 and 5). Steel 1B704 (0.40 CE_{IIW}) showed a single cracked weld at an arc energy assumed to be safe, according to the TWI predictive scheme (Fig. 3), while steel 1B457 produced cracking in three test welds at conditions also predicted to be safe by the nomogram — Fig. 5. However, the other steels behaved in accordance with the TWI predictive scheme. Indeed, for steels 1B885, 1B859 and 1B485, which corresponded to carbon equivalents of 0.31, 0.33 and 0.37, respectively, no HAZ cracking could be produced, even when the lowest practicable arc energies (~0.8 kJ/mm) were employed.

In three steels for which a crack threshold could be established, the critical HAZ hardness at which cracking occurred (defined as the lowest value of maximum hardness in a cracked sample, HV_{crit}) was observed to vary between 376 and 437 HV5 and generally appeared to decrease with lower CE_{IIW} — Fig. 6. However, for steel 1B704 where a single cracked weld was observed, this cracking occurred at a maximum HAZ hardness of 296 HV5.

CTS Test Data with Moisture Contamination

All CTS test weld results with moisture contamination are presented in Tables 11 and 12 for each steel composition examined. The cracking behavior is presented graphically in Fig. 7. The highest arc energy at which cracking was observed under dry conditions is also plotted.

For the steel of lowest carbon equivalent, 0.33 (1B859), no HAZ cracking was observed, even when consumables with a potential hydrogen level of 4.4 mL H_2/100 g (when used in nominally dry conditions) were employed to weld a block covered with frost. The combination of frost, no preheat and use of the highest Scale D consumable (4.4 mL H_2/100 g) constitutes the worst case examined, but cracking was not induced for the lowest practicable arc energy.

The lowest uncracked result for the CTS tests performed on steel 1B433 of 0.43 CE_{IIW} was observed to be at 1.46 kJ/mm. This is ~0.2 kJ/mm higher than that observed for the same steel/consumable combination when welding was performed without contamination and does not represent a significant effect of surface moisture.

Metallographic Observations of Transverse CTS Test Specimens

CTS welds made by the SMAW and FCAW processes showed similar flat or convex bead surface profiles. However, the root geometries for both processes were often different as shown in Fig. 8A and B. The flux cored wire welds invariably showed an acute angle between the weld metal and top plate in the root region of the vertical leg of the CTS test block. This was always an obtuse angle in shielded metal arc welds. When heat-affected-zone cracking was observed, it was always in the vertical leg of the fillet weld and initiated at the root region in the grain-coarsened HAZ.

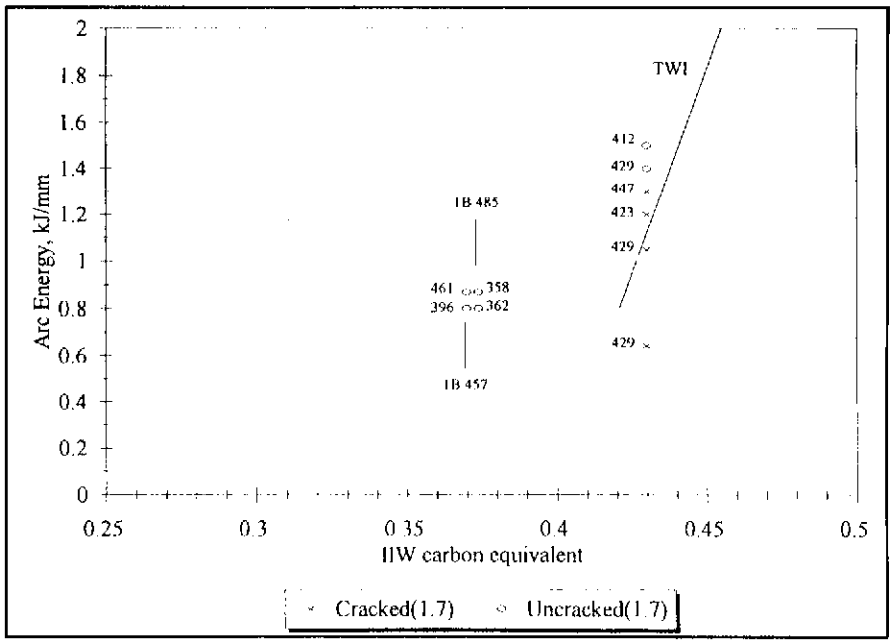

Fig. 2 — Controlled thermal severity test cracking data (150 mm combined thickness, no preheat, FCAW, 1.7 mL H_2/100 g).

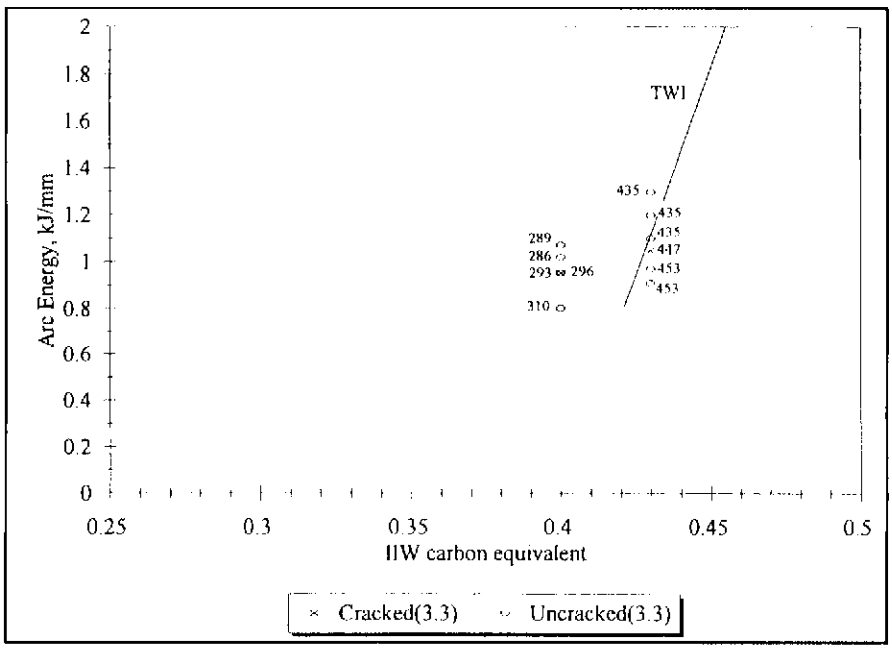

Fig. 3 — Controlled thermal severity test cracking data (150 mm combined thickness, no preheat, SMAW, 3.3 mL H_2/100 g).

Discussion

Comparison of CTS Test Results with TWI Predictive Scheme

The CTS results presented in the plots shown in Figs. 2–5 indicated that, in general, good agreement was observed between the HAZ cracking behavior and that predicted by the TWI nomograms. For the Scale D hydrogen level and a combined thickness of 150 mm, the

Table 8 — CTS Test Weld Data for Plate 18704 (50-mm thickness, 150-mm combined thickness, 0.40CE_{IIW})

Weld No.	Diffusible H_2 mL/100 g Deposited Weld Metal	Welding Parameters: Travel Speed, mm/min	Welding Parameters: Arc Energy, kJ/mm	Weld Cooling Characteristics: $Dt_{800-500}$, s	HAZ Hardness HV5[a]	Mean Weld Metal Hardness HV5	HAZ Cracking/No Cracking, C/NC	Proportion of Faces Cracked from a Total of Six
W53	4.4	255	0.89	—	303–252 280	283	NC	0
W52	4.4	246	0.93	—	303–260 285	265	NC	0
W41	3.9	—	0.9	3.0	299–234 268	258	NC	0
W40	3.9	—	1.0	3.2	280–244 263	266	NC	0
W37	3.9	475	1.01	—	296–262 280	268	NC	0
W30	3.3	260	0.8	2.8	310–262 291	286	NC	0
W28	3.3	234	0.95	3	296–274 288	297	C	4
W26	3.3	223	0.95	—	293–249 268	269	NC	0
W24	3.3	203	1.02	—	286–257 269	257	NC	0
W32	3.3	187	1.07	—	289–241 271	286	NC	0

(a) Presented as max.–min.
average

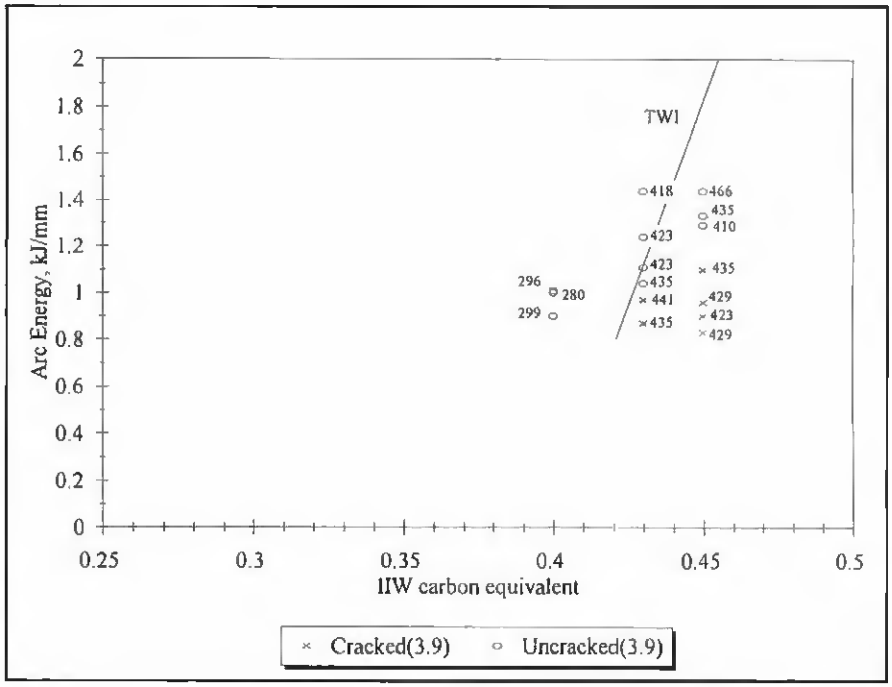

Fig. 4 — Controlled thermal severity test cracking data (150 mm combined thickness, no preheat, SMAW, 3.9 mL H_2/100 g).

scheme predicts HAZ cracking can be avoided without preheat at low arc energies (~0.8 kJ/mm) with steels whose carbon equivalent is less than approximately 0.42. For the majority of situations examined experimentally, this was indeed the case. However, three steels exhibited behavior that required further consideration, and these will be treated individually below.

First, the low-sulfur steel 1B789 (0.43CE_{IIW}, 0.19%C) showed cracking at marginally higher arc energies than predicted when welding was performed with consumables that gave 1.7 mL H_2/100 g deposited weld metal and 4.4 mL H_2/100 g deposited weld metal (Fig. 2 and 5, respectively). However, it should be noted that the cracked result of highest arc energy was only ~0.25 kJ/mm above the TWI "safe" prediction line. To put this in perspective, BS 7363 states that crack/no crack boundaries should preferably be quoted to within 0.3 kJ/mm. Thus, it is questionable whether the behavior of this steel is adequately described by the scheme or not. However, this steel does have a very low sulfur content (<0.002%), and the possible adverse effect of this on the risk of HAZ hydrogen cracking (Ref. 10) has not been taken into account in initially plotting the results in Figs. 2–5. If allowance for a low sulfur effect is taken into account by increasing the carbon equivalent value (Ref. 4 suggests it may be necessary to increase this by 0.03), then the behavior is adequately described.

Another steel that showed apparently anomalous cracking behavior was 1B704 (0.40 CE_{IIW}). Again, this may be considered as a low-sulfur steel for the prediction of weld procedures to avoid HAZ cracking, thus effectively making this a 0.43 CE_{IIW} steel. One incidence of cracking was observed at 0.95 kJ/mm arc energy when welding was performed with the 3.3 mL H_2/100 g deposited weld metal, hydrogen-potential shielded metal arc consumables — Fig. 3. This result is therefore in accordance with the TWI scheme. In addition to the effect of low-sulfur content, however, the high weight percent of nickel and copper (0.80 and 0.94 wt-%, respectively) is also noted in the composition, and this may also have contributed to cracking behavior. Indeed, a steel of this composition was reported by Pargeter and Hart to produce HAZ cracking under conditions not expected based on the TWI nomograms (Ref. 11); it may be that such levels of nickel and copper are not adequately described by the CE_{IIW}.

Finally, the other steel in which HAZ cracking was observed under apparently safe welding conditions was 1B457 (0.37 CE_{IIW}, 0.17 wt-% carbon) — Fig. 5. Notably, cracking was observed only when welding was performed with the consumables that showed the highest hydrogen potential (4.4 mL H_2/100 g deposited weld metal), which still conformed to Scale D. Also, the maximum HAZ hardnesses observed with this steel were significantly higher than those of similar carbon equivalent steels used in this

work. From consideration of the maximum hardness values obtained for a given cooling rate, it would appear that the hardenability of this steel is close to or beyond the upper hound of behavior originally introduced by Bailey (Ref. 3) into the nomogram scheme. Why this should be is not clear from the chemical analysis of the steel, but it should be noted that this steel has an untypically high niobium level for today's structural steels, and the steel also has higher carbon and lower manganese levels than are typical of many of today's structural steels. The increased hardenability associated with niobium-containing steels is accounted for in certain other carbon equivalent formulas used to assesss a given steel's weldability (Refs. 12–14).

To summarize, the present CTS test work for combined thicknesses up to 150 mm has confirmed that, in general, steels with a low-carbon equivalent can indeed be welded successfully in line with TWI guidelines without the application of preheat when low-hydrogen consumables (<5 mL H_2/100 g deposited weld metal) are used. The data obtained in this work consolidate the limited CTS data previously acquired at TWI for identical plate thicknesses and hydrogen levels without preheat (Ref. 15). No shortcomings in the TWI predictive scheme were highlighted by the previous work, although only two steels were investigated. It would be expected that, as the hydrogen level of the consumable is lowered, the cracking tolerance of hard heat-affected zones would increase, *i.e.*, the critical hardness for cracking would be expected to rise. Comparison of the critical hardnesses measured in the present work with those obtained for test welds deposited with Scale B (~12 mL/100 g) shown in Fig. 9 do indicate that this expected trend has been observed (Ref. 16).

Table 9 — CTS Test Weld Data for Plate 1B789 (50-mm thickness, 150-mm combined thickness, 0.43CE_{IIW})

Weld No.	Diffusible H_2 mL/100 g Deposited Weld Metal	Welding Parameters: Travel Speed, mm/min	Welding Parameters: Arc Energy, kJ/mm	Weld Cooling Characteristics: $\Delta t_{800-500}$ s	HAZ Hardness HV5 [a]	Mean Weld Metal Hardness HV5	HAZ Cracking/No Cracking, C/NC	Proportion of Faces Cracked from a Total of Six
W12	4.4	187	1.13	—	429–401 / 416	277	NC	0
W18	4.4	180	1.22	4.4	435–367 / 413	275	C	4
W19	4.4	167	1.3	5.2	423–391 / 412	261	NC	0
W14	4.4	173	1.32	—	418–376 / 402	258	C	2
W21	4.4	156	1.4	4.8	435–401 / 419	258	NC	0
W16	4.4	156	1.45	—	404–353 / 388	255	NC	0
W17	3.9	246	0.87	2.8	435–407 / 419	283	C	5
W15	3.9	234	0.97	—	441–388 / 406	257	C	6
W11	3.9	213	1.04	—	435–423 / 429	281	NC	0
W13	3.9	187	1.11	—	423–396 / 414	281	NC	0
W22	3.9	167	1.24	5	423–274 / 356	263	NC	0
W20	3.9	156	1.44	—	418–268 / 353	236	NC	0
W27	3.3	234	0.91	2.8	453–412 / 431	325	NC	0
W25	3.3	223	0.97		453–362 / 404	280	NC	0
W23	3.3	195	1.05	—	447–386 / 416	313	C	4
W33	3.3	187	1.1	—	435–310 / 378	286	NC	0
W31	3.3	173	1.2	4	435–371 / 398	275	NC	0
W29	3.3	167	1.3	—	435–407 / 421	277	NC	0
W36	1.7	675	0.64	—	429–295 / 349	338	C	6
W35	1.7	491	1.05	—	429–274 / 381	303	C	6
W38	1.7		1.2	4	423–286 / 371	287	C	5
W39	1.7	No data	1.3	4	447–310 / 368	280	C	4
W43	1.7	350	1.4	—	429–353 / 389	264	NC	0
W42	1.7	323	1.5	—	412–317 / 370	289	NC	0

(a) Presented as max.–min. / average

Comparison of SMAW and FCAW Processes

Steel 1B789 produced similar crack/no-crack boundary conditions of ~1.3 kJ/mm for both the flux cored arc welds at 1.7 mL H_2/100 g and the shielded metal arc welds at 4.4 mL H_2/100 g, while some reduction in critical arc energy might reasonably have been expected. As was noticed earlier, the root profiles of the test fillet welds were different for both processes. The acute angle observed between the weld metal and top plate of flux cored arc welds represents an increased local stress concentration in comparison to the same region for shielded metal arc welds — Fig. 8. This may be an explanation for the absence of an improvement in the cracking risk of the lower hydrogen flux cored arc welds relative to the shielded metal arc welds referred to above. Thus, until more data have been generated, these results suggest that some caution should be exercised when developing weld procedures for this process.

CTS Test Results with Moisture Contamination

Turning now to the CTS test welds that were deposited with moisture contamination, the results are plotted in Fig. 7. Testing performed on the 1B433 (0.45 CE_{IIW}) steel showed the presence of water contamination prior to welding only shifted the crack/no-crack threshold from 1.3 kJ/mm to roughly 1.5 kJ/mm for welds deposited using Scale D consumables without preheat. This shift is within the 0.3 kJ/mm tolerance limit for threshold arc energy as defined in BS 7363:

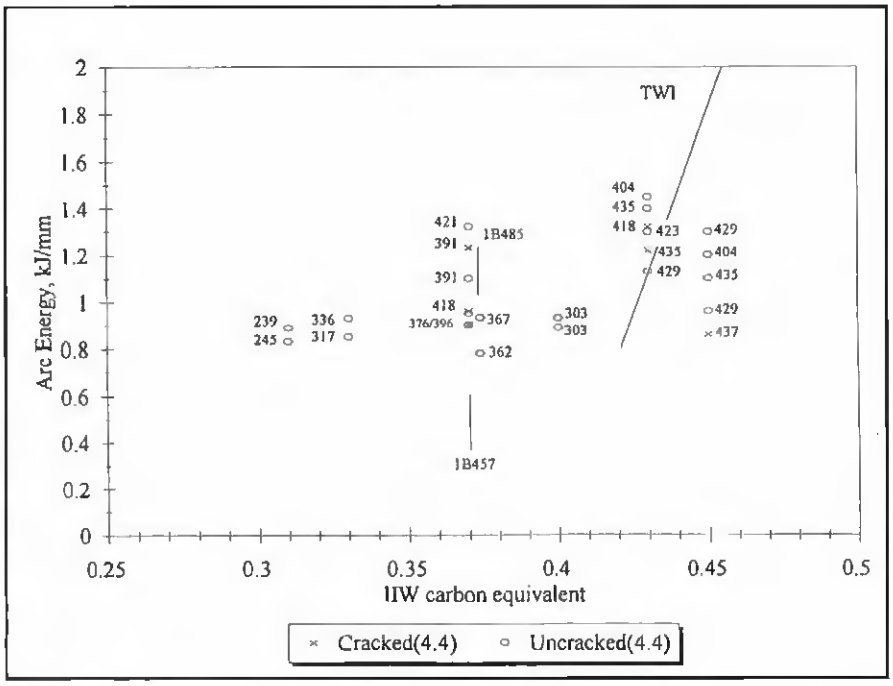

Fig. 5 — Controlled thermal severity test cracking data (150 mm combined thickness, no preheat, SMAW, 4.4 mL H_2/100 g).

Table 10 — CTS Test Weld Data for Plate 18433 (50-mm thickness, 150-mm combined thickness, 0.45CE_{IIW})

Weld No.	Diffusible H_2 mL/100 g Deposited Weld Metal	Welding Parameters: Travel Speed, mm/min	Welding Parameters: Arc Energy, kJ/mm	Weld Cooling Characteristics: $\Delta t_{800-500}$, s	HAZ Hardness HV5[a]	Mean Weld Metal Hardness HV5	HAZ Cracking/No Cracking, C/NC	Proportion of Faces Cracked from a Total of Six
W1	4.4	260	0.86	—	437–387 / 422 (HV10)	302 (HV10)	C	1
W7	4.4	234	0.96	—	429–401 / 419	291	NC	0
W5	4.4	195	1.1	4	435–407 / 423	321	NC	0
W3	4.4	180	1.2	4.8	404–371 / 392	270	NC	0
W9	4.4	167	1.3	—	429–407 / 416	271	NC	0
W2	3.9	260	0.83	3.3	429–389 / 409	295	C	5
W10	3.9	246	0.9	—	423–386 / 411	283	C	5
W8	3.9	234	0.96	—	429–412 / 422	281	C	3
W6	3.9	195	1.1	4	435–412 / 422	284	C	4
W4	3.9	161	1.29	—	410–376 / 388	256	NC	0
W64	3.9	166	1.33	—	435–407 / 423	265	NC	0
W65	3.9	150	1.44	4	466–407 / 429	263	NC	0

(a) Presented as $\frac{\text{max.–min.}}{\text{average}}$

1990. In this context it should be noted that the appreciable quantity of surface water only led to an increase of ~1 mL H_2/100 g in deposited weld metal diffusible hydrogen giving 4.9 mL H_2/100 g, still just meeting Scale D. Further indications of a minimal effect of surface moisture were demonstrated by the uncracked results obtained in steel 1B859 (0.33 CE), which was successfully welded with 0.9 kJ/mm arc energy. Observation of the welding operation revealed that most surface moisture was evaporated by heat from the arc before deposition of weld metal. This could account for the small increase in diffusible weld metal hydrogen observed despite the apparently appreciable surface coverage of water. While it is clearly not good general practice to weld on joint preparations contaminated by moisture or even frost, these results indicate that the concern to use preheat to "dry the plate," even when preheat is not needed for cooling rate control to avoid cracking, may have been unduly highlighted.

Overall Status and Practical Implications

The results obtained in the present work have highlighted the benefits of employing low-hydrogen consumables in order to carry out the welding of structural C-Mn steels without preheat. In addition to using a low-hydrogen potential wire/electrode, the benefit of low-carbon equivalent steels has also been substantiated if welding is to be successfully performed without preheat. The guidelines presented in the TWI nomograms would thus appear to be a good starting point for generating safe welding procedures without preheat that avoid HAZ cracking. The present results have also served to remind that low sulfur levels may increase the risk of HAZ hydrogen cracking and that due consideration of this possibility should be given when devising welding procedures.

The present study has been aimed at validating guidelines for the avoidance of HAZ hydrogen cracking at low hydrogen levels, but due consideration must also be given to avoiding weld metal hydrogen cracking. Certainly for welding C-Mn steels, general experience is that welding procedures devised to avoid HAZ cracking will also avoid weld metal hydrogen cracking, although standards such as BS 5135 (Ref. 2) and pr EN 1011 (Ref. 5) give guidance as to when these general rules may not apply. If very low-hydrogen-level (<5 mL H_2/100 g) consumables are being used to avoid the need for preheat to prevent HAZ hydrogen cracking, this will obviously benefit the avoidance of weld metal hydrogen cracking. Indeed,

Pargeter's data indicate that for C-Mn steel weld metals, the weld metal cracking risk at Scale D (<5 mL H_2/100 g) hydrogen level is low such that preheat is not needed (Ref. 17). For the welding of high-strength steels with alloyed weld metal, however, this is less likely to be the case unless hydrogen levels much less than 5 mL/100 g — perhaps of the order of the proposed Scale E (<3 mL H_2/100 g) — are used (Ref. 5). However, there are currently few data for higher strength steels for a firmer statement to be made.

Summary and Conclusions

A series of CTS tests has been performed on seven C-Mn steels with carbon equivalents 0.31–0.45 CE_{IIW}. Shielded metal arc welds and flux cored arc welds were deposited onto 50-mm-thick plates using consumables that conformed to the Scale D hydrogen level. An assessment of the HAZ cracking behavior has been made and compared to previous relevant data, in particular to predictive nomograms developed at TWI. In addition, further CTS testing was performed using identical materials with test blocks that were covered with various degrees of moisture. The following conclusions were derived from the work:

1) Heat-affected-zone hydrogen cracking can be avoided in some steels with a low carbon equivalent when welded at combined thicknesses of up to 150 mm (6 in.) without preheat using very low-hydrogen consumables, *i.e.*, giving <5 mL H_2/100 g deposited weld.

2) The HAZ cracking behavior at very low consumable hydrogen levels (<5 ml. H_2/100 g) of a range of old and modern C-Mn steels was found to be generally satisfactorily described by the TWI predictive scheme, although recognition of the adverse effects of low sulfur level needed to be taken into account.

3) The presence of surface moisture on CTS test blocks just before welding was found to have little or no effect on the risk of HAZ cracking, in agreement with little or no effect on measured weld hydrogen level. However, this does not negate the need to follow general good practice in respect of cleanliness and freedom from moisture on weld preparations.

4) Limited tests with a very low (1.7 mL H_2/100 g) hydrogen flux cored arc weld showed no reduction in the risk of cracking compared to tests made with an SMAW consumable giving 4.4 mL H_2/100 g. This may be due to a more severe root stress concentration observed in the flux cored arc welds. Further testing is needed to establish if the behavior of flux cored arc welds is significantly different than that of shielded metal arc welds.

Table 11 — CTS Test Data for Plate 1B859 (50-mm thickness, 150-mm combined thickness, 0.33CE_{IIW}) Welded with Moisture Contamination Using Consumables That Gave 4.4 mL/100 g under Dry Conditions

		Welding Parameters		Weld Cooling Characteristics				
Weld No.	Nature of Moisture Contamination	Travel Speed, mm/min	Arc Energy, kJ/mm	$\Delta t_{800-500}$, s	HAZ Hardness HV5	Mean Weld Metal Hardness HV5	HAZ Cracking/No Cracking, C/NC	Proportion of Faces Cracked from a Total of Six
W48	Dew (13°C)	240	0.9	—	313–289/304	257	NC	0
W49	Dew (13°C)	240	0.93	—	329–285/304	263	NC	0
W50	Dew (6°C)	234	0.9	—	321–282/304	262	NC	0
W51	Frost (–1°C)	240	0.94	2.9	332–265/313	271	NC	0

* Presented as max.–min./average

Table 12 — CTS Test Data for Plate 1B433 (50-mm thickness, 150-mm combined thickness, 0.45CE_{IIW}) Welded with Moisture Contamination Using Consumables That Gave 3.9 mL/100 g under Dry Conditions

		Welding Parameters		Weld Cooling Characteristics				
Weld No.	Nature of Moisture Contamination	Travel Speed, mm/min	Arc Energy, kJ/mm	$\Delta t_{800-500}$, s	HAZ Hardness HV5	Mean Weld Metal Hardness HV5	HAZ Cracking/No Cracking, C/NC	Proportion of Faces Cracked from a Total of Six
W68	Water droplets	192	1.16	—	450–381/420	262	C	2
W67	Water droplets	180	1.25	—	447–371/429	270	C	4
W69	Water droplets	152	1.46	—	429–401/420	273	NC	0
W66	Water droplets	133	1.61	—	429–407/415	256	NC	0

* Presented as max.–min./average

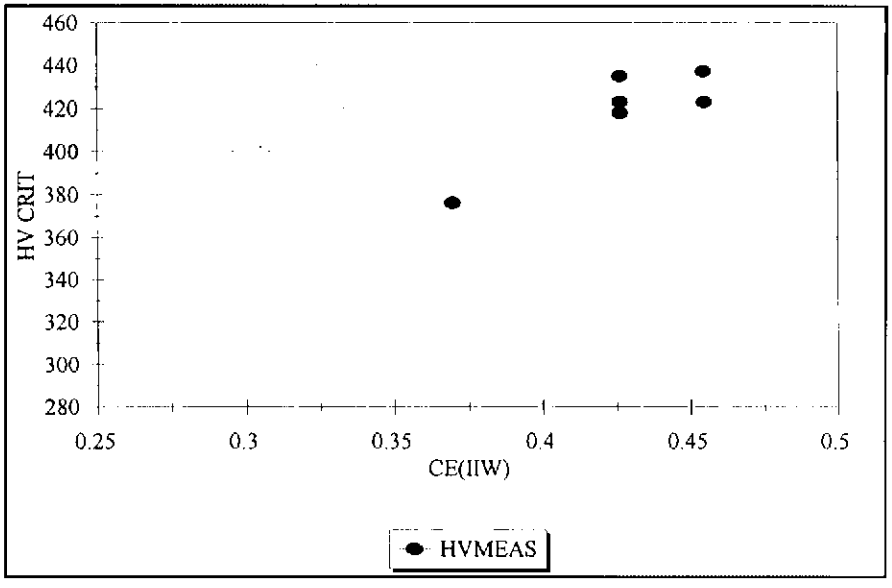

Fig. 6 — Critical hardness to cause cracking from CTS test without preheat.

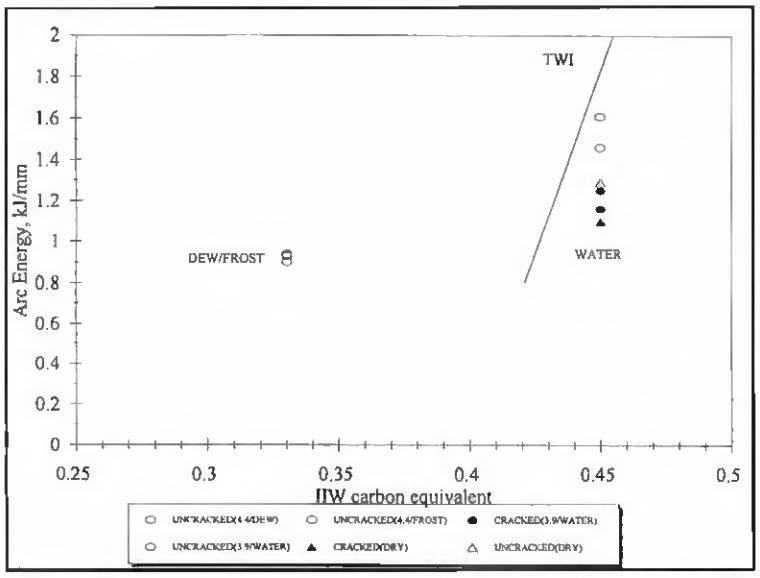

Fig. 7 — Controlled thermal severity test cracking data with moisture contamination (150 mm combined thickness, no preheat, SMAW, Scale D).

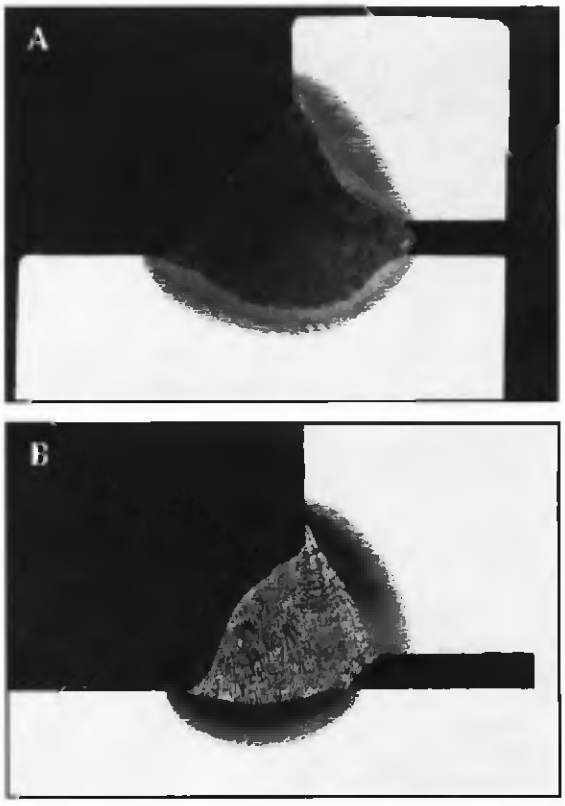

Fig. 8 — Macrographs showing cross sections of CTS welds. A — FCAW, 1.2 kJ/mm arc energy; B — SMAW, 1.2 kJ/mm arc energy.

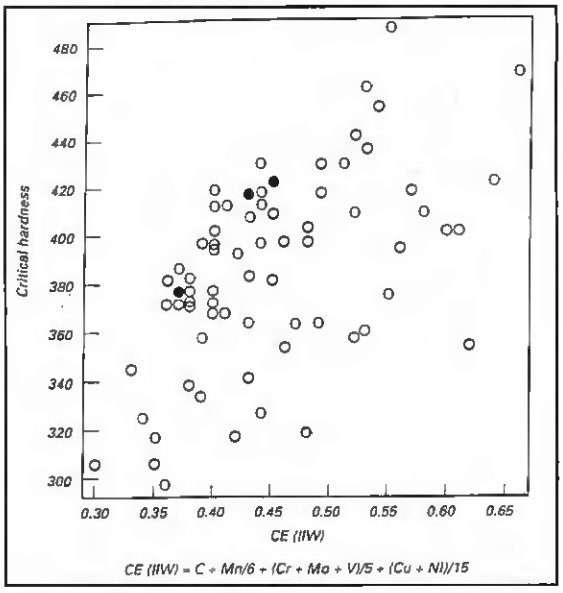

Fig. 9 — Critical hardness vs. CE_{IIW} for CTS test data at Scale B hydrogen level. Filled circles represent data from present work.

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