Hydrogen in Consumable Guide Electroslag Welds—Its Sources and Significance

A threshold level for weld metal hydrogen that is achieved under extreme welding conditions seems to exist for cracks to occur at prior austenite grain boundaries

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ABSTRACT. An investigation into the amount of diffusible hydrogen in consumable guide electroslag weld metal has been performed. A liquid metal extraction technique was developed to provide samples for the hydrogen analysis. The results show that the use of Arcos BV flux gave a slightly larger range of hydrogen values in the electroslag weld metal as compared to Linde 124 or Hobart PF201 flux. The average hydrogen content was not influenced by slag cap height, current type or polarity, but was found to increase significantly by:

1. Applying wet asbestos.
2. Welding under an atmosphere with a high moisture content.
3. Using water-soaked flux.

Samples extracted from various distances from the weld start indicated that diffusible hydrogen has a higher value close to the weld start, but decreases to a relatively constant value with several centimeters.

Intergranular cracks, at prior austenite grain boundaries and along the ferrite veins, were observed in the bottom locations of welds when the average weld metal hydrogen content at the top locations exceeded 3 ml/100 g. Such cracks were observed less frequently at the top location of welds, and only when the hydrogen content was approximately 4 ml/100 g.

The cracks are thought to be hydrogen-induced since fractography and metallography indicated that such cracks did not form at high temperatures, and because a threshold value of hydrogen seems to exist, below which intergranular cracking is not observed. This threshold value was found to decrease under conditions of high external restraint. Otherwise, threshold values of hydrogen were achieved only with extreme welding conditions. A few solidification cracks were also found in the electroslag weld metal, but no relationship between the incidence of intergranular cracking and solidification cracking was found to exist.

Author's Note: The diffusible hydrogen levels quoted in this paper are all measured under mercury, and the data quoted from references employing glycerine as the collecting fluid have been converted to equivalent mercury values (Ref. 15) using the relationship.:

$$H_{Hg} = 1.5H_{gly} + 0.66$$

Introduction

Microcracking and the hydrogen content in electroslag weld metal have been the focus of much attention in the recent past. Microcracks have been found in the weld metal of members in several bridges in the U.S.A. that were initially welded using the consumable guide electroslag welding process. That diffusible hydrogen in the weld could be responsible for such microcracking was inferred from a past experience when the mechanical tests of consumable guide low alloy electroslag weld metal showed a lack of ductility, as indicated in side bend specimens and a low percentage of elongation in tensile specimens. The ductility was restored after a low temperature postheat treatment, a common treatment used to avoid hydrogen cracking in weld metals.

The research effort to study the cause of microcracking in consumable guide electroslag welding or hydrogen content in electroslag weld metal has been minimal. The literature indicates that the variables such as flux moisture content (Ref. 1, 2), atmospheric humidity (Ref. 1-6), flux basicity (Ref. 1, 5-8), slag cap height (Ref. 3, 4), restraint levels (Ref. 1, 2), and electrical input parameters (Ref. 1, 4, 6, 7) can have influential roles on hydrogen pick-up or microcracking behavior in electroslag processes. There is no available literature which considers the variables such as gap width, or the application of wet asbestos (used to prevent slag leakage between the cooling shoes and the plate) as influencing hydrogen pick-up or microcracking behavior in electroslag welding.

The microcracking behavior reported in the literature on the consumable guide electroslag welding process is generally characterized by the number of cracks seen per weld or per unit area (Ref. 1, 3, 8). Extreme conditions have been used in producing these cracks. The number of microcracks or the average length of cracks is then qualitatively related to the severity of hydrogen sources (atmospheric humidity, flux moisture, etc.). These microcracks are characterized by their path, which always follows the prior austenite grain boundary outlined with pro-eutectoid ferrite, and thus are also termed as grain boundary separations. Konkol and Domis (Ref. 1) have looked at microcracks with respect to their solidification structure to determine whether the microcracks are hot cracks. They concluded that since the cracks did not follow the solidification cell boundaries, they are not hot cracks but are hydrogen-induced or cold cracks. Apparently no one has performed fractography on the microcrack surfaces.

Even though there have been a few individual studies on the subject of hydrogen or microcracking in electroslag

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welds, none of the previous studies have systematically studied variables such as flux moisture content, atmospheric humidity, flux basicity, slag cap height, restraint levels, electrical input parameters, use of wet asbestos, or gap width, and investigated their effects on the hydrogen content and cracking behavior. The work to determine the hydrogen content in the weld metal has usually been performed with electroslag cast ingots (Ref. 7), while work using electroslag welding is confined mainly to monitoring cracking behavior. However, there has been little work which relates actual hydrogen data to cracking behavior in electroslag welds. Thus, in the present work, the sources of hydrogen in electroslag welds have been identified by performing a systematic study which includes all the above-mentioned variables. The hydrogen data was then related to the observed cracking behavior in the electroslag weld metal.

Experimental Procedure

Materials

An AWS EH13K-EW welding electrode that was 3.2 mm (⅛ in.) in diameter was used throughout the present study; the base metal was 63.5 mm (2½ in.) thick ASTM Grade A36 steel.

Commercially available fluxes were used. These were Hobart PF201, Arcos BV, and Linde 124. Each of the three fluxes were with the manufacturer's recommended guide tube. Arcos BV flux is reported to be more basic (basicity index approximately 3—Ref. 1) than Linde 124 or Hobart PF201, their basicity indices being close to 1.

Flux Moisture Level

A total of four flux moisture levels was used in the present study, i.e., dry, wet, very wet, and soaking wet flux. The dry flux condition relates to as-received flux that is stored at 200°C (392°F) for 24 hours (h) prior to use. The wet and very wet flux conditions relate to the dry flux that is stored in a humidity chamber set at 60% and 90% relative humidity (RH) respectively for 24 h.

The soaking wet condition, denoting 15 wt% water addition to dry flux, is an overly severe test condition, and is not expected to be encountered in practice. The moisture content of the flux after 24 hours at each level of RH is given in Table 1.

Atmospheric Humidity Levels

Two atmospheric humidity levels,—dry and humid—were initially used in this work. The dry condition denotes the passage of dry synthetic compressed air, supplied from a cylinder onto the weld area during the course of electroslag welding. The humid atmospheric condition was simulated by supplying and circulating compressed air that had been humidified by its passage through three

Table 1—Moisture Level of the Flux After 24 Hours Exposure at Each Level of Relative Humidity

Flux	Relative humidity, %	Moisture, wt %
Arcos BV	60	0.010
Arcos BV	90	0.082
Hobart PF201	60	0.006
Hobart PF201	90	0.025
Linde 124-S	60	0.013
Linde 124-S	90	0.023

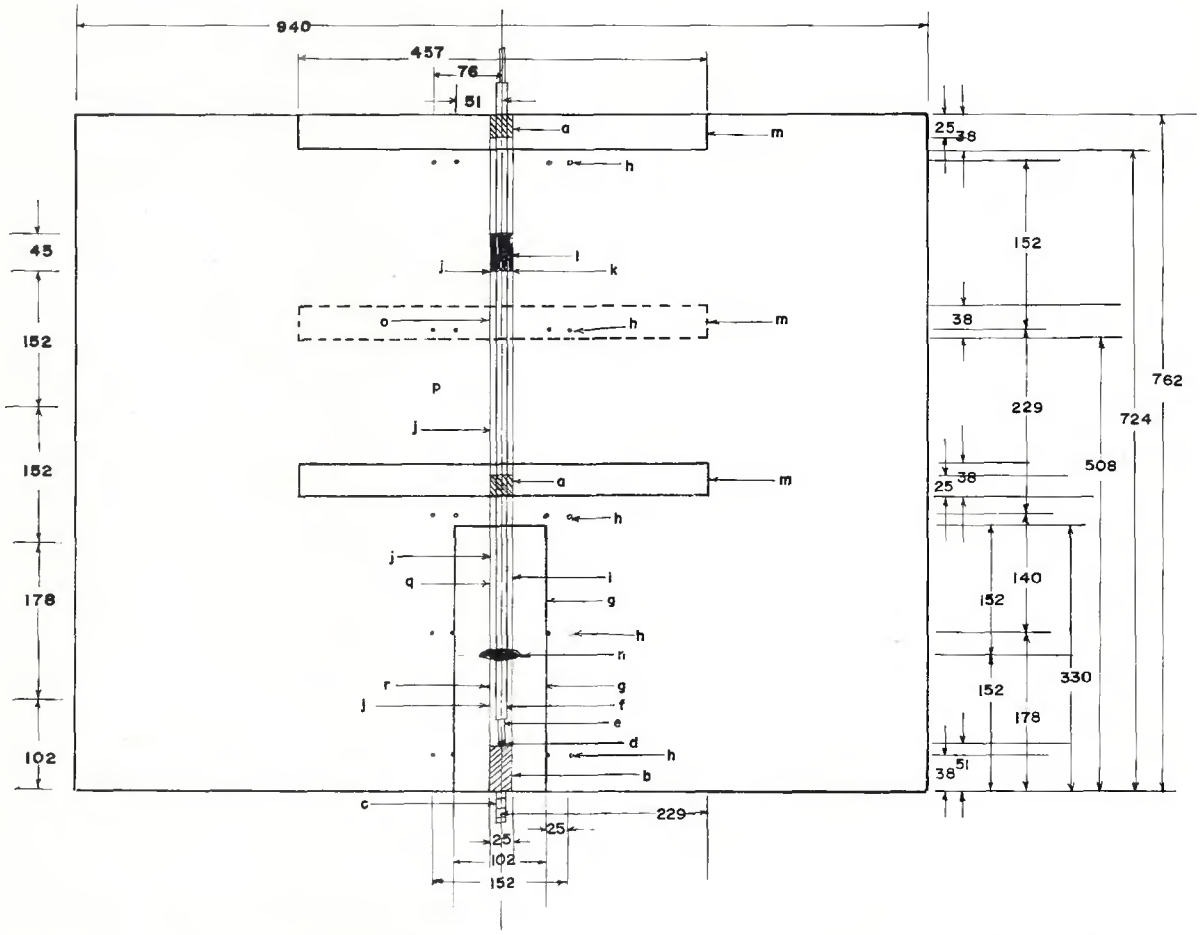

Fig. 1—Schematic set-up for consumable guide electroslag welding showing various locations: (a) spacers; (b) sump; (c) grounding stud; (d) steel wool; (e) electrode wire; (f) consumable guide; (g) cooling shoe; (h) punch marks for restraint measurements; (i) weld gap; (j) locations where hydrogen samples were taken; (k) top of the weld; (l) slag cap; (m) strongbacks; (n) wet asbestos; (o) location of top metallography section; (p) location of tensile test specimen; (q) location of bend test specimen; (r) location of bottom metallography section

Erlenmeyer flasks. The first two flasks contained water at room temperature and 40°C (104°F), respectively; the third empty flask acted as a water trap to prevent the condensed water as well as the escaped water from the second flask from entering the molten slag pool.

For both levels of humidity, the flow rate was maintained constant at 4.5 liters/minute (75 ml/s or 9.5 cfb) using a flow meter. The air passed from the flasks into the weld area via two mild steel tubes which could be raised or lowered into the weld gap so that the air was always blown onto the top surface of the molten slag. Neither of the tubes was insulated. The air was supposed to be saturated with moisture when it passed through water kept at 40°C (104°F). However, the water content of the air dropped due to condensation in the uninsulated connecting tubes and the water trap.

The moisture content of the air was measured by passing the air through two glass tubes filled with a 50-50 wt-% mixture of phosphorus pentoxide and Drierite for a known length of time. The weight gain per unit time was then used as a reference when subsequent experiments on increasing the moisture content of the air were conducted.

A moisture content of 0.0013 g/s was observed when the flow rate of air was 4.5 liters/minute (75 ml/s or 9.5 cfb). The moisture content of the air could be increased to 0.0023 g/s using insulated and shortened connecting tubes and by increasing the air flow rate to 7.5 liters/minute (125 ml/s or 15.9 cfb). In addition, water was added to the third flask and heated to 40°C (104°F). One electroslag weld was performed using this high level of humidity.

Table 2—Conditions Used for Standard Electroslag Weld

Voltage—37 V
Current—600 A (constant potential power source)
Gap—25.4 mm (1 in.)
Polarity—DC electrode positive (reverse polarity)
Flux—Arcos BV-dry
Welding electrode—3.2 mm diameter EH13K-EW
Slag cap height—45 to 51 mm (1.8 to 2.0 in.)
Flow rate of air—4.5 liters/min (75 cm^3/s or 9.5 cfh)
Temperature of first water flask—room temperature
Temperature of second water flask—40°C (104°F)
Temperature of water trap—room temperature (contains little water)
Atmospheric moisture content—0.017 g/liter or 0.079 g/min
Water flow rate—18.26 liters/min (shoe cooling), i.e. 4.8 gallons/min

Electroslag Welding

The dimensions of the welding setup are shown schematically in Fig. 1. Four 25 × 25 × 12.7 mm (1 × 1 × ½ in.) steel spacers were tack-welded to the base metal plates across the joint gap to obtain a 25 mm (1 in.) gap width. A 25.4 × 63.5 × 51 mm (1 × 2½ × 2 in.) piece was cut from the base metal and welded to the bottom of the weld gap to act as a sump for the start of the electroslag weld.

To start the weld, steel wool was placed in contact with the electrode wire and the sump. About 100 g of the flux was poured into the weld gap, and an arc was struck to melt the flux. A constant potential power source was used and except where stated otherwise, the welding parameters were 37 volts (V), 600 amperes (A), and DC electrode positive polarity. The slag cap height was generally maintained in the range of 45 to 50 mm (1.8 to 2.0 in.) by adding 5 g of flux for every 50 mm (2.0 in.) of the weld to make up for the loss of slag between the weld and the cooling shoes, during the course of welding.

The present work is divided into two parts. In Part 1 of the study, the influence of different combinations of the moisture levels, fluxes, and atmospheric humidity levels mentioned earlier, on weld metal hydrogen content and microcracking was investigated. The measurements of weld metal hydrogen content showed that the combination of humid atmosphere and dry Arcos BV flux resulted in the highest hydrogen content in the weld metal. Thus, for welds in Part 2, a standard condition with the parameters given in Table 2 was invoked, and the effect of the following additional variables was examined:

1. 51 mm (2 in.) gap—voltage was increased to 40 V to ensure complete fusion of side walls.
2. Wet asbestos applied between the cooling shoes—in practice, whenever a poor fit-up exists between the cooling shoes or the cooling shoes and the base plate, wet asbestos is applied to plug the gaps and to prevent slag or weld metal leaks.
3. DC negative electrode polarity.
4. Alternating current.
5. Soaking wet flux.
6. Slag cap height—low was 32 mm (1.3 in.) and high was 62.5 mm (2.46 in.).
7. Ultra high humidity atmosphere—water content of the air was 0.0023 g/s.
8. Restraints—three levels of restraints were employed as noted below.

Low restraint level corresponds to the use of spacers and the sump. Medium restraint was obtained by the use of strongbacks (Fig 2), two on one side at heights of approximately 330 and 710 mm (13 and 28 in.) and the third on the other side at a height of 510 mm (20 in.) from the plate bottom—Fig. 1. High restraint level was achieved by the use of a restraining bar (Fig. 2) welded at the top of one side, along with the three strong-

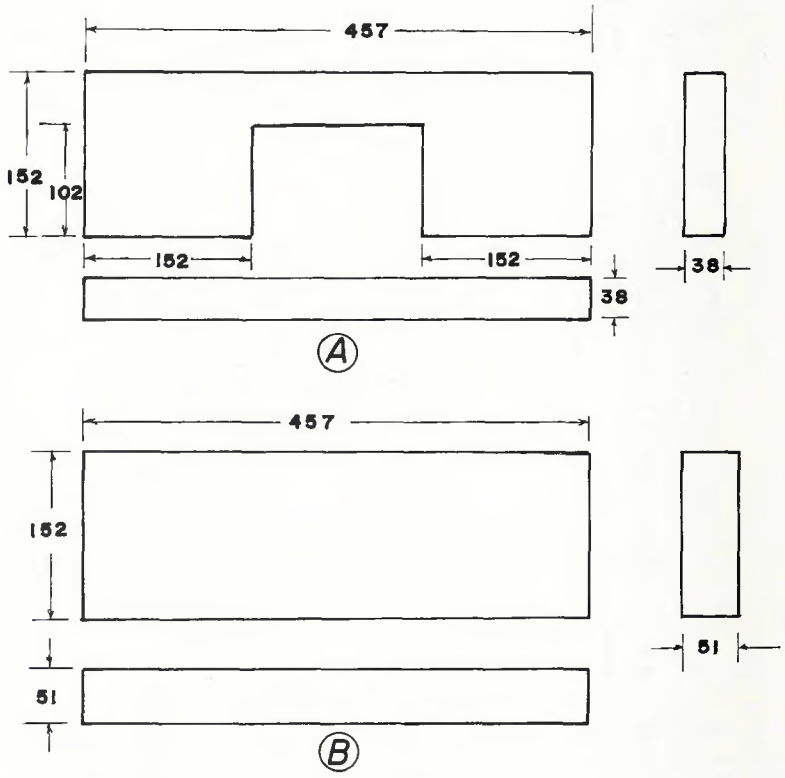

Fig. 2—Dimensions of (A) strongbacks and (B) restraining bar

backs used to obtain the medium restraint levels. The restraint level was qualitatively indicated by the measurements of the inward contraction of four points located on either side of the weld as shown in Fig. 1.

Postweld Test Procedures

Hydrogen Sampling

Individual hydrogen samples were removed by inserting a 7 mm (0.3 in.) I.D. silica pipette into the molten pool during the welding process, and drawing a 100 to 150 mm (3.94 to 5.91 in.) molten sample of the weld. A spring-loaded grease-damped 50 ml syringe acted as the vacuum device to draw and hold the sample in the silica pipette. Once the sample was taken, the silica pipette was broken and crushed in a bucket of water, and the water-quenched sample was removed, washed in alcohol, and placed in a container of dry ice.

The total time for sampling was approximately 15 s for each sample. After all the samples were taken, they were placed in a cooled vice, broken in half, and then transferred to tubes containing mercury, as per ISO 3460 for determining the diffusible hydrogen content (Ref. 9).

From a single weld, four hydrogen samples were taken from three locations: approximately 230, 380, and 530 mm (9.06, 15.0, and 20.9 in.) above the weld start. No samples were taken at the top of the first shoe (50mm − 1.96 in. − above the weld start) initially. However, at the later stages of the present study, it was felt that a hydrogen sample taken at the top of the first shoe might produce a sample of higher hydrogen content than from the other locations, as most of the grain boundary cracks found were situated close to the bottom portion of the weld.

Mechanical Testing

The finished electroslag weld was left in the fixture for 48 h before the weld was sectioned. Weld metal tensile and bend test specimens were machined from T/4 locations of the weld at levels of 90 to 240 mm (3.5 to 9.45 in.) from the top of the weld.

Tensile and bend tests were performed on a Baldwin Universal testing machine according to the ASTM Specification (Ref. 10). The hardness of some welds was measured using a Vickers hardness testing machine with a 10 kg load.

Metallography

One transverse and one longitudinal section were cut out from both the top and bottom of the weld. The sections were next surface ground and dye penetrant checked using Ardrox 985-P2 high sensitivity penetrant with Ardrox 9D6 developer. The cracks were observed using ultraviolet light. The number of cracks and their locations were recorded. These specimens were then etched with 10-15% HNO_3 acid in water to reveal the weld profile.

The specimens containing the cracks were further sectioned in the vicinity of the cracks for microscopic examination. The polished sections were etched with 2% nital to reveal the transformed structure and etched with either Oberhoffer's reagent or Saspa etch (saturated picric acid etch with a wetting reagent − Ref. 11) to reveal the solidification structure. The specimens were then examined with an optical microscope.

Fractography

Further characterization of the cracks was performed by examining the surfaces of some cracks in a Cambridge scanning electron microscope (SEM). The cracks were generally small and before the surface could be examined the cracks had to be opened. This was accomplished by first reducing the thickness of the specimen and then breaking open the cracks with a hammer blow at low temperature. One-half of the crack was then placed in an inhibited acid solution to remove rust or corrosion products.

The inhibited acid solution does not attack the steel, but removes the inclusions. Therefore, to preserve the inclusions (if any) on the cracked surface, certain specimens containing cracks were not etched or cleaned after opening the crack and before being examined. The inclusions which were seen on the crack surface were analyzed qualitatively using a Kevexray x-ray energy analyzer attached to the SEM.

Results

Diffusible Hydrogen Content of the Electroslag Weld

The average room temperature diffusible hydrogen content of the electroslag weld metal (hereafter referred to as weld metal hydrogen content) for all the welds in Parts 1 and 2 of the study is shown in Tables 3 and 4. The values for the average weld metal hydrogen content given in Table 4 are calculated from the results of samples extracted from the three locations mentioned earlier and the individual weld metal hydrogen values for some of the electroslag welds are shown in Table 5.

The electroslag welds performed with the soaking wet flux, the high restraint, and the high humidity atmosphere had a sample extracted from the top of the first shoe, as well as the three standard locations. The effect of the additional sample location on the average weld metal hydrogen content is given in Table 4. Plots of the hydrogen distribution for some of the welds performed in Part 2 of the present study are shown in Fig. 3.

The total and the diffusible hydrogen content of the samples extracted from an electroslag weld performed using the standard conditions is shown in Table 6. The difference between the total and the diffusible hydrogen is within the precision of the diffusible hydrogen measurements. The total hydrogen content of the wire used to deposit the electroslag welds in Part 1 and 2 of this work was between 0.1 and 0.3 ml/100 g, as measured by the subfusion vacuum extraction technique.

Table 3—Diffusible Hydrogen Content of Electroslag Weld Metal—Part 1

Weld no.	Flux type	Flux condition	Atmosphere condition	Slag cap height mm	Average weld metal hydrogen content, ml/100g
1	Arcos BV	Wet	Humid	64	2.1
2	"	Dry	Dry	64	1.9
3	"	Dry	Dry	45	1.0
4	"	Wet	Humid	51	1.3
5	"	Wet	Humid	51	2.0
6	"	Wet	Dry	51	1.2
7	"	Very wet	Dry	51	1.3
8	"	Very wet	Humid	32	2.0
9	"	Dry	Humid	45	2.2
10	"	Very wet	Humid	48	1.2
11	Hobart PF201	Dry	Dry	30	1.5
12	"	Wet	Dry	35	0.7
13	"	Dry	Humid	45	1.3
14	"	Very wet	Dry	45	0.9
15	"	Wet	Humid	35	0.9
16	"	Very wet	Humid	38	0.8
17	Linde 124	Dry	Dry	45	1.0
18	"	Very wet	Humid	51	1.3
19	"	Very wet	Dry	51	1.1
20	"	Dry	Humid	51	1.5

Mechanical Properties

The tensile properties and the results of bend tests for all the welds deposited using the three fluxes are given in Table 7. In Part 1 of the study, welds deposited using Linde 124 flux showed lower percentage of elongations than those deposited when using the other two fluxes. However, one weld incorporating the use of wet asbestos in Part 2 yielded a still lower percentage of elongation, and reduction in area. The fracture surface of the tensile specimen showed some "fish eyes".

Hardness values, HV, measured at different sections of the welds varied between 150 to 205.

Metallography

The limited metallography performed on the welds obtained using Linde 124 flux or Hobart PF201 showed essentially no cracks in the weld metal. However, one weld performed using wet Hobart PF201 flux with a humid atmosphere and a slag cap height of 35 mm (1.38 in) showed a transgranular crack with respect to prior austenite grain boundary.

Some typical microstructures observed in the welds are shown in Fig. 4. All welds consisted of a pro-eutectoid ferrite (polygonal or Widmanstatten side plates) outlining the prior austenite grain boundaries. Within the prior austenite grains, the microstructure consisted of ferrite-carbide aggregate. Pearlite, visible only at high magnifications, was located adjacent to the prior austenite grain boundaries – Figure 4D. The ferrite-carbide aggregate became coarser still when a 51 mm (2 in.) gap was employed.

Weld metal, deposited using Linde 124 flux, also had regions exhibiting a fan-like structure emanating from the grain boundary or within the grain. This microconstituent, presumably upper bainite, could be responsible for the lower percentage of elongations observed in these welds.

The main objective in performing a metallographic examination was to investigate the morphology of the cracks (i.e., intergranular or transgranular with respect to the prior austenite grain) found in the electroslag welds. The number of cracks, their location and type, as determined metallographically for different welding conditions, are given in Table 8.

Approximately 88% of the observed intergranular cracks were located in the bottom sections of the electroslag welds, whereas approximately the same percentage of the less numerous transgranular cracks were observed in the section removed from the top of the weld. The intergranular cracks were observed to be confined to approximately the W/4 to 3W/4 location, where W denotes the width of the weld.

The appearance of some of the intergranular and transgranular cracks after

Table 4—Diffusible Hydrogen Content of Electroslag Weld Metal—Part 2

Weld no.	Variable studied	Average weld metal hydrogen content, ml/100g
9[a]	Standard condition	2.2
21		1.6
22		2.4
23		2.9
24		1.7
5[a]	51 mm gap	2.0
25		3.3
26		3.3
27	Wet asbestos	6.5
28		3.4
29		3.3
30		3.1
31		3.5
32	DC negative electrode polarity	2.9
33		2.6
34	AC	2.2
35		1.9
36	Soaking wet flux	2.8, 5.9[b]
37		3.9, 5.7[b]
38	Low slag cap: 32 mm	2.0
39		1.6
40		2.1
1[a]	High slag cap: 63.5 mm	2.1
2[a]		1.9
41		1.6
42		2.0
43	Standard condition but with restraining bar	2.1, 2.8[b]
44	High humidity atmosphere	3.8, 4.0[b]

[a]Weld from Part 1.
[b]Average of four sample locations (including bottom location of the weld).

Table 5—Diffusible Weld Metal Hydrogen Values at Different Locations in the Electroslag Welds, ml/100 gm

Weld no.	Variables studied	Sample location from bottom of the weld, mm[a]			
		50	230	380	530
21	Standard condition	n/a	1.6	1.2	1.6
22	(dry flux, humid atmos.)	n/a	3.4	2.5	2.9
26	51 mm weld gap	n/a	4.8	2.2	2.9
28	Wet asbestos	n/a	5.0	2.7	2.5
31		n/a	3.8	3.6	3.2
27		n/a	7.5	5.0	n/a
29		n/a	3.3	4.3	2.6
33	DC-ve polarity	n/a	2.7	2.5	2.7
35	AC	n/a	2.1	1.6	2.1
37	Soaking wet flux	16.43	4.8	3.4	3.4
40	Low slag cap (32 mm)	n/a	2.0	1.9	2.3
42	High slag cap (63.5 mm)	n/a	2.3	1.8	1.9
43	Standard condition with restraining bar	4.2	1.9	2.3	n/a
44	Standard condition with high humidity atmosphere	4.4	4.5	2.1	4.1

[a]n/a = not analyzed.

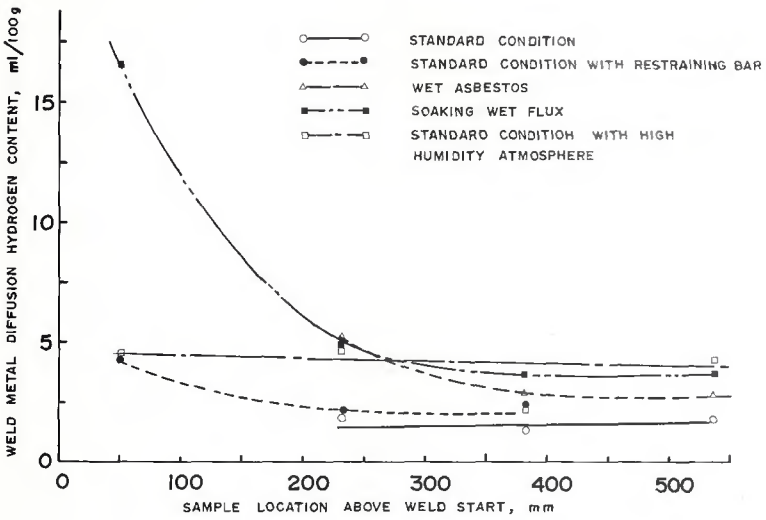

Fig. 3—Weld metal diffusible hydrogen content at different locations of the electroslag welds

Table 6—Total Hydrogen Vs. Room Temperature Diffusible Hydrogen Values in a Standard Electroslag Weld

Sample location	Total hydrogen[a] ml/100g	Room temperature[b] diffusible hydrogen, ml/100g
1. (254 mm above weld start)	1.5	2.0
2. (432 mm above weld start)	2.5	1.8
3. (559 mm above weld start)	1.7	1.5
Average	1.9	1.7

[a]Analyzed by fusion method.
[b]Analyzed by mercury method.

Table 7—Mechanical Properties of the Electroslag Welds Produced Using Different Fluxes in Part 1 and 2

Flux	YS,[a] MPa	UTS,[a] MPa	Elongation (51 mm G.L.)	R.A.,[a] %	Bend test result
Linde 124	365-383	510-545	15-20.5	50-55	Passed
Hobart PF201	330-359	516-539	24-31	59-69	
Arcos BV	318-391	521-590	22-30	47-71	
Arcos BV[b]	307	543	14	18	

[a]YS—yield strength; UTS—ultimate tensile strength; RA—reduction in area.
[b]Only one tensile test which showed "fish-eyes" on the fracture surface.

etching with 2% nital is illustrated in Figs. 5 and 6. The solidification structure in the vicinity of the intergranular and the transgranular cracks is shown in Fig. 7.

Fractography

The surfaces of the intergranular and the transgranular cracks are shown in Fig. 8. The uncleaned surfaces of the cracks showed the presence of inclusions as shown in Figs. 8C and D.

Restraint

As stated earlier, the inward contraction of the base plates was used as a qualitative index of the weld joint restraint since its magnitude is expected to be smaller at higher joint restraints. The data collected from some welds is tabulated in Table 9.

Observations and Discussion

Hydrogen Distribution in Electroslag Welds

Scatter in hydrogen values measured at the top three locations indicated that the measuring accuracy is approximately ±0.5 ml/100 g. There is some evidence that the samples extracted 50 mm (1.97 in.) from the weld start yield higher hydrogen values than those from 230, 380, and 530 mm (9.06, 15.0, and 20.9 in.) from the weld start—Fig. 3 and Table 5.

The present study suggests that the hydrogen content in the weld metal is initially high, then after a short period of time, reduces to a relatively constant value. The initial value is primarily influenced by the amount of moisture present in the surroundings. For example, the excess moisture content of the soaking wet flux available at the weld start provided 15 to 16 ml/100 g of hydrogen

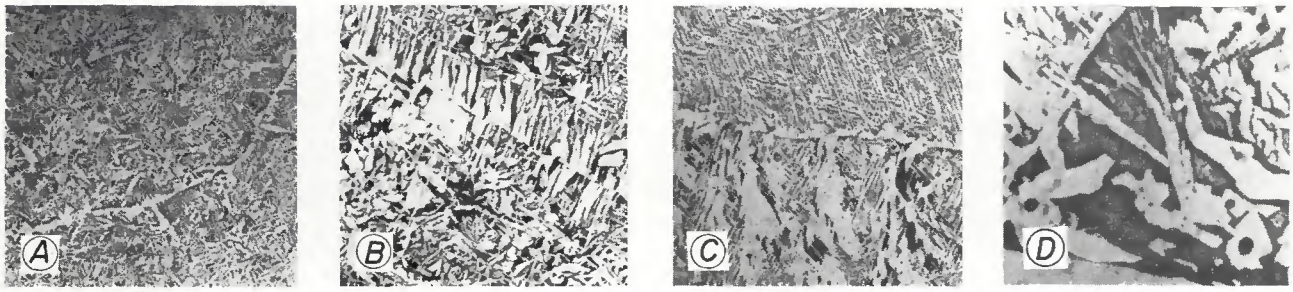

Fig. 4—Microstructures of electroslag welds produced using: A—Arcos BV flux (ESW 3), X100; B—Hobart PF201 flux (ESW 14), X200; C—Linde 124 flux (ESW 19), X100; and D—Hobart PF201 (ESW 12), X800 (A, B, C and D reduced 50% on reproduction).

Table 8—The Type, Number, and Locations of Cracks Observed in the Electroslag Welds in Part 2

Condition	Weld no.	Top of weld		Bottom of weld	
		Type of crack	No. of cracks[a]	Type of crack	No. of cracks[a]
Low Slag Cap	38	Transgranular	1	N.S.[c]	
(32mm)	39	Transgranular	1	None	0
High Slag Cap	41	Transgranular	3	N.S.[c]	
(63.5mm)					
Wet asbestos	27	Transgranular	2		
		Intergranular	17	None	0
Wet asbestos + (low K)[b]	28	None	0	Intergranular	97
Wet asbestos + (med. K)[b]	29	Intergranular	2	Intergranular	25
Wet asbestos + (low K)[b]	30	None	0	Intergranular	38
Wet asbestos + (med. K)[b]	31	Transgranular	5	Intergranular	28
DC -ve	33	Transgranular	5	None	0
Soaking wet	36	None	0	Transgranular	2
flux	37	Transgranular	2	Intergranular	6
High restraint	43	None	0	Intergranular	3
High humidity	44	Intergranular	7	Intergranular	2

[a]No. of cracks in a total weld area of ≃7600 mm².
[b]K—restraint.
[c]N.S.—not sectioned.

compared to 4 to 5 ml/100 g of hydrogen with much less moisture content available with the dry flux, or in the presence of wet asbestos or condensed moisture at the shoes. As the weld progressed, the available moisture was reduced due mainly to evaporation until a quasi-equilibrium state existed between the weld metal hydrogen and its environment to provide a constant value of the hydrogen content.

Similar distributions in hydrogen content have been reported by Paton (Ref. 4) and Pocklington (Ref. 7) for steel ingots cast by the electroslag process. Pocklington reports that the process of hydrogen pickup is related to the reaction between FeO and H or to the amount of FeO in the CaF_2-CaO slag system. As the ingot length increases, the amount of FeO in the slag also increases and hence the hydrogen content decreases.

Pocklington also found no conclusive evidence regarding the form in which hydrogen exists in the weld metal, but assumed the atomic form (H) to suit the model presented. Similar values of hydrogen in welds made using various polarities (AC, DC +ve or −ve) indicate that hydrogen could exist as OH^- or H^+, but again OH^- was selected to suit his model. Mitchell and Smailer (Ref. 12) state that OH^- is extremely stable in fluoride base slags, such as CaF_2-CaO slags used in electroslag remelting, but becomes less stable as the slag basicity is decreased.

The decay in the hydrogen content in the weld metal found in the present work is similar to the hydrogen level decay reported for electroslag remelting where the OH^- ion is felt to be responsible for the weld metal hydrogen pickup. In the present study, however, the decay is felt to occur due to the reduction in available moisture in the surrounding environment. Paton (Ref. 4) and Nishio, *et al.* (Ref. 13) noticed the accumulation of hydrogen along the length of the cast ingots or the

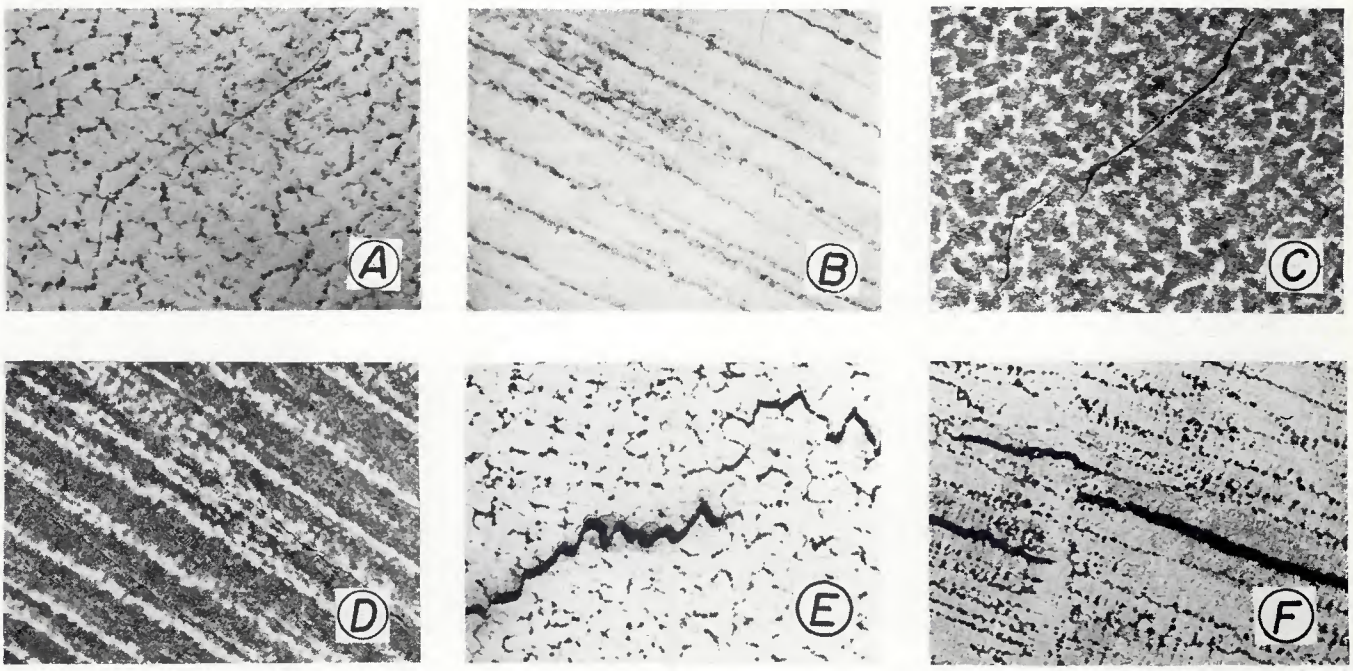

Fig. 5—Microstructures as revealed by 2% nital etch showing two types of cracks. Intergranular cracks: A—longitudinal section of ESW 28, X25; B—same as A, X150, C—transverse section of ESW 31, X150. Transverse cracks: D—transverse section of ESW 31, X25; E—transverse section of ESW 41, X100; F—longitudinal section of ESW 33, X25 (A, B, C, D, E and F reduced 28% on reproduction)

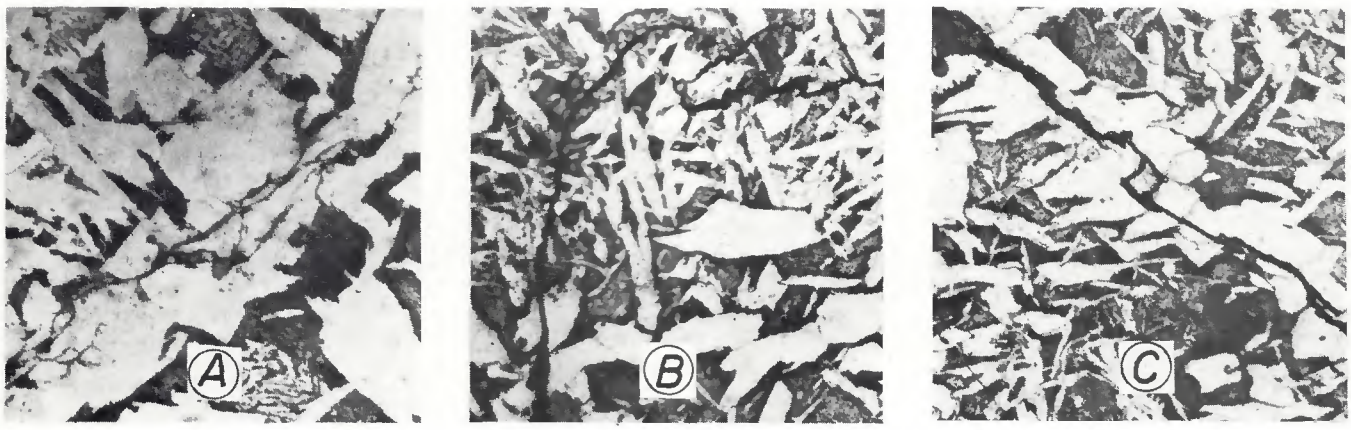

Fig. 6—Intergranular cracks and the cross sections of the electroslag welds showing: A—inclusions at the crack (ESW 44), X800; B and C—sheared ferrite grains and the termination of cracks away from the grain boundary (ESW 30), X500 (A, B and C reduced 28% on reproduction)

welds made by electroslag processes using a shielding of saturated water vapor. Such accumulations of hydrogen were not observed in the present study at any humidity levels of atmosphere.

Zeke, *et al.* (Ref. 14) explained that hydrogen may accumulate, decrease, or remain constant as the length of the cast ingots increases and the exact hydrogen distribution is related to the filler metal/flux combination used in the electroslag process. The choice of flux had no effect on the distribution of hydrogen in the electroslag welds in the present study.

Hydrogen Levels

The evidence gathered in Part 1 suggests that hydrogen pickup in weld metal is virtually the same with either Hobart PF201 or Linde 124 flux; the basicity of both being approximately 1. A slightly larger hydrogen content is evident when Arcos BV flux with basicity 3 is used.

This result is in agreement with that of Nakano, *et al.* (Ref. 5) who report that higher flux basicity increases the hydrogen content in the slag and in the weld metal, and that the diffusible hydrogen levels are mainly controlled by the distribution of hydrogen between slag and metal. However, the degree to which the amount of hydrogen is affected by flux basicity is not comparable since an increase in flux basicity, from 0.42 to 1.33 in Nakano's study, resulted in a substantial increase in hydrogen from 3 ml/100 g to 8 ml/100 g. On the other hand, when the basicity of the flux is increased in the present work from 1 to 3, only a slight increase in hydrogen results, 1 ml/100 g to 2 ml/100 g.

The presence of humid atmosphere or the moisture content of the wet or very wet flux does not result in a significant gain in hydrogen content in the weld metal for any of the three fluxes. This may be due to the small moisture content of the flux or the air.

Part 2 of the present work indicates that hydrogen content in the electroslag

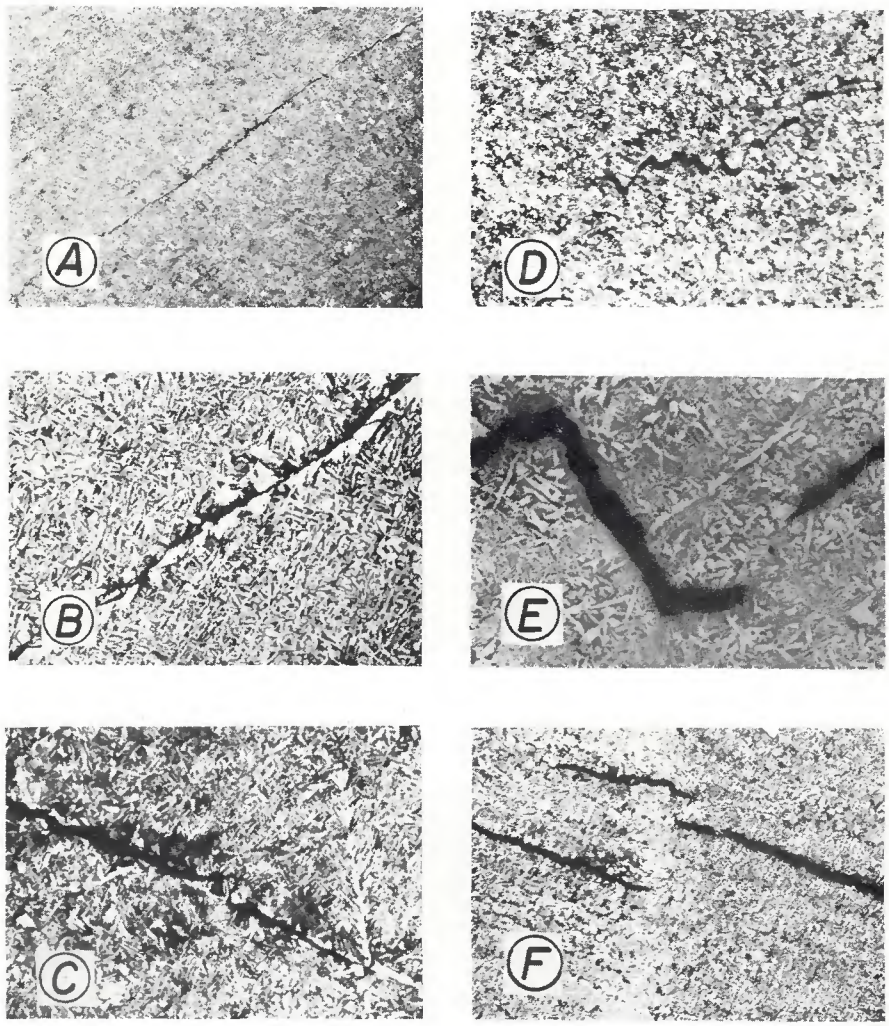

Fig. 7—Solidification structures around cracks, X25 (reduced 28% on reproduction): A—transverse section (ESW 30) intergranular crack, Saspa etch; B—longitudinal section (ESW 30) intergranular crack, Saspa etch; C and D—same as A and B but with Oberhoffer's etch; E—transverse section (ESW 31) transgranular crack, Saspa etch; F—longitudinal section (ESW 33) transgranular crack

weld metal is increased by:

1. The use of high moisture atmosphere.
2. Applying wet asbestos.
3. The use of soaking wet flux.
4. Increasing the gap width.

Electroslag welding in a hot humid environment and applying wet asbestos to prevent slag spillages are common practices which result in an approximate average hydrogen value of 4 ml/100 g, compared to 2 ml/100 g for the standard conditions. Although only one test with a high moisture content in the atmosphere was performed, in the present study the results support investigations by Nishio, *et al.* (Ref. 13) and by Nakano, *et al.* (Ref. 15) wherein the hydrogen content of the weld metal increases with the partial pressure of moisture in the atmosphere.

Nishio, *et al.* (Ref. 13) observed higher weld metal hydrogen contents when some chemicals were used for the prevention of slag spillage during the course of electroslag welding, and related the moisture content in the chemicals to the weld metal hydrogen content. Similarly, in the present study, the use of wet asbestos with its high moisture content led to a much larger range of hydrogen values than the presence of high humidity atmosphere. The importance of properly fitting cooling shoes and the potential hazards of wet asbestos are, therefore, self-evident.

The investigation of hydrogen pickup during electroslag refining by Pocklington (Ref. 7) and electroslag remelting by Forno, *et al.* (Ref. 6) show that hydrogen values can be very high—up to 24 ml/100 g, depending upon atmospheric moisture content, slag system, and starting technique, i.e., solid start vs. liquid start using DC or AC power supplies.

The highest weld metal hydrogen content measured in the present work was 15 to 16 ml/100 g at the start of a weld with soaking wet flux. This drastic increase can be attributed to the unrealistic amount of water present in flux (15%) at the start of the weld—a situation which should never happen in practice. The condition of soaking the flux with water before use to introduce hydrogen in the weld metal, illustrates the extremity one must go to before substantial hydrogen levels are introduced into the weld metal from the flux. Thus, it appears that the flux can be exposed to relatively high humidity environments and not affect the quality of the weld so long as the flux is not exposed to rain.

The increase in gap width also increased the hydrogen content in the weld metal, without increasing the available hydrogen in the weld surroundings, such as flux, atmosphere, or wet asbestos. The increase is most likely due to the increase in the reaction area (either slag-metal or atmosphere slag) which allows more of the available hydrogen to enter the weld metal.

The present study indicates that changing the polarity of the electrode from positive to negative results in a slight increase in the average value of the weld metal hydrogen content. Altering the current type from DC to AC did not affect the average or the maximum value. Contrary to the present observations, Paton (Ref. 4) found that electroslag casting using DC −ve polarity resulted in a reduction of the ingot hydrogen content, as compared to using AC or DC +ve polarity.

The depth of the slag pool or cap did not influence the hydrogen pickup in the weld metal, and this observation is supported by Paton (Ref. 4). Kunihiro and Nakajima (Ref. 3), on the other hand, concluded that lower slag cap heights are accompanied by an increase in propensity to intergranular cracking, and therefore, by an increased hydrogen content.

Cracking Behavior

The transgranular cracks, as viewed under an optical microscope, are larger and traverse many more prior austenitic grains on a transverse section of the weld than the intergranular cracks. The intergranular cracks are relatively thin and tend to be restricted to one or two prior austenite grain boundaries. The transgranular cracks, when the section is etched with a reagent to bring out the solidification structure, become interdendritic and follow the solute rich boundaries (Fig. 7E and F). The intergranular cracks randomly intersect the dendrites when viewed on the transverse and longitudinal sections of the electroslag weld (Fig. 7A to D).

The fracture surface of the transgranular cracks is generally smooth, indicative of a low energy tear, and when viewed at low magnification, the dendritic growth pattern is evident. The fracture surface of the intergranular cracks show a quasi-cleavage surface with evidence of surface fissures and micropores—Fig. 8.

It is obvious from the above description of the transgranular cracks that they occurred at a high temperature and are solidification cracks. It is felt that the intergranular cracks occur at a much lower temperature, below the transformation temperature. Fig 6A and C shows an intergranular crack that is transgranular with respect to the pro-eutectoid polygonal ferrite at the prior austenite grain boundaries suggesting that ferrite grain nucleated and grew before the formation of the cracks.

Cause of Intergranular Cracks

It is well known that weld metal cold cracks are caused by the presence of hydrogen, the formation of a susceptible microstructure, and the development of welding stresses due to internal and external restraint. There is also some evidence in the literature which suggests that welding flaws such as solidification cracks, inclusions, fit-up discontinuities, etc., can nucleate cold cracks by causing stress concentrations.

The electroslag weld metal intergranular cracks occurred when the standard welding conditions were used in conjunction with wet asbestos or soaking wet flux, or high humidity atmosphere or the high restraint level. The initial three conditions increased the average diffusible hydrogen at the top three levels in the electroslag weld metal to above 3 ml/100 g as shown in Fig. 3. This strongly suggests that hydrogen is involved in the incidence of electroslag weld metal inter-

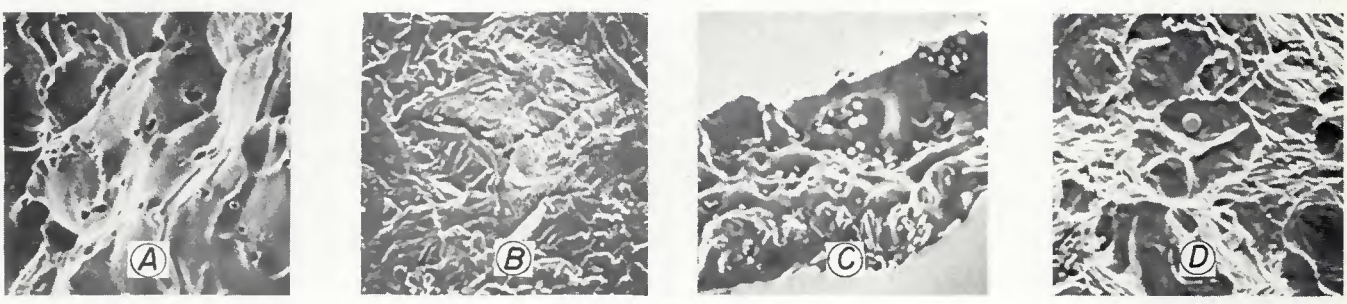

Fig. 8—SEM fractographs: A—transgranular crack (ESW 26), X950; B—intergranular crack (ESW 30), X1000; C—transgranular crack showing inclusions (ESW 40), X850; D—intergranular crack showing inclusions (ESW 44), X1850 (A, B, C, and D reduced 50% on reproduction)

Table 9—Contractions Across the Electroslag Welds, mm[a]

Position above plate bottom, mm[b]	Weld 22		Weld 28		Weld 30		Weld 31		Weld 43	
	102	178	102	178	102	152	102	152	102	152
699	2.39	3.58	4.78	4.11	4.78	4.90	2.77	2.97	1.40	0.97
547	2.39	3.58	4.37	3.58	3.96	3.71	2.77	2.97	3.20	2.79
318	1.60	1.98	3.58	2.67	2.77	1.73	1.98	2.18	2.72	2.69
178	0.79	2.39	1.98	1.40	1.79	1.73	1.79	1.60	1.96	2.03
38	0.20	1.98	1.19	1.22	0.41	1.60	0.58	0.99	0.84	1.04

(a) Welds 22, 28, and 30—low restraint; weld 31—medium restraint; weld 43—high restraint.
(b) 25.4 mm = 1 in.

granular cracking.

Since most of the cracks and higher hydrogen values were seen at the bottom part of the welds, it was not possible to establish unambiguously the minimum hydrogen value needed for their occurrence. However, an average hydrogen value of 3 and 4 ml/100 g for the top three sample locations was required for intergranular cracks to be observed in the bottom and top sections of the welds, respectively—Table 5 and Fig. 9. It may, therefore, be inferred that for the weld metal chemistry and microstructure, and the low restraint conditions employed in the study, the threshold value of hydrogen for intergranular cracks to occur is approximately 4 ml/100 g.

Nakano, *et al.* (Ref. 5) and Nishio, *et al.* (Ref. 13) focused attention mainly on the role of hydrogen in causing electroslag weld metal intergranular cracks. The threshold value for cracking was found to be between 5 and 6 ml/100 g which is higher than the present study's suggested threshold of approximately 4 ml/100 g. The absence of intergranular cracking in the 51 mm (2.0 in.) gap width electroslag welds at hydrogen levels greater than 3 ml/100 g could be due to the slower cooling rate associated with the higher heat input per lineal millimeter used.

The degree of external restraint was varied (Table 9), but no difference in cracking behavior is evident for the electroslag welds under the two lower restraints imposed. Intergranular cracks could be produced for standard condition electroslag welding at hydrogen levels less than 3 ml/100 g only when the restraining bar was incorporated to give qualitatively the highest restraint.

High restraint levels assisting the formation of intergranular cracks have also been reported by Konkol, *et al.* (Ref. 1). The limited hardness results indicate the microstructure in the weld metal and HAZ are not susceptible to cold cracking in the conventional sense since the hardness is generally less than 200 HV even when the weld metal carbon equivalent (CE) is approximately 0.4. No heavy segregation of inclusions or impurities is seen on the surface of the cold cracks. However, the presence of some MnS and MnO inclusions situated in the middle of the cracks suggest that the inclusions may have aided the nucleation of the cold cracks.

No relationship was observed between the incidence of transgranular cracking and the weld metal hydrogen content, thus reinforcing the view that these cracks are indeed solidification cracks although transgranular (solidification) and intergranular (cold) cracks were observed in the same weld. The metallography and fractography did not reveal any association between them, i.e., the solidification cracks did not act as nucleating sites for the cold cracks.

The present work has then shown that hydrogen is the principal factor in causing electroslag welds to crack in the described fashion, and may be aided by the presence of inclusions and high external restraint. The influence of weld metal chemistry, as well as some additional variables, is being examined, and will be the subject of a separate paper.

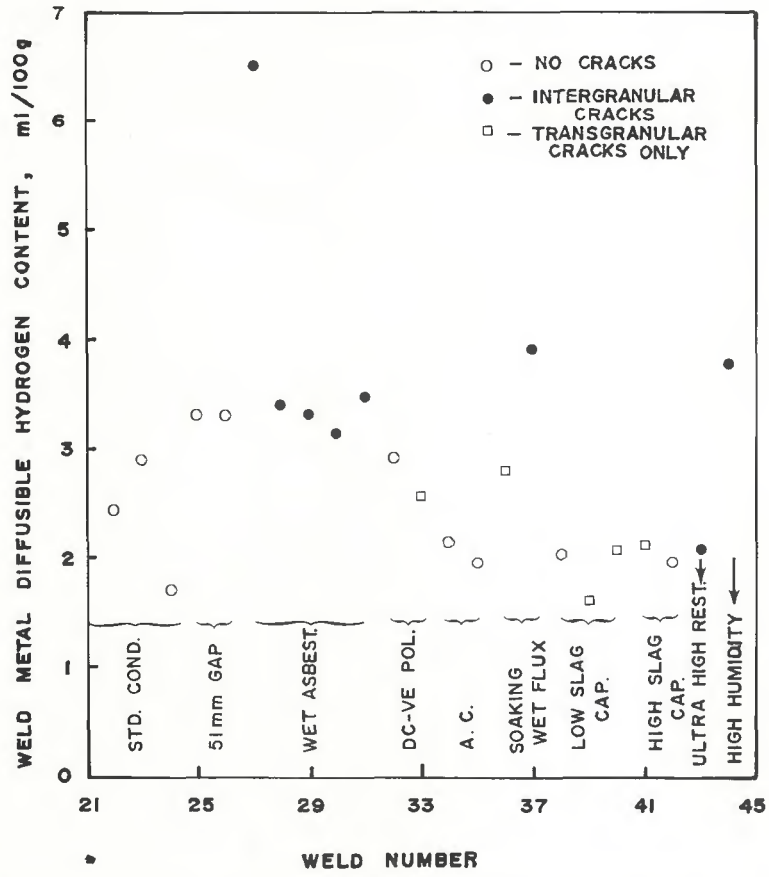

Fig. 9—Plots of weld metal diffusible hydrogen vs. weld number for electroslag welds of Part 2

Summary

1. The use of the Arcos BV flux ($B_I \geq 3$) gave a slightly larger range of hydrogen values in the electroslag weld metal (1 to 2.5 ml/100 g) than the use of either Linde 124 flux or Hobart PF201 flux ($B_I \simeq 1$) (.5 to 1.5 ml/100 g).

2. A flux moisture level of 15 wt-% was necessary to increase the average hydrogen content in the electroslag weld metal from approximately 2 ml/100 g to

approximately 3.5 ml/100 g, as measured from the top three sample locations.

3. The use of soaking wet flux also showed that the hydrogen content in the weld metal is initially high (15 to 16 ml/100 g in this case), and then decreases to a relatively constant value (between 3 and 5 ml/100 g).

4. An atmosphere of dry air at a flow rate of 7.5 liters/minute (16 cfh) plus moisture (picked up at a rate of 0.0023 g/s) increased the hydrogen content in the weld metal from approximately 2 ml/100 g to 4 ml/100 g.

5. The slag cap height, the current type, or polarity did not influence the average hydrogen content in the electroslag weld metal.

6. Intergranular cracking (with respect to the prior austenite grain boundary) was seen in welds where the standard welding conditions were modified by: (a) wet asbestos; or (b) soaking wet flux; or (c) high restraint level; or (d) high moisture content atmosphere (0.0023 g/s).

7. A threshold value of 4 ml/100 g for weld metal hydrogen content is suggested for intergranular cracking to occur in the mild steel weld metal.

8. The hydrogen value necessary to observe intergranular cracking is decreased by increasing the degree of external restraint.

9. Increasing the gap width from 25 to 51 mm (1 to 2 in.) increased the hydrogen above the 3 ml/100 g value, but no intergranular cracking was seen.

10. Solidification cracks were seen in welds using a low slag cap, a high slag cap, wet asbestos, DC −ve electrode polarity, and soaking wet flux with moist air.

11. Solidification cracks were also present in the welds containing the intergranular cracks but there was no relationship between the solidification cracks and the incidence of intergranular cracks.

12. The fractography of the intergranular cracks showed a quasi-cleavage fracture surface while the solidification cracks showed a smooth fracture surface.

13. The mechanical properties of the weld metal were not influenced by the presence of intergranular cracks or by its hydrogen content.

Acknowledgments

The authors wish to thank B.A. Graville, now at the Welding Institute of Canada, for initially suggesting the principle of the sample extraction technique, and P. Cheung for experimental assistance. The research program was partially funded by the National Research Council of Canada and undertaken in the Corporate Research and Development Centre of AMCA International Limited of Montreal which gave permission for the publication of this paper.

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