Effects of Electrode Composition, Flux Basicity, and Slag Depth on Grain-Boundary Cracking in Electroslag Weld Metals

An acidic flux, a high slag depth, and high-silicon electrodes are found to help eliminate grain-boundary cracking

BY P. J. KONKOL

ABSTRACT. Previous research investigations showed that grain-boundary separations, which are small crack-like imperfections usually less than ¼ in. (6.4 mm) long in electroslag weld metals, are due to the presence of hydrogen, which can result from moist flux or from moisture in the atmosphere above the weld pool. These studies indicated that the amount of cracking was reduced by lowering moisture content, using a neutral rather than a basic flux, lowering external restraint, decreasing the weld-cooling rate, or using a postweld heat treatment. To determine the importance of other factors involved, such as grade of steel welded, flux basicity, slag depth, and electrode composition, electroslag welds were made under conditions of relatively high external restraint and high moisture levels above the slag in 2 in. (51 mm) thick plates of A36 and A588-75 Grade A steel.

The consumable guide electroslag welding process was used, and a small steel gas-carrier tube was positioned beside the guide tube to provide an atmosphere of air having 19 or 40% water vapor above the molten slag. Welds were made with American Welding Society (AWS) EM13K-EW (1.0Mn-0.5Si) or EA3 (2.0Mn-0.5Mo) electrodes, with five fluxes having basicities from 0.7 to 5.1. A number of welds were made in which three different slag depths were used; ½, 1¼, or 2¼ in. (13, 38 and 57 mm). Additional welds were made with EH14-EW (1.9Mn), EH11K-EW (1.6Mn-1.0Si), and EH10Mo-EW (1.8Mn-0.7Si-0.5Mo) electrodes.

The results showed little difference in the amount of grain-boundary cracking in electroslag welds made in A36 and A588 plates. The amount of cracking decreased with decreasing flux basicity (B). Very little cracking was observed in welds made with acidic ($B < 1$) fluxes. Cracking was eliminated by increasing the slag depth to 2¼ in. (57.2 mm). The high-silicon electrodes, EH11K-EW and EH10Mo-EW, substantially lowered the amount of cracking. The reasons for the beneficial effect of silicon in reducing cracking are not fully understood.

As shown previously, it should be possible to eliminate grain-boundary separations by using welding practices that minimize moisture pickup and other sources of hydrogen or by allowing hydrogen to diffuse out of the weld during cooling or during postweld heat treating. The present work indicates that using an acidic flux, maintaining a high slag depth, and using high-silicon electrodes are also beneficial. However, the use of the two high-silicon electrodes investigated (EH11K-EW and EH10Mo-EW) resulted in excessively high weld-metal tensile strength.

Introduction

Occasionally, small crack-like imperfections (usually less than ¼ in., 6 mm, long) have been observed in electroslag welds made by fabricators under production conditions; these imperfections have caused concern about the use of electroslag welding (ESW) for critical applications, such as tension members in bridges (Ref. 1). These crack-like imperfections are frequently called grain-boundary separations or cracks. To help establish the use of this economical welding process in bridges and other critical applications, the causes of grain-boundary cracking need to be identified, and procedures to avoid their occurrence must be established.

Previous studies (Ref. 1) indicated that grain-boundary cracking occurred in weld metals made with a variety of electrodes and steel-plate compositions and were not associated with segregation of alloying elements or impurities.

Recent studies (Ref. 2) have shown that grain-boundary cracking could be produced by the addition of moisture to the welding flux or to the atmosphere above the molten flux or slag. The presence of such cracks could be reduced or eliminated by reducing external restraint, by lowering the moisture content, or by using a low-temperature postweld heat treatment. Thus, the cracking appeared to be hydrogen-induced. Similar studies conducted at Lehigh University (Ref. 3) showed that grain-boundary cracking could also be produced from hydrogen in the electrode or in the atmosphere above the molten slag.

These studies suggest that it should be possible to eliminate grain-boundary cracking by using welding practices that minimize moisture pickup or other sources of hydrogen, or by allowing hydrogen to diffuse out of the weld during cooling or during postweld heat treating. However, these practices are not always feasible during the production of electroslag weldments. The present studies were initiated to determine the extent to which the base metal, flux characteristics, and electrode chemical composition affected the level of cracking. Two steel grades (A36 and A588) were included in the present study to

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Table 1—Chemical Composition of Plates Used to Fabricate Electroslag Weldments, % (Ladle Analysis)

Steel grade	Heat no.	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Al
A36	73B400	0.22	0.97	0.006	0.026	0.20	0.03	0.03	0.02	0.02	–	0.024
A36	72E134	0.21	0.98	0.005	0.025	0.19	0.04	0.06	0.05	0.02	0.03	–
A36	75E556	0.20	1.06	0.005	0.022	0.21	0.03	0.02	0.04	0.03	0.02	–
A588-75 grade A	70B539	0.14	1.14	0.005	0.026	0.27	0.32	0.19	0.59	0.03	0.04	0.04
A588-80a grade A	69E735	0.12	1.04	0.012	0.029	0.44	0.40	0.23	0.55	0.03	0.03	0.03

Table 2—Chemical Composition of Electrodes Used to Fabricate Electroslag Weldments, %

Electrode type	Designation[a]	C	Mn	P	S	Si	Cu	Ni	Cr	Mo
Med-Mn-Si	EM13K-EW	0.09	1.00	0.006	0.013	0.51	0.10	–	–	–
Mn	EH14-EW	0.14	1.91	0.007	0.022	0.04	0.24	0.05	0.05	0.01
Mn-Mo[c]	EA3[b]	0.14	2.00	0.007	0.021	0.03	0.03[d]	–	–	0.52
Mn-Si	EH11K-EW	0.11	1.64	0.016	0.023	0.98	0.21	0.03	< 0.05	< 0.01
Mn-Si-Mo	EH10Mo-EW	0.12	1.80	0.011	0.010	0.65	0.19	0.03	0.05	0.49

[a] AWS 5.25-78, *Specification for Consumables used for Electroslag Welding of Carbon and High-Strength, Low-Alloy Steels.*
[b] AWS 5.23-80, *Specification for Bare Low-Alloy Steel Electrodes and Fluxes for Submerged Arc Welding.*
[c] Manufacturer's analysis.
[d] Exclusive of copper coating.

determine whether steel composition and/or strength level affected the degree of cracking.

With regard to flux characteristics, prior studies indicated that a basic flux (Ref. 2) and low slag depth (Ref. 4) contributed to cracking. Thus, the effects of flux basicity and slag depth were investigated.

Although grain-boundary cracking is the result of hydrogen in the weld, the degree of cracking may also be affected by the microstructure and hardness of the weld metal; this, in turn, is affected by its chemical composition. To determine the effect of electrode composition on grain-boundary cracking, the effects of silicon in both manganese and manganese-molybdenum electrodes were studied.

As part of a supplementary program to improve the notch toughness of electroslag weld metals, the Charpy V-notch (CVN) energy absorption of several weldments, made with various electrodes and fluxes in the present investigation, was determined. Also, welding-procedure qualification tests were conducted by using weldments made with a EH10Mo-EW electrode, which initially appeared to be promising with respect to both toughness and cracking resistance.

The results of the various studies are described in this paper.

Materials

The steel plate used for the majority of the weldments in the present study was 2 in. (51 mm) thick ASTM A36 plate obtained from three different heats. Selected weldments were also made with 2 in. thick ASTM A588-75 Grade A plates from a single heat. Weldments for the welding-procedure qualification tests were made from 2 in. thick A36 and A588-80a Grade A plates. The chemical compositions of the heats are shown in Table 1.

The majority of weldments were made using an AWS 3⁄32 in. (2.4 mm) diameter EM13K-EW electrode, a Mn-Si electrode. Other electrodes investigated included EH14-EW (Mn), EH11K-EW (Mn-Si), EH10Mo-EW (Mn-Si-Mo), and EA3 (Mn-Mo) of AWS A5.23-80. The chemical compositions of the electrodes are shown in Table 2.

To determine the effect of flux type on the occurrence of grain-boundary cracking, five commercially available fluxes that ranged in basicity from 0.73 to 5.1 were used. The chemical compositions of the fluxes are shown in Table 3.

Experimental Work

Fixturing

All weldments were fabricated with a high level of external restraint that was achieved by means of 2 × 6 × 28 in. (51 × 152 × 711 mm) restraint bars that were attached with ½ in. (13 mm) throat fillet welds across the top of each weldment, as shown in Fig. 1. A 4 in. long (102 mm) starter block was placed 17 in. (432 mm) below the top of the plates. The length and width of the welded plates

Table 3—Chemical Composition of Fluxes Used to Fabricate Electroslag Weldments

Flux type	A2	A1	N	B1	B2
Flux basicity[a]	0.73	0.80	1.0	2.7	5.1
Flux Composition,[b] %:					
SiO_2	40.1	38.6	37.3	12.6	3.4
Al_2O_3	4.1	14.6	17.2	1.1	19.0
CaO	8.6	19.0	30.3	–	55.8
CaO[c]	8.6	11.5	19.5	22.0	14.9
MgO	< 0.2	4.0	7.0	0.4	1.7
MnO	40.4	23.5	7.1	1.7	1.6
FeO	0.1	0.4	0.2	1.0	0.8
Fe_2O_3	2.1	0.4	1.0	–	1.0
TiO_2	0.2	1.0	0.7	18.0	3.6
CaF_2[c]	2.0	10.4	15.0	36.1	57.0

[a] Basicity (B) = $\frac{CaO + MgO + CaF_2 + \frac{1}{2}(MnO + FeO)}{SiO_2 + \frac{1}{2}(Al_2O_3 + TiO_2 + ZrO_2)}$
[b] Assuming the elements are present as oxides except as noted.
[c] Assuming all F is present as CaF_2 and excess Ca from CaF_2 is present as CaO.

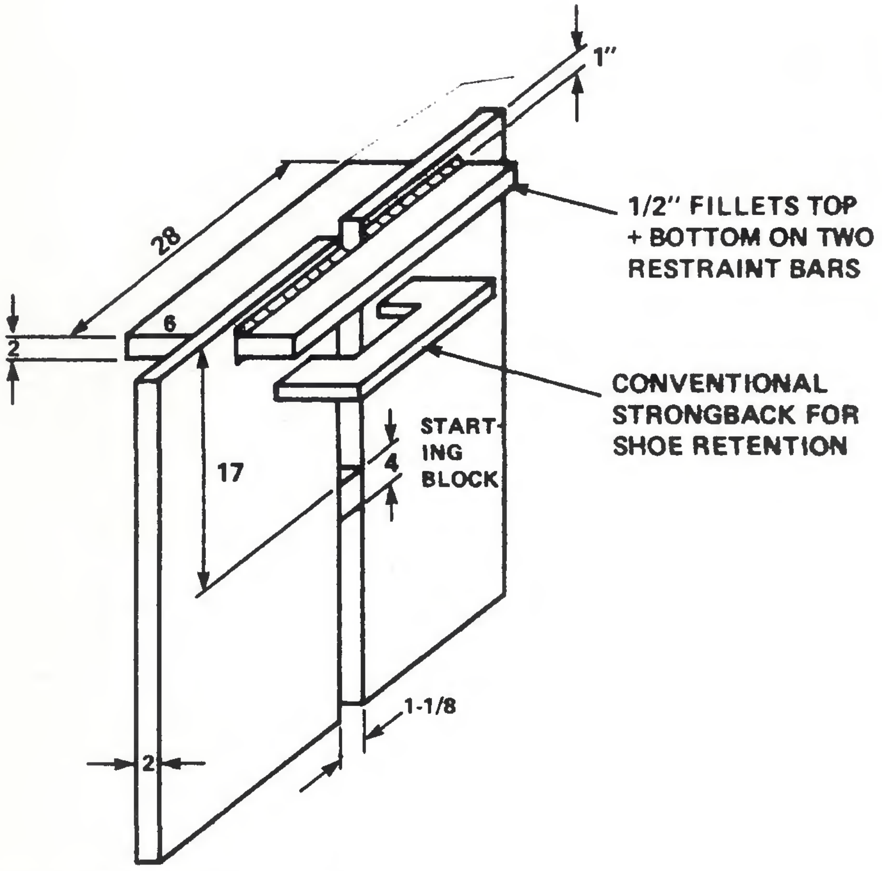

Fig. 1—Fixturing for weldment with restraint bars. All dimensions in inches

varied with each weldment, because the plates were cut and reused in further studies after each weld was made. However, for every plate, the width and length were equal to or greater than 14 in. (356 mm) and 21 in. (533 mm), respectively.

Moisture Addition

Control of the moisture level of the air above the molten slag during welding was achieved by blowing air through a ¼ in. (6.4 mm) outside-diameter steel tube that was attached parallel to the guide tube. During welding, both tubes were melted slightly above the molten slag.

A weldment with the controlled-atmosphere apparatus is shown in Fig. 2. The partial pressures of water vapor in the air were 36, 142, and 301 mm mercury, which correspond to 5, 19, and 40 vol-% H_2O, respectively, and were obtained by bubbling air through water at 90, 138, and 169°F (32, 59, and 76°C), respectively. The technique is described in detail in a previous study (Ref. 2).

Table 4—Conditions Held Constant during Fabrication of Electroslag Weldments(a)

Process type:	Single, fixed consumable-guide tube	
Shoe type:	Water-cooled, copper, 18 in. long, 2 gallons per minute flow rate.	
External restraint	High	
Postweld treatment	None	
Guide-tube type	½ in. O. D., bare	
Slag depth, inch	1½, except where varied	
Electrode diameter, in.	³⁄₃₂	⅛
Welding current, A	550-650	550-600
Welding voltage, V	43	40
Electrode feed rate, ipm:	220	100
Energy input, kJ/in.	2400	2300

(a) 1 inch = 25.4 mm; 1 gallon = 3.785 liters; 1 ipm = 0.423 mm/s; 1 kJ/inch = 0.0394 kJ/mm

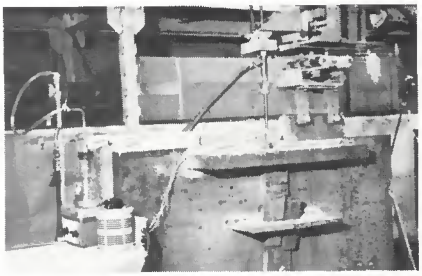

Fig. 2—Setup for electroslag weldment with high external restraint and moisture addition to the welding atmosphere

Welding

Except for plate grade, electrode type, flux type, and moisture level, all welding conditions shown in Table 4 were held constant. The combinations of welding parameters that were intentionally varied are shown in Table 5.

When ⅛ in. diameter (3.2 mm) electrodes were used, the welding voltage and electrode-feed rate were lowered to obtain the approximate fill rate and energy input of welds made with the ³⁄₃₂ in. diameter (2.4 mm) electrodes. The tops of the shoes were butted against the underside of the restraint bars, and the welding was terminated when the slag reached the top of the shoes. The shoes were left in place with the water running for about 4 hours (h) after welding to bring the weldment to room temperature in a relatively short time. The weldments were left with the restraint bars intact for at least 48 h before sectioning to allow any delayed cracking to occur.

To determine the reproducibility of the cracking data, eight weldments representing low, medium, and high levels of cracking were repeated. The results were analyzed statistically to determine what levels of differences in cracking were significant.

Cracking Measurement

A section containing the weld metal, which was 3 in. wide (76 mm) by plate thickness by the length of the weld (about 13 in. or 330 mm), was oxygen-cut parallel to the direction of welding. Each section was machined to the quarter-thickness location by removing ½ in. (13 mm) of metal from both sides on a plane parallel to the plate surfaces and weld faces. The two machined surfaces were surface-ground, etched lightly, and examined for grain-boundary separations by using dye penetrant.

The number of cracks observed on both surfaces at the ½ in. (13 mm) depth was counted and recorded. An additional ¼ in. (6.4 mm) of metal was then removed from both sides, and these surfaces were again examined for cracking. Indications that were located within 1 in. (25.4 mm) of the start or finish of the weld were disregarded. The average number of cracks observed at the ½ and ¾ in. (13 and 18.8 mm) depths was used for the data analysis and is reported in Table 5.

Additional Studies

On selected weldments, the ½ in. (13 mm) thick section that remained after the dye-penetrant examination was sectioned for analysis of the chemical composition, for metallographic examination, for microhardness measurements, and for mechanical-property (impact and tension) determinations.

Eight CVN specimens were machined from the weldments such that their orientation was transverse to the welding direction and the axis of the notch was normal to the plate surface at the midthickness of the weld on the weld centerline. The eight CVN specimens were tested at 0°F (−18°C). The highest and lowest values were discarded, and the average of the six remaining values was reported.

Longitudinal 0.252 in. (6.4 mm) diameter tension specimens were also machined from several weld sections. The specific weldments involved are listed in Table 6.

Welding-Procedure Qualification Tests

An electroslag weldment was made in a 2 in. (51 mm) thick plate of both A36 and A588-80a Grade A steels by using EH10Mo-EW electrode and Flux N. The welding conditions were the same as shown in Table 4 except that restraint bars were not used and moisture was not added to the atmosphere above the slag.

After welding, standard welding-procedure-qualification-test specimens were obtained and tested in accordance with the AWS Structural Welding Code (Ref. 5); these consisted of transverse tension specimens, side-bend-test specimens, longitudinal 0.505 in. (12.8 mm) diameter all-weld-metal tension specimens, and CVN impact-test specimens. The number and location of the specimens are shown in Fig. 3.

Table 5—Description of Parameters Used in Fabricating Electroslag Weldments and Number of Cracks Detected

		Electrode				Number of cracks		
Weldment code	Plate grade	Type	Diameter, in.[a]	Flux type	Moisture in atmosphere, %	½ in. depth	¾ in. depth	Avg.
Comparison of Plate Grade:								
1164	A588	EA3	3/32	N	19	4	3	4
1204	A36	EA3	3/32	N	19	67	–	67
1178	A588	EM13K-EW	3/32	N	19	36	20	28
1214	A36	EM13K-EW	3/32	N	19	8	9	9
1249	A36	EM13K-EW	3/32	N	19	89	112	101
1148	A588	EA3	3/32	N	5	0	0	0
1208	A36	EA3	3/32	N	5	0	0	0
1173	A588	EM13K-EW	3/32	B2	19	54	115	85
1230	A36	EM13K-EW	3/32	B2	19	137	–	137
Effect of flux basicity:								
1197	A588	EA3	3/32	A1	19	1	–	1
1154	A588	EA3	3/32	B2	19	520	–	520
1217	A36	EM13K-EW	3/32	A2	19	2	–	2
1286	A36	EM13K-EW	3/32	B1	19	194	–	194
Reproducibility:								
1246	A36	EM13K-EW	3/32	N	40	110	106	108
1285	A36	EM13K-EW	3/32	N	40	98	173	136
Effect of slag depth:								
1296	A36	EM13K-EW	3/32	N (½ in.)	19	111	116	114
1324A	A36	EM13K-EW	3/32	N (½ in.)	19	50	50	50
1324B	A36	EM13K-EW	3/32	N (1¼ in.)	19	4	30	17
1295	A36	EM13K-EW	3/32	N (2¼ in.)	19	0	0	0
1470	A36	EM13K-EW	3/32	N (2¼ in.)	19	3	–	3
Effect of electrode type:								
1250	A36	EH14-EW	3/32	N	19	5	24	15
1352	A36	EH14-EW	⅛	N	19	0	0	0
1383	A36	EH14-EW	⅛	N	40	127	62	95
1402	A36	EH14-EW	⅛	N	19	6	12	9
1204	A36	EA3	3/32	N	19	67	–	67
1403	A36	EA3	3/32	N	40	333	297	315
1251	A36	EH11K-EW	⅛	N	19	0	0	0
1318	A36	EH11K-EW	⅛	N	40	0	2	1
1366	A36	EH11K-EW	3/32	N	19	0	1	1
1337	A36	EH10Mo-EW	⅛	N	19	0	0	0
1349	A36	EH10Mo-EW	⅛	N	19	0	0	0
1384	A36	EH10Mo-EW	⅛	N	40	7	26	17

[a] 1 in. = 25.4 mm.

Table 6—Tests of Electroslag Weld Metals

Weldment no.	Chemical composition	Metallographic examination	Microhardness	Charpy V-notch	Tension
1204	x		x	x	
1214	x				x
1217	x				x
1230	x				x
1246	x	x			x
1249	x				x
1250	x		x	x	x
1251	x				x
1286	x				x
1295	x				
1318					x
1337	x		x	x	x
1349					x
1352	x				
1366	x		x	x	x

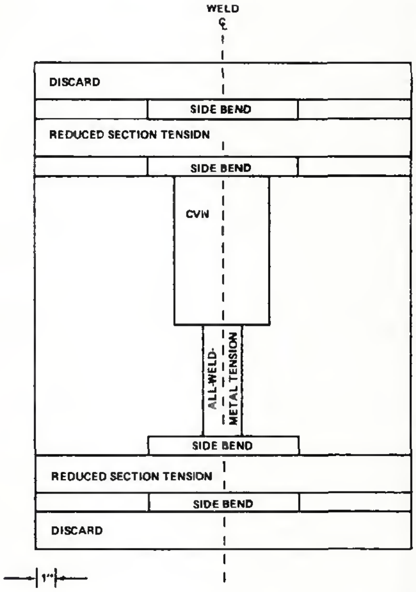

Fig. 3—Layout of AWS welding procedure-qualification test specimens

Results and Discussion

The number of cracks observed at distances of ½ and ¾ in. (13 and 19 mm) from each surface of all the weldments investigated are shown in Table 5.

Examination of the data in Table 5 shows that, in general, the level of cracking is higher at the ¾ in. (19 mm) distance than at the ½ in. (13 mm) distance. The greater degree of cracking was probably caused by the expected higher residual tensile stresses near the center of the weld and higher hydrogen concentrations because of greater diffusion distance to the weld surface. The effects of individual variables are discussed in the subsequent sections.

Reproducibility-of-Cracking Data

A comparison of the eight sets of weldments that exhibited low, medium, and high levels of cracking that were repeated by using the same parameters is shown in Table 7. In most cases, the degree of cracking was similar between similar welds. However, in two of the sets, the cracking differed by an order of magnitude. A comparison of three of the sets (1251 and 1366; 1250 and 1352; 1214 and 1249) showed little difference in chemical composition between similar welds—Table 8. A statistical analysis of the data by analysis of variance and/or regression techniques indicated that, within 95% confidence limits, there is a real difference between two individual

Table 7—Reproducibility of Weld-Cracking Data

Weldment code	Electrode type	Flux type	Moisture in atmosphere, %	Average no. of cracks[a]
1337	EH10Mo-EW	N	19	0
1349	EH10Mo-EW	N	19	0
1251	EH11K-EW	N	19	0
1366	EH11K-EW	N	19	1
1250	EH14-EW	N	19	15
1352	EH14-EW	N	19	0
1402	EH14-EW	N	19	9
1217	EM13K-EW	A2	19	2
1283	EM13K-EW	A2	19	0
1214	EM13K-EW	N	19	9
1249	EM13K-EW	N	19	101
1246	EM13K-EW	N	40	108
1285	EM13K-EW	N	40	136
1296	EM13K-EW	N (½ in.)	19	114
1324A	EM13K-EW	N (½ in.)	19	50
1295	EM13K-EW	N (2¼ in.)	19	0
1470	EM13K-EW	N (2¼ in.)	19	3

[a] Average of the cracking observed at ½ and ¾ in. (13 and 19 mm) depths.

Table 8—Chemical Composition of Electroslag Weld Metals, %

Weld code	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	Al	N	O
1204	0.18	1.27	0.008	0.024	0.08	0.17	0.02	0.01	0.23	—	0.005	0.006	0.006	0.0246
1214	0.16	0.94	0.006	0.019	0.31	0.08	0.01	0.02	< 0.01	< 0.01	< 0.002	0.005	0.005	0.0153
1217	0.17	1.00	0.006	0.020	0.27	0.07	0.01	0.02	< 0.01	< 0.01	< 0.002	0.006	0.005	0.0228
1230	0.17	0.95	0.006	0.016	0.24	0.08	0.02	0.01	< 0.01	< 0.01	0.008	0.006	0.005	0.0071
1246	0.16	0.89	0.006	0.021	0.32	0.08	0.01	0.02	< 0.01	< 0.01	< 0.002	0.006	0.005	0.0135
1249	0.16	0.89	0.006	0.021	0.26	0.08	0.03	0.02	< 0.01	0.016	< 0.002	< 0.002	0.005	0.0120
1250	0.19	1.22	0.009	0.025	0.08	0.10	0.04	0.04	< 0.01	0.016	0.002	< 0.002	0.005	0.0173
1251	0.17	1.22	0.011	0.024	0.49	0.14	0.04	0.04	< 0.01	0.016	< 0.002	< 0.002	0.006	0.0093
1286	0.17	0.91	0.006	0.017	0.19	0.09	0.03	0.03	< 0.01	0.017	0.002	< 0.002	0.005	0.0160
1295	0.16	0.88	0.007	0.020	0.33	0.08	0.04	0.02	< 0.01	0.015	—	< 0.002	0.004	0.0109
1296	0.14	0.89	0.006	0.018	0.31	0.09	0.03	0.02	< 0.01	—	—	< 0.002	0.006	0.0222
1337	0.16	1.35	0.009	0.017	0.38	0.13	0.05	0.03	0.22	—	—	< 0.002	0.006	0.0092
1352	0.18	1.28	0.006	0.023	0.10	0.13	0.05	0.03	0.01	0.015	—	0.002	0.004	0.0154
1366	0.16	1.26	0.012	0.024	0.53	0.17	0.04	0.04	0.01	0.012	—	0.002	0.006	0.0132

Table 9—Effect of Plate Grade on Degree of Grain-Boundary Cracking

Weldment code	Plate grade	Electrode type	Flux type	Moisture in atmosphere, %	Average no. of cracks
1164	A588	EA3	N	19	4
1204	A36	EA3	N	19	67
1178	A588	EM13K-EW	N	19	28
1214, 1249	A36	EM13K-EW	N	19	9, 101
1148	A588	EA3	N	5	0
1208	A36	EA3	N	5	0
1173	A588	EM13K-EW	B2	19	85
1230	A36	EM13K-EW	B2	19	137

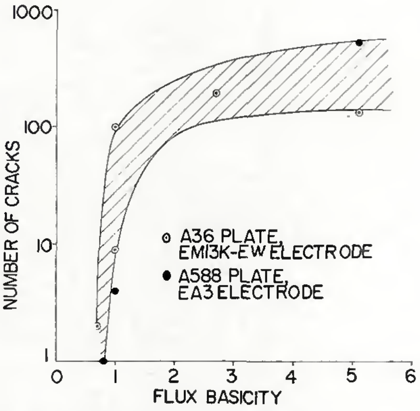

Fig. 4—Effect of flux basicity on number of grain-boundary separations observed in electroslag weld metal

counts if the difference between the logarithms of the number of cracks counted plus one [$\log_{10}(n + 1)$] exceeds 1.48. Thus, in subsequent discussion of the factors that affect cracking, this variability in amount of cracking must be considered. Such factors as guide-tube position, slag depth, well-pool geometry, shoe fit-up, residual-stress level, or gas-flow rate may have contributed to this variability.

Effect of Plate Grade

A comparison of four sets of welds in which the only variable was plate grade (A36 vs. A588-75 Grade A) is shown in Table 9. Statistical analysis of these data indicates that there is no significant difference in cracking between welds made in A36 and A588 steel.

Effect of Flux Basicity

The effect of increasing flux basicity from 0.7 to 5.1 on increasing the amount of cracking is shown in Table 10, and the data are plotted in Fig. 4. Similar cracking behavior was observed in both steels. The basic fluxes ($B > 1.5$) resulted in the most cracking (137 to 520 cracks); the neutral flux, flux N ($B = 1.0$), resulted in moderate cracking (4 to 101 cracks); and the acidic fluxes—Fluxes A2 and A1 ($B < 1$)—resulted in the fewest cracks (i.e., 1 and 2).

The reason for the detrimental effect of basic fluxes on cracking may possibly be related to the increased dissolution of water vapor into basic molten slags (Ref. 6), with subsequent transfer of hydrogen into molten weld metal. Another possible explanation is that low-basicity (acidic) fluxes generally result in high oxygen levels in the weld metal.

High oxygen contents limit the amount of hydrogen that will dissolve in the metal (Ref. 7). For example, weld 1217, made with the acidic flux A2 ($B = 0.7$), had 0.0228% oxygen compared with 0.0071% oxygen in weld 1230 made with the basic flux B2 ($B = 5.1$). However, for the other welds in this study, no correlation between cracking and oxygen content was observed.

Effect of Slag Depth

The depth of molten slag is difficult to measure and control during consumable-guide welding. When the minimum amount of flux is added to prevent audible arcing during welding, the depth of solidified slag at the end of the weld averages about 1¼ in. (32 mm). By adding less flux and more flux than was necessary, slag depths of ½ and 2¼ in. (13 and 57 mm), respectively, were obtained.

The effect of slag depth on degree of grain-boundary cracking is shown in Table 11. Again, considerable scatter in a number of cracks was observed. However, there was a statistically significant effect of increased slag depth on reducing the amount of cracking. The welds made with a 2¼ in. (57 mm) slag depth exhibited little or no cracking in the presence of 19% moisture in the atmosphere. This is in agreement with other work (Ref. 4) in which cracking was eliminated when the slag depth was increased to 1.9 in. (49 mm).

The reason for the lower amount of cracking with increased slag depth is not known. It could possibly be related to elimination of arcing, lowering of slag-bath temperature, changes in circulation patterns of the molten slag, or lowering of hydrogen concentration in the slag because of the greater slag volume.

As shown in Table 8, the only significant effect of increasing slag depth from ½ in. or 13 mm (weld 1296) to 2¼ in. or 57 mm (weld 1295) on weld-metal chemical composition was to lower the oxygen content from 0.0222 to 0.0109%. However, as noted in the previous discussion of the effects of weld-metal oxygen, this would be expected to increase the amount of hydrogen-induced cracking.

Effect of Electrode Composition

As shown in Table 12, the use of electrodes containing 1.6 to 1.8% manganese and 1.0 and 0.7% silicon (EH11K-EW and EH10Mo-EW, respectively) substantially lowered the amount of grain-boundary cracking compared with the use of EH14-EW and EA3, which are similar in composition except for silicon. Cracking was nearly eliminated when the high-silicon electrodes were used in the presence of 19% moisture and was significantly lowered in the presence of 40% moisture.

Table 10—Effect of Flux Basicity on Degree of Grain-Boundary Cracking[a]

Weldment code	Plate grade	Electrode type	Flux type	Flux basicity	Average no. of cracks
1197	A588	EA3	A1	0.8	1
1164	A588	EA3	N	1.0	4
1154	A588	EA3	B2	5.1	520
1217	A36	EM13K-EW	A2	0.7	2
1214, 1249	A36	EM13K-EW	N	1.0	9, 101
1286	A36	EM13K-EW	B1	2.7	194
1230	A36	EM13K-EW	B2	5.1	137

[a] All welds were made with 19% moisture in the atmostphere.

Table 11—Effect of Slag Depth on Degree of Grain-Boundary Cracking[a]

Weldment code	Slag depth in.[b]	Average number of cracks
1296	½	114
1324A	½	50
1214	1¼	9
1249	1¼	101
1324B	1¼	17
1295	2¼	0
1470	2¼	3

[a] All welds were made with EM13K-EW electrode, flux N, and 19% moisture in the atmosphere.
[b] 1 in. = 25.4 mm

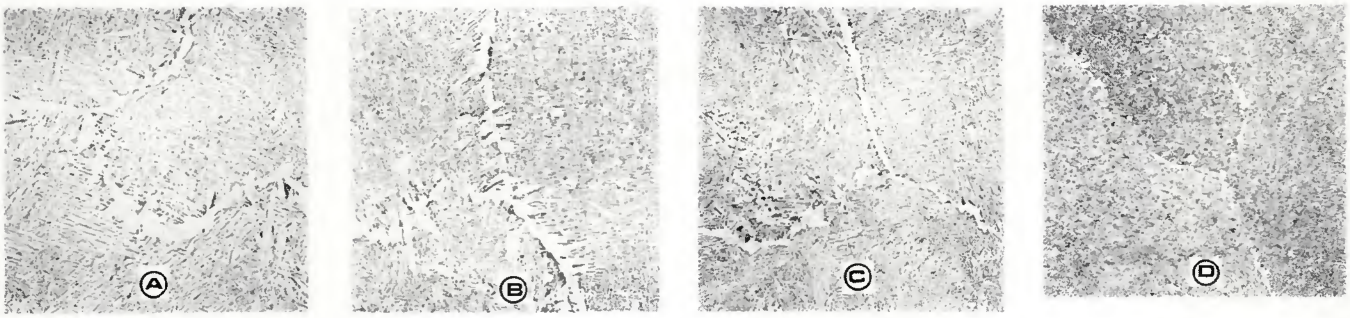

Fig. 5 — Effect of electrode composition on microstructure of electroslag weld metals: A — weld 1250; EH 14-EW (1.9Mn); B — weld 1366; EH11K-EW (1.6Mn-1.05i); C — weld 1204; EA3 (2.0Mn-0.5Mo); D — weld 1337; EH10Mo-EW (1.8Mn-0.7Si-0.5Mo). Nital-Picral etch. X100 (reduced 26% on reproduction)

The effect of silicon content on weld microstructure is shown in Fig. 5. The morphology of the grain-boundary ferrite was changed from predominantly polygonal to predominantly side-plates, and the matrix was changed from a coarse to a fine Widmanstatten structure by the use of EH11K-EW (1.6Mn-1.0Si) rather than EH14-EW (1.9Mn) electrodes — Fig. 5A and 5B. The weld-metal silicon content was increased from 0.08 to 0.10 to 0.49 to 0.53% — Table 8 (welds 1250 and 1352 vs. 1251 and 1366, respectively).

For the EA3 electrode, (2Mn-0.5Mo), the amount of grain-boundary ferrite was lower than that for EH14-EW or EH11K-EW, and the matrix was primarily bainite, Fig. 5C. EH10Mo-EW electrode (1.8Mn-0.7Si-0.5Mo) resulted in very little grain-boundary ferrite and a matrix that appeared to be acicular ferrite — Fig. 5D. In these welds the silicon content was raised from 0.08 to 0.38% (welds 1204 and 1337).

Although it appears from Fig. 5 that lowering the amount of grain-boundary ferrite was beneficial, grain-boundary cracking has been observed in weld metals that contained no grain-boundary ferrite (Ref. 2). Thus, the reason for the beneficial effect of silicon on reducing grain-boundary cracking cannot be explained on a microstructural basis.

It was also postulated that the cracking was confined to the grain-boundary ferrite because it was softer than the matrix, and silicon would reduce cracking by solid-solution strengthening the ferrite. Thus, microhardness readings were obtained on the four weld metals shown in Fig. 5. The results in Table 13, however, show that silicon increased the hardness of the matrix and slightly lowered the hardness of the ferrite, thus *increasing* the difference in hardness.

In the absence of a satisfactory microstructural explanation for the effect of silicon on cracking, it is postulated that silicon may affect the solubility or diffusivity of hydrogen in the weld metal. Silicon does lower the solubility of hydrogen in liquid iron (Ref. 8); however, the effect is believed to be relatively small for the range of silicon contents in this investigation (Ref. 9).

Another possible mechanism is the effect of silicon on inclusion type. As silicon content increases, the predominant inclusion type would be expected to change from MnO to $MnSiO_2$ to SiO_2. It is suggested (Ref. 9) that inclusion types can differ in their ability to absorb hydrogen and can either enhance or retard hydrogen cracking. However, little work has been done in this area.

Notch Toughness of Weld Metal

The results of the CVN impact tests obtained from material at the midthickness of the weld metal of selected weldments are shown in Table 14. These results indicate that a weld metal made with EH10Mo-EW electrode and flux N exhibited excellent notch toughness: 51 ft-lb (69 J) at 0°F (−17.8°C). Thus, this electrode initially appeared to be attractive in terms of both resistance to grain-boundary cracking and high notch toughness.

Welding-Procedure Qualification Tests

To determine whether electroslag welds made with high-silicon electrodes would have adequate mechanical properties for structural applications, standard AWS Welding-Procedure Qualification tests of electroslag weldments of A36 and A588-80a Grade A steel were conducted by using EH10Mo-EW electrode. The results are shown in Table 15.

Although the weld region exhibited adequate soundness as evidenced by the transverse-tension-and side-bend-test results, the tensile strength of the weld metals exceeded that specified in the AWS A5.25-78 specification for ESW consumables (Ref. 13). In addition, the tensile elongation was lower than the specified minimum, and the CVN energy-absorption values at 0°F of 27 and 14 ft-lb (37 and 19 J) were much

Table 12—Effect of Electrode Composition on Degree of Grain-Boundary Cracking

Electrode type	Nominal composition	Average number of cracks[a] 19% moisture		40% moisture	
EH14-EW	1.9Mn	(1250, 1352, 1402)	15, 0, 9	(1383)	95
EH11K-EW	1.6Mn-1.0Si	(1251, 1366)	0, 1	(1318)	1
EA3	2.0Mn-0.5Mo	(1204)	67	(1403)	315
EH10Mo-EW	1.8Mn-0.7Si-0.5Mo	(1337, 1349)	0, 0	(1384)	17

[a] Numbers in parentheses are weld codes.

Table 13—Microhardness of Electroslag Weld Metals

Weldment code	Electrode type	Microhardness, HV 0.1[a] Matrix	Grain-boundary ferrite	Difference
1250	EH14-EW (1.9Mn)	235	218	17
1366	EH11K-EW (1.6Mn-1.0Si)	246	207	39
1204	EA3 (2.0Mn-0.5Mo)	243	238	5
1337	EH10Mo-EW (1.8Mn-0.7Si-0.5Mo)	268	220	48

[a] Average of five Vickers diamond-pyramid-hardness impressions with a 100 gram load.

lower than the 51 ft-lb observed previously. Thus, EH10Mo-EW electrode with flux N does not appear to be suitable for ESW from a mechanical-property standpoint.

The high strength and low ductility of electroslag weld metal made with EH10Mo-EW electrode may be due to the relatively high alloy content of the electrode (1.8Mn-0.7Si-0.5Mo). To determine whether the molybdenum-free high-silicon electrode (EH11K-EW) investigated would result in lower strength weld metal, the tensile properties that were obtained from the weld metal of weldments 1318 and 1366 (made with EH11K-EW electrode) were compared with that for weldment 1337 made with EH10Mo-EW electrode.

The results in Table 16 show that EH11K-EW electrode also resulted in weld-metal tensile strengths in excess of the 80 ksi (551 MPa) maximum for A36 steel specified in AWS A5.25-78. Thus, neither of the two high-silicon electrodes would meet classification requirements of AWS A5.25-78 when used with neutral flux N, and these electrode-flux combinations would not be suitable for use in electroslag weldments that must meet AWS D1.1 specification requirements.

General Discussion

It was previously shown (Ref. 2) that grain-boundary cracking was caused by hydrogen in the weld metal; thus it should be possible to minimize or eliminate cracking by using welding practices that minimize moisture pickup or other sources of hydrogen or by allowing hydrogen to diffuse out of the weld by slow cooling or by postweld heat treatment.

The present work indicates that, if these measures are impractical, additional procedures of using an acidic flux or maintaining a high slag depth would also be beneficial. However, it is not clear whether the beneficial effects are because of a lower hydrogen level in the weld metal. Use of a high-silicon electrode is also beneficial in reducing cracking but may not be beneficial in terms of mechanical properties.

Table 14—Notch Toughness of Electroslag Weld Metals

Weldment code	Electrode type	Flux type	Moisture in atmosphere, %	CVN energy absorbed at 0°F (−18°C), ft-lb[a]
1250	EH14-EW	N	19	19
1251	EH11K-EW	N	19	20
1349	EH10Mo-EW	N	19	51
1214, 1249	EM13K-EW	N	19	29, 22
1217	EM13K-EW	A2	19	19
1286	EM13K-EW	B1	19	16
1230	EM13K-EW	B2	19	10

[a] 1 ft-lb = 1.356 J

Table 15—Results of Electroslag Welding Procedure-Qualification Tests with the Use of EH10Mo-EW Electrode[a]

	A36 steel	A588-80a grade A steel
Qualification test:		
Transverse tensile strength, ksi	82.5	85.3
Fracture location	Base metal	Base metal
Side-bend-test results	Passed	Passed
All-weld-metal tensile properties:		
Yield strength (0.2% offset), ksi	65.9	65.3
Tensile strength, ksi	97.3	98.5
Elongation in 2 in., %	20.0	21.1
Reduction of area, %	50.2	47.4
CVN energy absorption, ft-lb:		
Weld metal (0°F), (−18°C)	27	14
AWS A5.25-78 requirements[b]		
Yield strength, ksi	36 min	50 min
Tensile strength, ksi	60/80	70/90
Elongation, %	24 min	22 min

[a] 1 ksi = 6.89 MPa; 1 ft-lb = 1.356 J

[b] "Specification for Consumables Used for Electroslag Welding of Carbon and High-Strength, Low-Alloy Steels."

Conclusion

To further define the factors that affect the incidence of grain-boundary cracking in electroslag weld metal, additional studies were conducted to determine the effects of steel grade, flux basicity, slag depth, and electrode composition. The results are summarized as follows:

1. Electroslag welds made in A36 and A588-75 Grade A plates showed no statistically significant difference in amount of grain-boundary cracking.
2. Grain-boundary cracking increased with increasing flux basicity. Very little cracking was found in welds made with acidic (B < 1) fluxes.
3. Grain-boundary cracking was nearly eliminated in highly restrained welds made in the presence of 19% percent moisture above the slag by increasing the slag depth to 2¼ in. (57 mm).
4. EH11K-EW and EH10Mo-EW electrodes, which contain 1.0 and 0.7% silicon, respectively, substantially lowered the amount of grain-boundary cracking in highly restrained electroslag weldments in the presence of up to 40% moisture above the slag.
5. Electroslag weld metals deposited with the EH11K-EW and EH10Mo-EW electrodes and a neutral flux exhibited

Table 16—Tensile Properties of Weld Metals Deposited with High-Silicon Electrodes in A36 Steel

Weldment code	Electrode type	Moisture in atmosphere, %	All-weld-metal tensile properties[a] Yield strength (0.2% offset), ksi	Tensile strength, ksi	Elongation in 1 in. %	Reduction of area, %
1337	EH10Mo-EW	19	56.6	86.3	30.0	65.4
			57.7	87.2	23.0	60.7
1366	EH11K-EW	19	68.0	100.6	27.0	64.5
1318	EH11K-EW	40	54.7	84.2	27.0	65.6
			55.0	84.5	23.0	56.4

[a] Longitudinal 0.252 in. (6.4 mm) diameter specimens at midthickness location. Also, 1 ksi = 6.89 MPa; 1 in. = 25.4 mm.

tensile strengths that exceeded the maximums imposed in the American Welding Society filler-metal specification for electroslag-welding consumables.

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