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Fracture Toughness of Electroslag Welded A537G Steel

Study shows that fracture toughness can be improved by heat treatment after welding

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ABSTRACT. This paper reports an investigation of the properties of a 2 in. thick electroslag weldment in A537G steel plate using both conventional Charpy impact tests and fracture mechanics testing methods. The properties across the weld joint (i.e., weld metal, heat-affected zone and base metal) were studied in the as-welded, the welded and stress relieved, and the normalized and stress relieved condition. Conventional mechanical properties of these zones were also determined.

Precracked Charpy specimens were used to determine the dynamic fracture toughness of the weldment, while the static fracture toughness was determined using compact tension specimens. Transverse (T) orientation specimens were used.

The weld was made with a commercial electrode and flux combination that resulted in a weld deposit having approximately matching chemical composition with the base plate. A ⅛ in. diam single electrode was used to fill the approximately 1 in. gap between the 2 in. thick plates. An oscillation speed of about 8 per minute was employed. The welding current was 700 A and a welding voltage of 40-42 V was used. The resulting properties of the weldment were a base metal yield point and tensile strength of 52, and 75 ksi respectively, with a weld metal yield point and tensile strength of 68 and 95 ksi, respectively (as welded). Stress relief at 1150 F for 2 h did not alter the tensile properties of the weld metal or base metal significantly, in fact the yield strength of the weld metal was slightly increased. Normalizing at 1650 F for 2 h, followed by stress relief at 1150 F for 2 h, produced a weld metal yield and tensile strength of 59 and 80 ksi, respectively. The Charpy 15 ft-lb transition temperatures of the various zones indicated that in the as-welded plate the base metal (with a transition temperature of −47 F) was tougher than the weld metal (+36 F) or the heat-affected zone (+8 F). After stress relief the weld metal improved in toughness (to a transition temperature of −65 F) as did the heat-affected zone, but to a lesser extent (to −10 F). Full retreat-

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Table 1 — Chemical Composition (Wt %) of ASTM A-537 G Base Metal and of Electroslag Weld Metal Deposit

C	Mn	P	S	Si	Cu	Ni	Cr	Mo
			Base Metal, 2 in. (51 mm)					
0.18	1.23	.010	.016	0.29	0.32	0.11	0.12	0.01
0.18	1.21	.013	.016	0.30	0.30	0.10	0.11	0.01
0.18	1.22	.011	.017	0.29	0.31	0.10	0.12	0.01
			Weld Metal					
0.17	1.52	.013	.015	0.15	0.24	0.09	0.08	0.34
0.17	1.49	.012	.016	0.15	0.24	0.08	0.09	0.31
0.17	1.52	.013	.016	0.18	0.31	0.10	0.09	0.27
0.16	1.51	.011	.015	0.17	0.30	0.10	0.09	0.27

Welding Conditions

Electrode: RACO 128	Flux: Arcos BV
Diameter: ⅛ in. (3 mm)	Travel speed: 1 ipm
Wire extension: 3 in. (76 mm)	Oscillations: 8 per min
Current: 700 A, ac	Slag depth: 2-2½ in. (51-64 mm)
Voltage: 40-42 V	Groove width: 1 in. (25 mm)

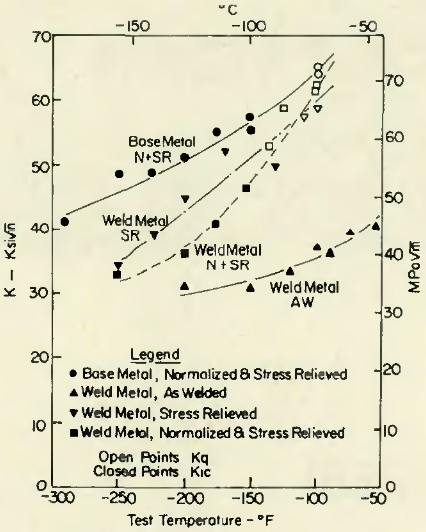

Fig. 1 — Fracture toughness data for base metal and weld metal in electroslag welded A537 steel

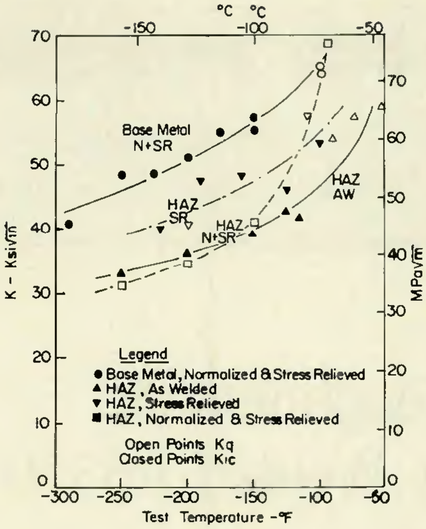

Fig. 2 — Fracture toughness data for base metal and heat-affected zone in electroslag welded A537 steel

Table 2 — Tensile Properties Data

Temp., F	.2% Y.S., ksi	Ult. T.S., ksi	Elong. (1 in.), %
Base Plate Normalized and Stress Relieved			
+ 76	51.2	74.1	34.8
− 75	64.1	84.6	34.7
−100	67.1	86.8	35.8
−150	74.4	91.5	36.0
−200	84.9	99.1	36.1
Weld Metal as-Welded			
+ 75	68.1	94.5	19.7
− 75	76.0	104.4	19.7
−100	79.4	107.0	19.0
−150	80.8	112.2	17.0
Weld Metal Stress Relieved			
+ 75	74.7	95.8	22.3
− 75	80.1	102.3	21.2
−100	81.9	105.4	21.0
−200	96.6	116.3	19.0
Weld Metal Normalized			
+ 75	59.2	80.3	33.7
− 75	67.7	90.6	33.5
−100	68.2	93.2	32.2
−110	71.1	93.6	32.0
−150	77.7	98.6	32.8
−200	87.8	105.5	32.8

ment of the weldment, i.e., renormalizing, produced weld metal and heat-affected zone toughnesses (transition temperature of −96 and −100 F, respectively) better than that of the base metal.

The static fracture toughness of the base metal (K_{IC} of about 70 ksi $\sqrt{in.}$ at −50 F) was well above the as-welded weld metal (K_{IC} of about 40 ksi $\sqrt{in.}$ at −50 F), or the heat-affected zone (K_{IC} of about 60 ksi $\sqrt{in.}$ at −50 F). Stress relief and normalizing progressively improved the weld metal K_{IC} toughness to values similar to the base metal at −50 F, but the heat-affected zone was not similarly progressively improved and remained below both weld metal and base metal in toughness at −50 F (at about 60 ksi $\sqrt{in.}$). With the exception of the somewhat lower toughness of the heat-affected zone, these trends were similar to those seen in the Charpy tests.

Introduction

During the past decade the application of steels with improved notch toughness has steadily increased for construction ranging from icebreaker vessels to storage tanks for liquified petroleum products. Carbon-manganese steels with small additions of other elements, made to fine grain practice and controlled rolled or heat treated, have provided an economical class of materials for use as low as −75 F (−60 C). An important representative of this class is ASTM A537G Class 1 steel, specified to have a minimum yield strength of 50 ksi (345 MPa) normalized, or 60 ksi (415 MPa) quenched and tempered, and (optionally) required to exhibit 15 ft-lb (20 J) V-notch Charpy energy at −75 F (−60 C).

For the production welding of steels of greater thicknesses, processes providing a high rate of metal deposit are attractive, for example the submerged arc or electroslag processes. The high rate of deposit possible by the electroslag process carries a penalty that may be troublesome with reference to steels chosen for their notch toughness. The high level of heat input inherent to electroslag welding imposes a correspondingly prolonged thermal cycle on the welded joint, and the metallurgical effect of the ensuing slow heating and cooling is to develop coarse grain sizes in the weld metal and heat-affected zones. In some steels the microstructures formed in the welded joint during slow cooling will be relatively softer and lower in tensile strength than the unaffected base metal that may have been previously heat treated. Thus it has been considered necessary in some applications to heat treat the weldment after the welding operation to restore tensile properties or notch toughness.

The study reported here was initiated by the Pressure Vessel Research Committee to determine how a low temperature steel such as A537 Class 1 would respond in its mechanical properties to electroslag welding and to subsequent heat treatments. The program was to determine the effects of welding, thermal stress relief, and normalizing plus stress relief on the tensile properties and on the notch toughness of this steel as measured by tension tests, Charpy tests, precracked Charpy tests, and compact tension tests. The weld metal, heat-affected zone, and unaffected base metal were to be tested by appropriate location of test samples.

Experimental Program

The Steel Weldment

The material for the test program was obtained as a shop welded joint in a 2 in. thick unheat treated ("G" condition) A537 steel plate. The chemical composition of the steel is given in Table 1, along with the welding conditions used and the resulting weld metal composition. Because the plates were welded in the as-rolled condition, no mechanical test samples were obtained from the A537 plate in the Class 1 condition, that is, the as-normalized condition. However, tests were conducted on normalized and stress relieved plate for which normalizing and stress relieving were performed after welding.

Heat Treatments

In addition to as-welded mechanical tests, samples were taken from weld metal, heat-affected zone (HAZ), and unaffected base metal (1) after postweld heat treatment at 1150 F (635 C) for 2 h, and (2) after normalizing at 1650 F (900 C) for 2 h and tempering at 1150 F (635 C) 2 h.

Testing Methods

All specimens for mechanical testing were sectioned from the weldment with the specimen axes transverse both to the welded joint and to the original rolling direction. Notched

Table 3 — Conventional Charpy V-Notch Transition Temperatures (F)

		Specimen condition		
Material	Criteria	As welded	Stress rel.	Norm. and stress rel.
Base metal	15 ft-lb	—	—	−90
	50% FF	—	—	−21
	20 mils	—	—	−85
Weld metal	15 ft-lb	+36	−65	−96
	50% FF	+90	+22	+25
	20 mils	+45	−40	−60
Heat-affected zone	15 ft-lb	+ 8	−10	−100
	50% FF	+81	+40	+ 3
	20 mils	+ 5	− 5	−90

Table 4 — Fatigue Precracked Charpy V-Notch Transition Temperature (F)

		Specimen condition		
Material	Criteria	As welded	Stress rel.	Norm. and stress rel.
Base metal	15 ft-lb	—	—	−47
	20 mils	—	—	−45
Weld metal	15 ft-lb	+65	+82	+25
	20 mils	+70	+95	+30
Heat-affected zone	15 ft-lb	+48	+45	−30
	20 mils	+70	+50	−25

specimens were prepared with the notch normal to the plane of the plate. In all cases the intent was to assure that the fracture path was contained in the region of the joint being evaluated.

The following mechanical tests were conducted:

1. Tension tests of 0.25 in. (6 mm) diam and 1 in. (25 mm) gage length were run on weld metal and base metal at temperatures from 75 F (25 C) to −200 F (−130 C).
2. Charpy tests of standard dimensions were run to determine the transition temperature ranges (by several criteria) of the weld metal, HAZ, and base metal. The notches were located at the centerline of the weld metal and in the coarse grained region of the HAZ. Additional Charpy tests were run containing fatigue-induced precracks of 0.01 to 0.04 in. (0.25 to 1 mm) depth beneath the standard V-notch.
3. Compact tension tests tested to ASTM E399-70T specifications were run with the notch similarly located in the weld metal, HAZ, and base metal in the as-welded, stress relieved, and normalized + stress relieved conditions. Both 1 T and 2 T specimens were used as needed to obtain valid tests. Load and crack opening displacement measurements were obtained from specimens tested over a range of temperatures.
4. Supplementary hardness measurements and microstructural examinations were included in the program.

Results and Discussion

Tension Tests

The results of the tension tests are summarized in Table 2. Both the weld metal and base metal meet the strength requirements of A537 Class 1. The weld metal retains a portion of its overmatching in relation to the base metal even after full reheat treatment. The low temperature tensile properties are useful in connection with fracture toughness evaluations.

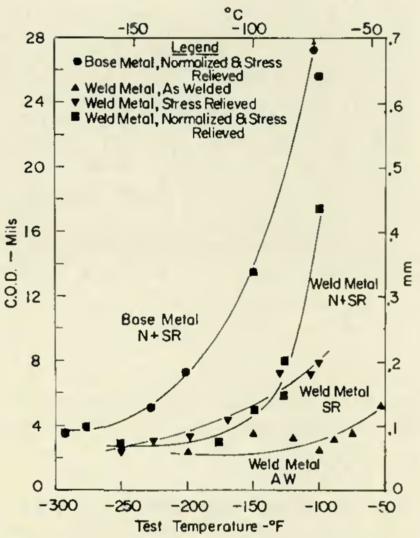

Fig. 3 — COD data for base metal and weld metal in electroslag welded A537 steel

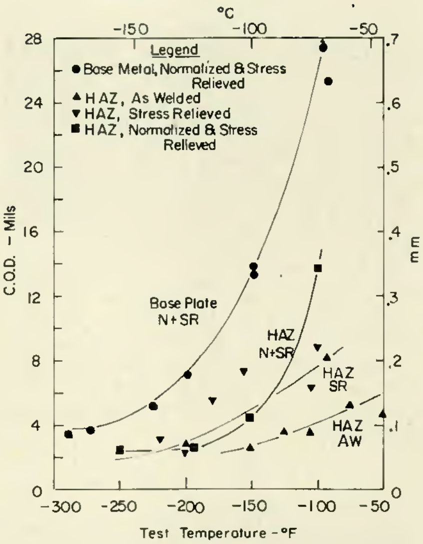

Fig. 4 — COD data for base metal and heat-affected zone in electroslag welded A537 steel

Standard Charpy Tests

Transition curves were established by series of about 25 specimens and plotted by computer. Transition temperatures as determined by 15 ft-lb energy, 20 mil (.38 mm) lateral contraction, and 50% fibrous fracture are listed in Table 3. The high transition temperatures developed in the weld metal and heat-affected zone after welding are apparent. Thermal stress relief toughens the weld metal appreciably but is of small benefit to the HAZ. After normalizing and stress relief the three regions attain very similar toughness levels.

Precracked Charpy Tests

The tests of Charpy specimens containing precracks induced by fatigue loading produced the data in Table 4. Again the as-welded weld metal and HAZ displayed transitions over 100 F (55 C) higher than the base metal. Unexpectedly, the precracked Charpy tests did not indicate as much benefit to the weld metal by heat treatment as that shown in standard Charpy tests. The heat-affected zone was substantially improved by normalizing and stress relieving.

Compact Tension Tests

The compact tension tests were run over a temperature range from −250 F (−155 C) to temperatures above those at which valid K_{IC} values could be obtained. If plane strain conditions were not attained, K_Q (max. load) was calculated. In addition, COD data were determined by the method of BSI DD10:1972. The results are displayed in Figs. 1 to 4.

The static fracture toughness of the

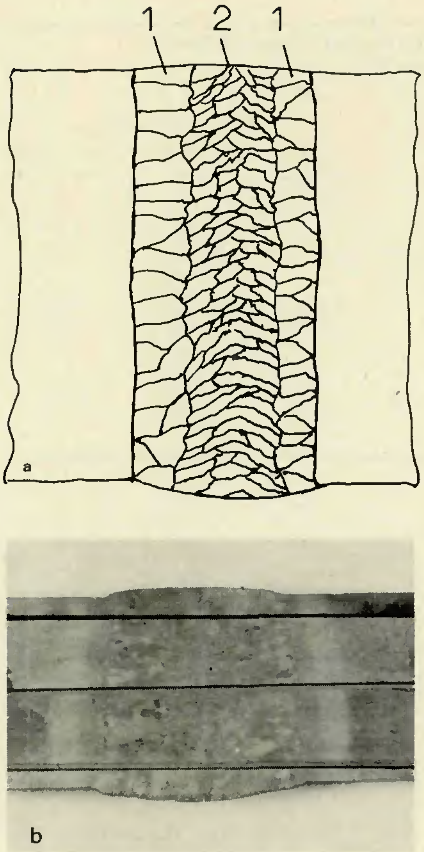

Fig. 5 — (a) Sketch of electroslag weld structure Type 1 (after Paton). Area 1 is coarse grained, area 2 has finer grains. (b) Transverse section of the weld area. Note the coarse grained and finer grained regions

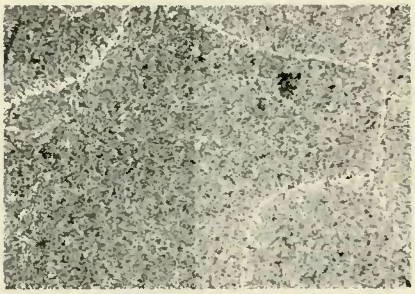

Fig. 6 — Microstructure of the weld metal in the as-welded condition. Note the large prior austenite grain size. 2% nital etch, X65, reduced 64%

normalized and stress relieved base metal reaches the limit of plane strain at temperatures of −100 F (−75 C) and above. The weld metal exhibits low K_{IC} values in all tests as high as −50 F (−45 C). Considerable improvement ensues from stress relief, but normalizing has no additional benefit. The as-welded HAZ is tougher than the weld metal but very similar to it after either heat treatment. The COD values show the same trends as those described for the fracture toughness. Some of the HAZ data are distorted by a tendency for the fracture path to migrate to the weld metal.

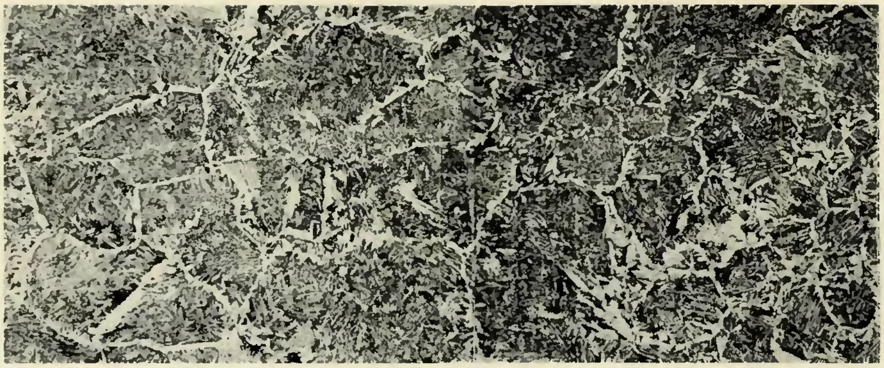

Fig. 7 — Microstructure of the heat-affected zone as-welded, 2% nital etch, X65, reduced 44%

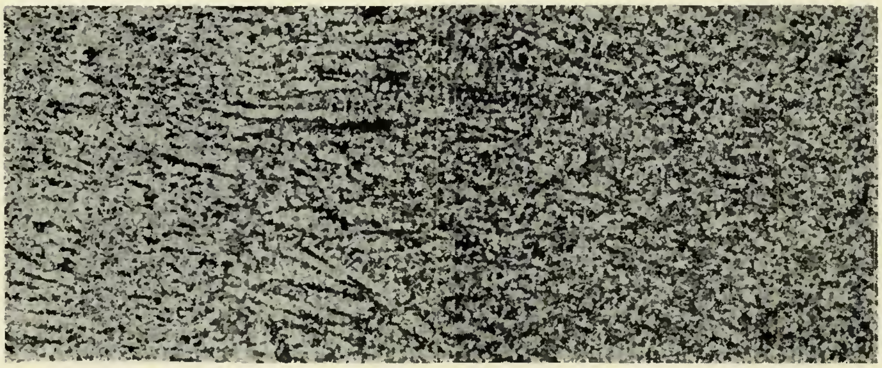

Fig. 8 — Microstructure of the heat-affected zone normalized and stress relieved. 2% nital etch, X65, reduced 44%

Metallographic Examination

The macrostructure of electroslag weld metal often takes the form shown in Fig. 5. Coarse columnar grains grow inward toward the center where a zone of somewhat finer grains develops. The coarseness of the weld metal is visible in Fig. 6, which shows only a portion of a grain. The heat-affected zone is much less coarse, as shown in Fig. 7, but the grain size is ASTM 0 to 1. Normalizing refines the grain size considerably but not completely (Fig. 8). In all cases the constituents of the microstructure are ferrite and pearlite, but their orientation and size are widely varied according to the thermal cycle imposed at their location by the welding operation. In carbon-manganese steels, it is the microstructure primarily that controls fracture toughness.

Summary

The results of this study may be summarized as follows:

1. The A537 steel normalized and stress relieved in 2 in. thickness showed good properties in notch toughness and fracture toughness tests above −100 F (−75 C).
2. In the as-welded condition, the weld metal and heat-affected zone of an electroslag weldment exhibited transition temperatures more than 100 F (55 C) above the base metal and suffered corresponding losses in fracture toughness.
3. Stress relieving erased a large fraction of the differences and normalizing + stress relieving removed nearly all the differences in Charpy V-notch toughness of the weld metal and HAZ compared to base metal. Fatigue-precracked Charpy tests did not corroborate this improvement for the weld metal.
4. The improvement in the weld metal and the HAZ possible by stress relief or by normalizing and stress relief is also shown clearly by fracture toughness tests.
5. The results of this study suggest that electroslag weldments will not provide the notch toughness expected of low temperature steels such as A537, unless heat treatment is subsequently applied.

Acknowledgment

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