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**Federal Highway
Administration**

Industrial Field Trials of Oregon Graduate Institute-Developed Electroslag Welding Technology

Research and Development
Turner-Fairbank Highway Research Center
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McLean, Virginia 22101-2296

FOREWORD

The purpose of this report is to document the results of field trials that demonstrated that laboratory-developed practices and procedures for electroslag welding can be incorporated into commercial fabrication facilities.

Results of field trials at four commercial fabricators using developed practices and procedures for electroslag welding are reported. Each site was provided with plate sections and consumables to provide a common basis for comparison of results. Impact toughness tests were conducted on welds from each site and compared to results obtained from laboratory tests. The results demonstrated that the developed practices can be incorporated into commercial practice.

This report is intended for welding engineers, weld inspectors, and those organizations concerned with welded fabrication of thick-section structural steel members.

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Director, Office of Advanced Research

NOTICE

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16. Abstract
The primary objective of this program was to demonstrate that the Oregon Graduate Institute (OGI)-developed electroslag welding (ESW) technology can be successfully implemented in commercial fabrication shops. Consequently, opportunity was provided to evaluate the transferability of ESW technology and to develop additional ESW mechanical property data from commercially fabricated weldments.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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LIST OF ABREVIATIONS

OGI	Oregon Graduate Institute
ESW	Electroslag Welding
HAZ	Heat-Affected Zone
CVN	Charpy V-Notch
UCS	Units of Crack Susceptibility

INTRODUCTION

The primary objective of this project was to demonstrate that the Oregon Graduate Institute (OGI)-developed electroslag welding (ESW) technology can be successfully implemented in commercial fabrication shops. Consequently, opportunity was provided to evaluate the transferability of ESW technology and to develop additional ESW mechanical property data from commercially fabricated weldments.

Four structural steel fabricators participated in the project by making a variety of electroslag welds following practices and procedures under their shop conditions. Each fabricator produced welds assigned from a matrix of A36, A572, and A588 alloy steels in 25-, 50-, and 76-mm thickness. An identifical set of welds were produced and then submitted to destructive and nondestructive evaluation methods for a complete comparison of results.

SUMMARY

Results of initial electroslag welding field trials at four commercial fabricators using OGI-developed and recommended practices and procedures are reported. Three alloys and three plate thicknesses were welded, including transition joints. The welding consumables and test plate sections were supplied in order to allow comparison between various site results and to have some comparative basis. Additionally, the same welds were made using the same materials in order to compare prior results, current results, and field results. Objectives included: (1) confirming that practices could be carried out in commercial fabrication facilities, (2) verifying that impact properties comparable to prior welds could be obtained, and (3) collecting input on the acceptability of electroslag welding practices.

A total of 33 welds were successfully completed on alloys A572, A588, and A36 steel plate. Welds were made on 25-, 50-, and 76-mm-thick plate and as a transition between 50- to 25- and 76- to 50-mm-thick plate. All fabricators were able to use the established procedures and they completed the welds after an initial demonstration weld. Subsequent welds were witnessed. Impact toughness assessment was conducted in weld metal and in the coarse heat-affected zone (HAZ) region immediately adjacent to the weld fusion line. The results confirmed that satisfactory weld metal toughness can be achieved at the weld midthickness, if a predominantly acicular ferrite microstructure is achieved. This can be achieved by using OGI-established guidelines and practices. As the plate thickness increases to 76 mm, the increased heat input requires additional attention to weld setup, alloying chemistry, and operating procedures in order to maintain satisfactory Charpy impact toughness.

Radiographic testing revealed hot cracking in one 76-mm-thick A36 alloy welded at a commercial site and one 76-mm-thick A572 weld. This occurrence has been explained based on a carbon equivalent analysis and indicates that for thicker sections, more attention must be paid to staying within safe weld metal carbon equivalent ranges.

Overall, the field trial results demonstrated that practices can be carried out in commercial facilities, that proper weld metal microstructure achieved by alloy and process control will result in satisfactory impact toughness, and that HAZ toughness is maximized when overall heat input is minimized. The latter is especially important as section thickness increases. Finally, carbon equivalent considerations should be taken into account as the section thickness increases.

BACKGROUND

The electroslag field trials reported in this report incorporate the practices and procedures for reliable electroslag programs conducted at the Oregon Graduate Institute under contract to the Department of Transportation.

Electroslag welding, a high deposition-rate welding process widely used 20 years ago, has been prohibited from use in tension members since the early 1970's due to problems with fabrication-related defects and concerns about low impact toughness. A technology was developed for applying the electroslag welding process that improves the reliability, toughness, and productivity of these weldments.

Improved ESW integrity and reliability were accomplished by modification of the consumable guide tube design; reduction of the weld joint spacing; use of alloyed tubular electrode wire; continuous flux additions; and by establishing a sound window of operation for voltage, current, and the rate of travel. Collectively, these newly developed practices and procedures result in a more uniform weld cross section, a tougher microstructure, improved HAZ toughness, and reduced probability of weld-related defects. Furthermore, these practices significantly reduced the welding time.

Laboratory analysis has included extensive microstructural evaluation, toughness determination (both by Charpy testing and by full-thickness plane strain fracture toughness testing), and large-scale fatigue testing. Finally, a satisfactory shielded metal arc weld repair technology was demonstrated, and acceptable fatigue behavior was confirmed. The results of the ESW improved practices and procedures, together with the results of all mechanical properties developed, are reported in detail in two Department of Transportation reports (DOT-11-9612 and FHWA-RD-87-026) and in a draft report.

An important consideration throughout the development of improved practices and procedures was the recognition that these improvements must be capable of being implemented in commercial fabricator facilities. Hence, a field trial program was designed to determine if OGI-developed practices could be successfully implemented in industry. This report contains a description and results of field trials conducted at four commercial fabricator sites and also at the developer's site for comparison.

PROCEDURE

All of the consumables and electroslag-specific equipment used for the field trials were provided by the developer. Supplied equipment included cooling shoes, electroslag wire feed drive assembly, electroslag wire feeder, flux metering system, control assembly, and weld monitoring devices, including an amperage strip chart recorder, digital volt meter, and electrode feed speed meter. The steel fabricators provided: a water supply for the weld cooling shoes, a flux storage oven, welding cables, a constant voltage direct current welding power supply, shop facilities, and welding personnel. All components, except for the cooling shoes, were commercial items.

TRAINING/MONITORING

Welder training at each fabricator site consisted of a single demonstration weld on a 25-mm-thick plate, and advice throughout the completion of the trial electroslag welds. The intent was to demonstrate that the welds could be made at each site, and training was provided only to the extent necessary in order to complete the welds. There was not enough time, nor the intent, during these trials to provide detailed or comprehensive operator training.

The ESW procedures for each weld were monitored by an engineer. Amperage was measured by an eddy current sensing device around the welding power cable, located approximately 500 mm from the ESW guide tube connection. Current values were traced on a time-based strip chart recorder and provided welding time records as well. Slag pool conditions were monitored by the amperage records. A current trace with only minor fluctuations indicated proper slag pool conditions. Current traces that exhibited spiking or extreme fluctuations indicated depleted slag pool conditions and were corrected by increasing the rate of continuous flux addition until the current was again stabilized.

Voltage was measured between the guide tube holder and the welding ground connection at the steel base plate. Any change in welding voltage was noted on the strip chart amperage record at the time of occurrence.

Wire feed speed was digitally displayed in inches per minute on a commercial wire feed meter. The electrode wire feeder was a dual-wire drive design with a single drive motor. Since both drive rolls turned at the same rate, only one electrode wire speed was monitored and the value was doubled on the 76-mm welds where two electrode wires were required.

ALLOYS

The steel plate required for welding in this project included 25-, 50-, and 76-mm-thick alloys of ASTM Type A36, A572-50, and A588. Plate was provided to the fabricator in 305- by 457-mm rectangular sections. Run-in and run-out material of matching composition was also provided for each weld. A list of alloys with manufacturers and heat numbers is provided in table 1.

Table 1. Alloy steels for ESW.

ASTM Alloy	Grade	Thickness (mm)	Manufacturer	Heat Number
A36-89	---	25	Geneva Steel	94A528
A36-89	---	50	Geneva Steel	96A984
A36-87	---	75	USIMINAS	129795
A572-85	50	25	Geneva Steel	91A245
A572-85	50	50	Geneva Steel	92E196
A572-85	50	75	Geneva Steel	2R8151
A588-88	A	25	Oregon Steel Mills	318528
A588-88	A	50	Oregon Steel Mills	323149
A588-88	A	75	Oregon Steel Mills	331483

WELD MATRIX

Each alloy group was welded in five joint configurations that included a 25-mm-thick butt weld, a 25- to 50-mm transition butt weld, a 50-mm butt weld, a 50- to 76-mm transition butt weld, and a 76-mm-thick butt weld. Both transition joints were designed with a 1 in 2.5 bevel on the thicker member as shown in the cooling shoe and weld joint diagram of figure 1. A set of transition cooling shoes was designed and fabricated to match the transition angle.

The full matrix of welds is provided in table 2, including the letter identification assigned to each weld. Upper case letters identify fabricator welds and lower case letters identify welds. Three additional 76-mm butt welds on A36 alloy were made beyond the balanced matrix of alloys and joint types. Those extra welds provided each fabricator with the experience of welding with the two-wire wing and web guide tube. The three extra welds were not included for mechanical property evaluation, but were radiographed and defects were reported. Each weld made by the fabricator was reproduced to provide a direct comparison of weld results.

Flux was premeasured and packaged for each weld condition, then dried in a flux oven at 120 °C for 24 h prior to welding by each fabricator. PF 201 electroslag welding flux was used for all welds in this project and was from the same lot number as that used in "Improved Fracture Toughness and Fatigue Characteristics of Electroslag Welds" research. Flux volumes and continuous feed rates are listed with the summarized weld procedures in table 3.

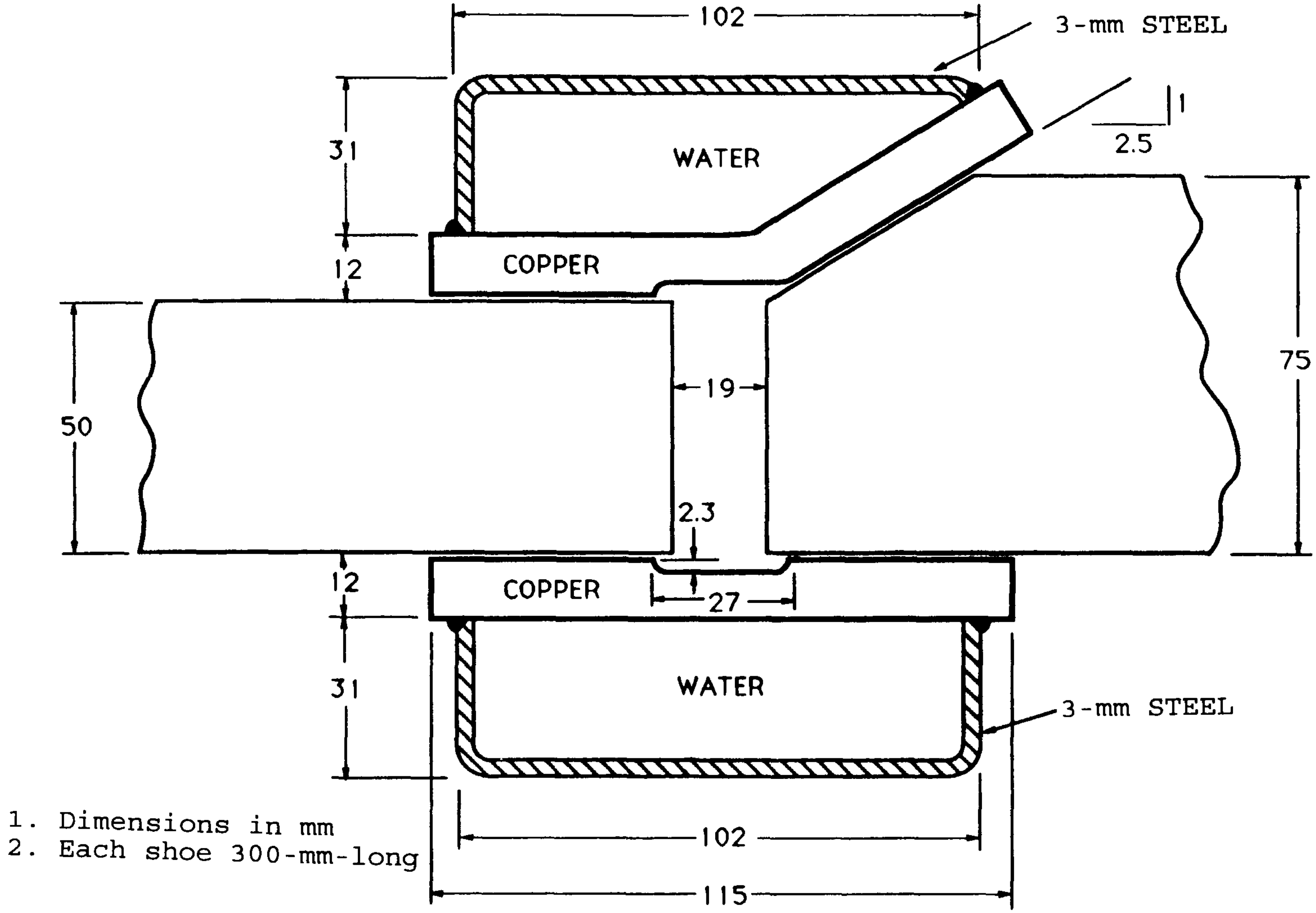


Figure 1. Schematic representation of 300-mm-long cooling shoes on a 1 in 2.5 transition joint.

Table 2. Weld identification.

Weld ID Field/Lab[1]	Alloy	Joint Type	Fabricator[2]
A/a	A36	25-mm Butt	R1
B/b	A572	25-mm Butt	R2
C/c	A588	25-mm Butt	R3
D/d	A36	25- to 50-mm Transition	R1
E/e	A572	25- to 50-mm Transition	R2
F/f	A588	25- to 50-mm Transition	R3
G/g	A36	50-mm Butt	R2
H/h	A572	50-mm Butt	R1
I/i	A588	50-mm Butt	R3
J/j	A36	50- to 76-mm Transition	R4
K/k	A572	50- to 76-mm Transition	R4
L/l	A588	50- to 76-mm Transition	R4
M/m	A36	76-mm Butt	R4
N/n	A572	76-mm Butt	R4
O/o	A588	76-mm Butt	R4

[1] Each weld is identified by an upper case letter that provides the alloy, joint type, and fabricator. For ease of comparison, the field welds are identified with capital letters and the lab welds are identified by the matching lower case letter.

[2] The fabricators are identified by their respective AASHTO geographic region:

R1 - Lancaster, PA
R2 - Montgomery, AL
R3 - Wausau, WI
R4 - Portland, OR

Table 3. Welding procedures.

	25-mm Butt Weld	25- to 50-mm Transition	50-mm Butt Weld	50- to 76-mm Transition	76-mm Butt Weld
Guide Tube	60- by 19-mm Wing	60- by 19-mm Wing	60- by 38-mm Wing	60- by 38-mm Wing	60- by 63.5 mm Wing and Web
Flux (grams)	100	100	190	190	280
Amperage	650	650	950	950	1300
Wire Feed (mm/min)	736	736	978	978	558 (X2)

Common Conditions

Flux Type	-	PF201
Flux Feed Rate	-	4 g/min
Electrode Wire	-	ST 8544, 0.937 mm
Joint Space	-	19 mm (23 mm at top of 76-mm-thick weld, 22 mm at top of all others)
Power Type	-	Direct current electrode positive
Voltage	-	36 to 37

ELECTRODE MATERIAL

Electrode wire for all of the comparison welds in the test matrix was limited to a 2.39-mm-diameter type TW8544. Composition of the electrode wire and guide tube for this project and the electroslag research programs are shown in table 4. The guide tubes were fabricated from 1.5-mm wall, J-525 seamless steel tubing and cold-rolled steel strap both of type AISI 1018 carbon steel. A diagram of the guide tube for each weld joint type is provided in figure 2.

Table 4. ESW consumables composition.

Material	C	Mn	Si	Ni	Mo	S	P	V
Electrode Wire								
TW 8544-86[1]	0.030	1.20	0.45	2.30	0.45	0.02	0.02	0.05
TW 8544-90[2]	0.017	1.05	0.25	2.70	0.43	0.01	0.01	0.04
TW 8544-91[3]	0.027	1.12	0.32	2.12	0.41	0.02	0.02	0.03
Guide Tube								
Tubing J-525[4]	0.180	0.45	0.23	---	---	---	---	---
Cold-Rolled Strap 1018	0.180	0.43	0.27	---	---	---	---	---

[1] TW 8544-86 used in the 1986 ESW Research "Improved Fracture Toughness and Fatigue Characteristics of Electroslag Welds."

[2] TW 8544-90 used in this 1991 ESW Demonstration Project.

[3] TW 8544-91 used for demonstration welds only, no mechanical properties reported.

[4] J-525 Tubing 6.35- by 1.24-mm wall, typical analysis.

WELDING

The consumable guide narrow gap ESW practices closely followed the recommendations in the report to the FHWA, entitled "Improved Fracture Toughness and Fatigue Characteristics of Electroslag Welds."(1987) A summary of welding procedures used for the five weld conditions in this project is provided on table 3. Included are detailed procedures (appendix A) and ESW practices (appendix B), as provided to each fabricator.

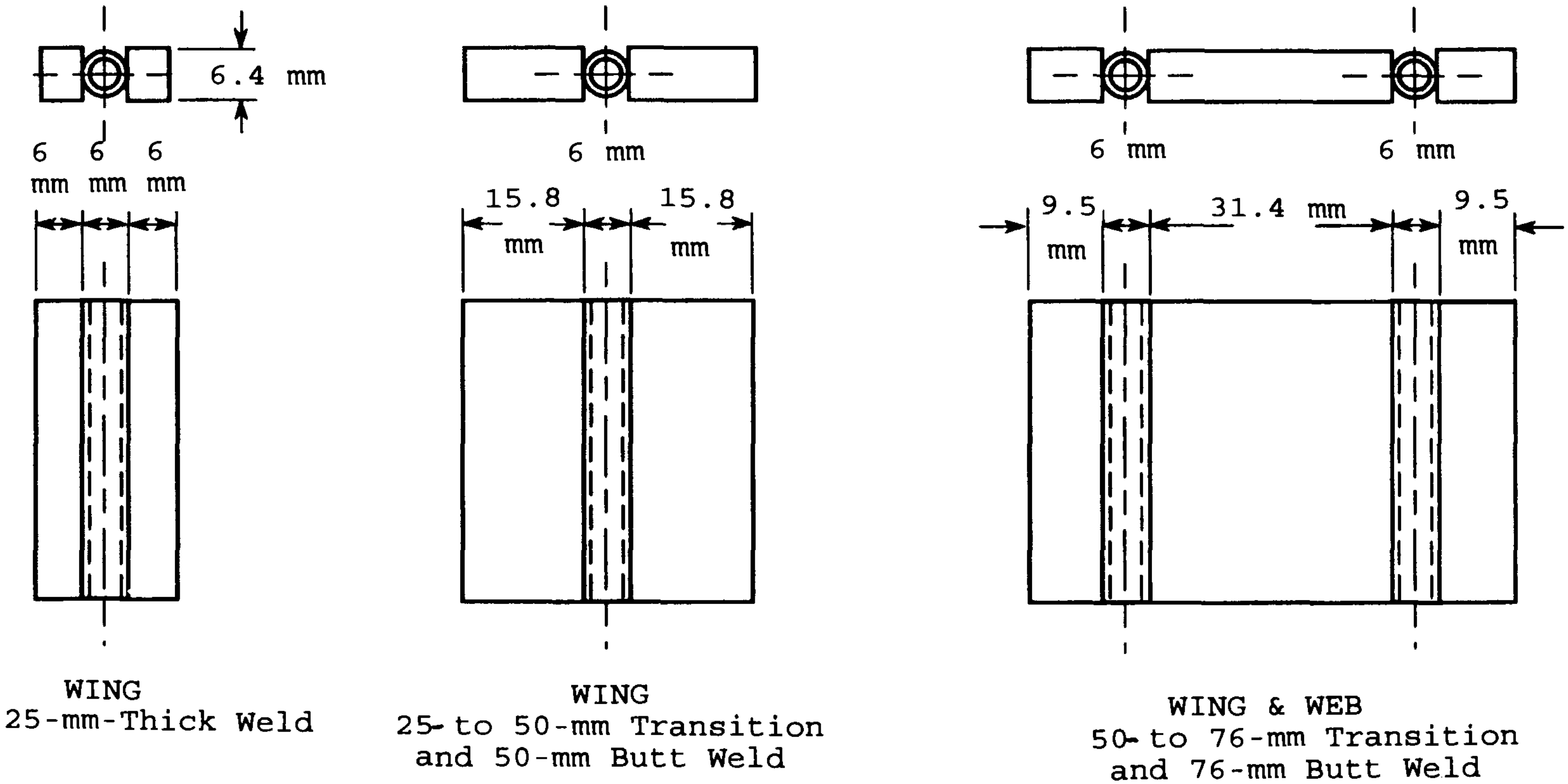


Figure 2. Guide tube design.

A fixture was provided to position the weld plates and avoid the use of strongbacks or braces that would otherwise require the use of tack welds outside the ESW joint area. This also simplified the weld setup and improved the consistency of restraint across the weld joint. Photographs of a complete weld setup, including the electrode wire drive and flux feeder, are shown in figure 3.

NONDESTRUCTIVE TESTING

Each weld was radiographically examined by a commercial inspection service in compliance with AWS D1.1 specifications. Nondestructive testing had not been performed on the plate material prior to welding, therefore, both the weld and adjacent plate material were carefully examined.

MICROSTRUCTURAL ANALYSIS

Every weld had a 12-mm transverse section bandsawed from a position 50 mm below its concluding end. After surface grinding the weld and base plate cross section, a 10-percent nital etchant solution was applied to reveal the grain structure of the weld metal and HAZ. Each weld macrosection was photographed and the weld volume was measured with a grid system on an Image Analysis System, as shown in figure 4. The computer imaging system determined the weld area by counting the pixels required to present the image on the monitor.

CHARPY IMPACT TESTING

Standard ASTM E23 Charpy V-notch (CVN) impact specimens were machined from the midplate thickness of each weld. Notch placement was determined by etching each Charpy bar with a 10-percent nital solution to reveal the weld metal grain structure. A minimum of three CVN tests were made at three locations: first, the weld centerline; second, the mid-distance between the weld centerline and fusion boundary (1/4W); and third, the coarse-grained HAZ. All three CVN locations are illustrated in figure 5. A schematic diagram of typical HAZ microstructure is given in figure 6 to demonstrate the difficulty of accurately locating the fracture path through course HAZ microstructure. Only HAZ Charpy impact tests exhibiting course-grain HAZ fracture surface characteristics were included in this test data. All three CVN regions were tested at -12 °C and an additional HAZ set was tested at 4 °C.

Three CVN bars were tested at 4 °C from each base material alloy and thickness to determine AASHTO zone 2 comparison. These bars were taken from midplate thickness to match the weld metal tests rather than the normal AASHTO 5.8-mm plate thickness position.

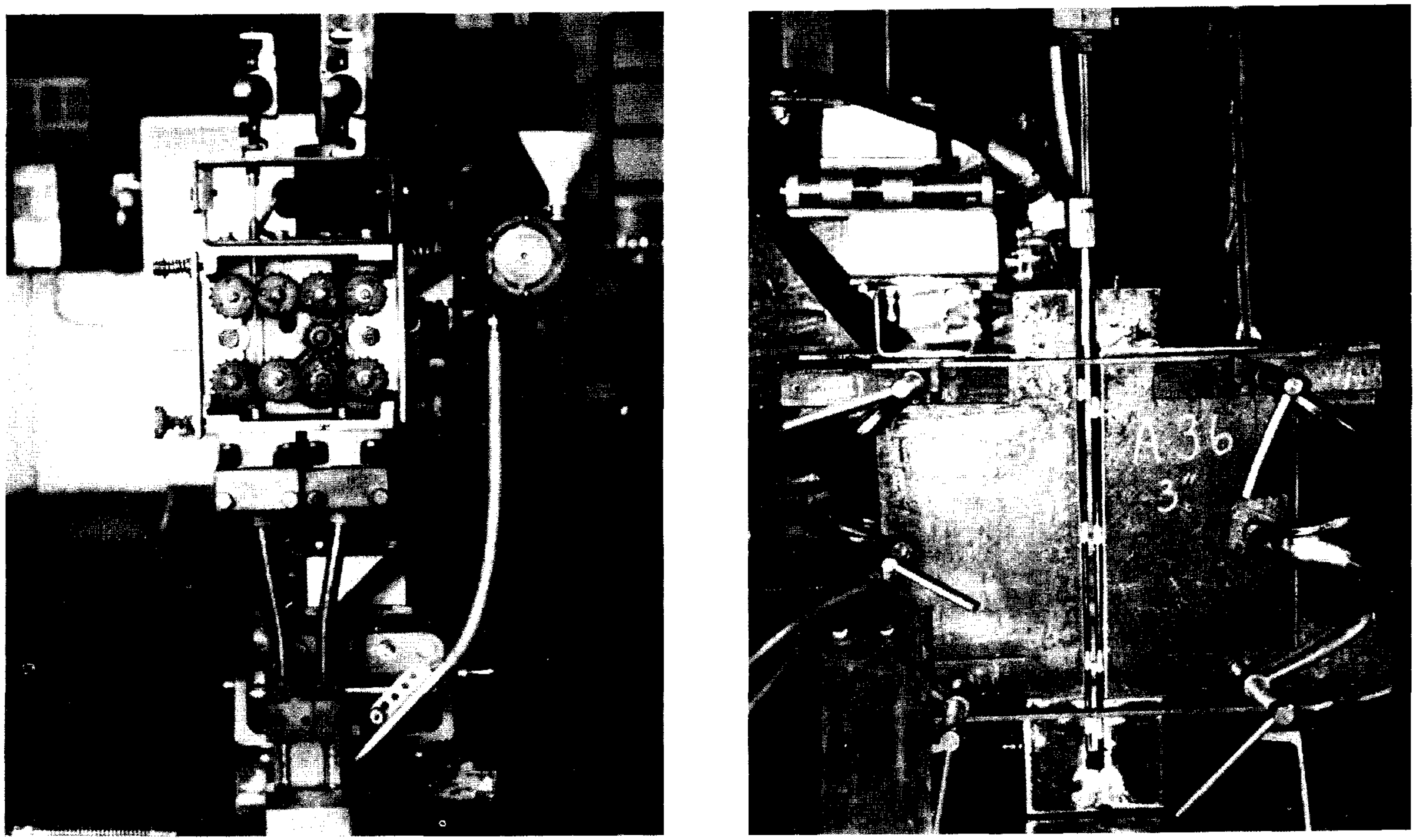


Figure 3. Weld setup.

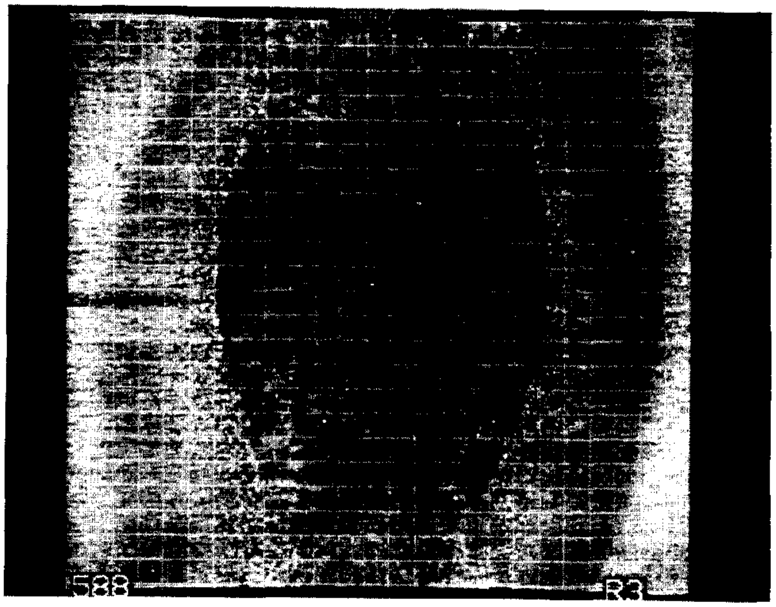


Figure 4. Weld area grid from an image analysis system superimposed upon 76-mm-thick ESW.

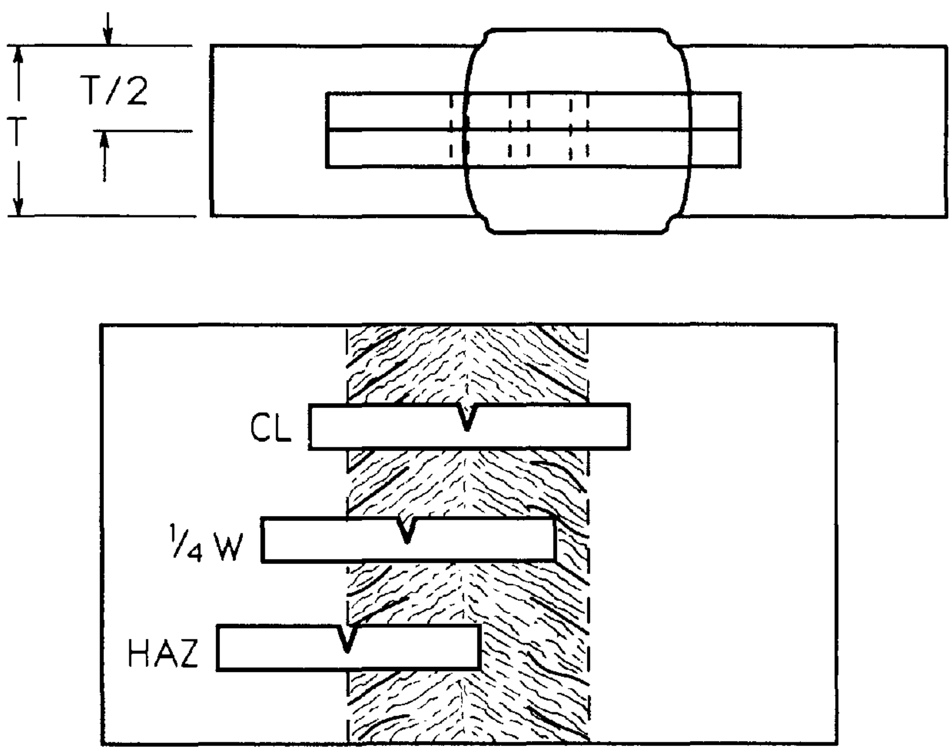


Figure 5. Charpy V-notch location in ESW.

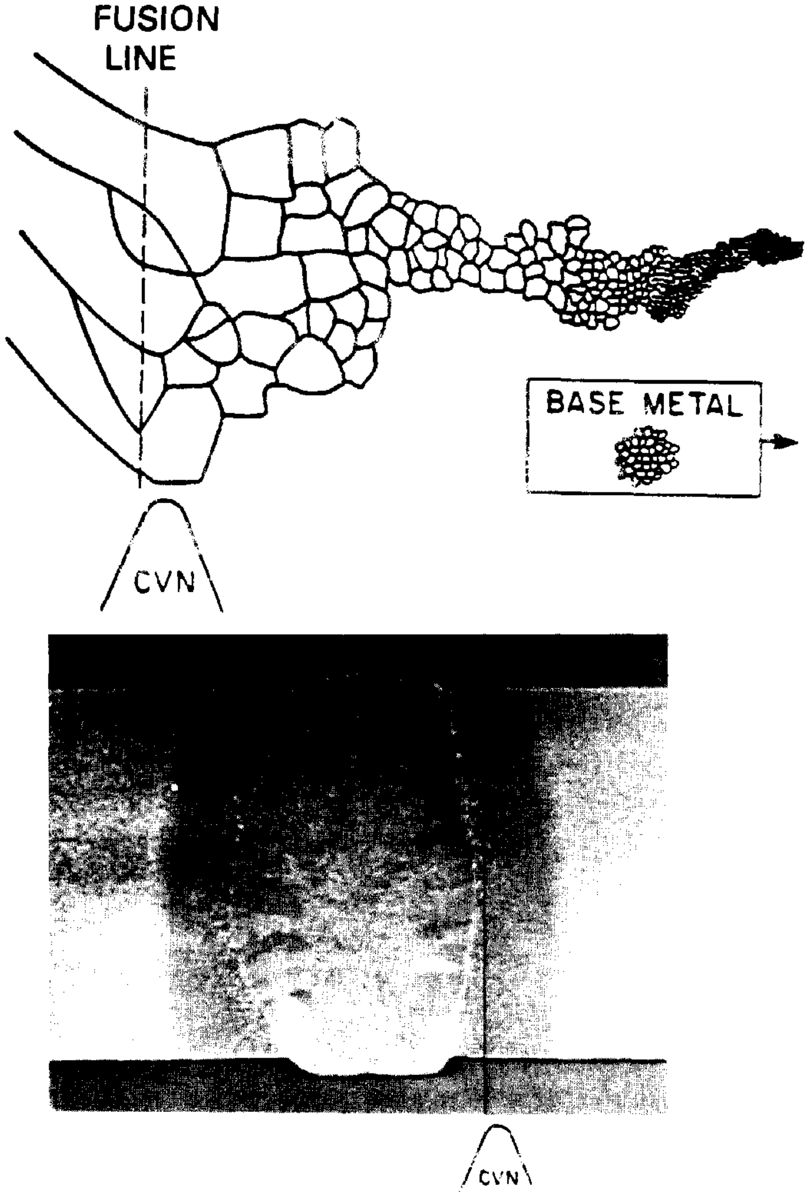


Figure 6. Charpy V-notch location for HAZ toughness values.

HARDNESS TESTING

Hardness testing was applied to every weld using the Rockwell B scale with a 1.58-mm ball indentor under 100-kg load. Hardness locations were identical to the CVN locations at the weld centerline, 1/4W, and HAZ, plus an additional location 25 mm from the weld fusion boundary in the unaffected base metal. All of these hardness tests were at the midplate thickness.

CHEMICAL ANALYSIS

Samples were removed from the center cross section of each weld and etched with a 2-percent nital solution to reveal the microstructure. Micrographs at X 50 magnification were made of each sample. Chemistry was determined for every weld through spark spectrographic analysis on samples removed from the same weld region as the micrometallographic samples.

RESULTS

PARTICIPATING STEEL FABRICATORS

One commercial steel fabricator from each of the four AASHTO regions participated in this project by completing the assigned welds shown in table 3. A list of participating fabricators is provided in table 5. Each fabricator had some experience with consumable guide standard practice ESW within the past 10 years, but none were presently using the process. Electroslag welding experience was not a prerequisite for participation in this program.

The demonstration program was open to any interested observers, particularly Federal, State, and commercial inspectors in the respective regions.

Table 5. Participant rubrics.

AASHTO Region	City and State	Date of Work	Power Supply
1	Lancaster, PA	4-30/5-3	DC1500
2	Montgomery, AL	5-6/5-8	RC1000
3	Wausau, WI	4-24/4-26	DC600
4	Portland, OR	5-14/5-16	R3S-600

EQUIPMENT

The welding power supplies used at each demonstration site are included in table 5. Domestic water was provided in each location for the ESW cooling shoes and the outlet hoses were routed to a visible drain to allow monitoring of general flow rates and water temperature.

TRAINING/MONITORING

Operator training was conducted at each fabricator location by an engineer, following the list of welding practices (see appendix B). All of the training welds were made on 25-mm-thick plate of unspecified alloy composition as provided by the fabricator.

Every weld was monitored by an engineer to guarantee compliance with welding procedures. Due to shipping damage to the recorder, strip chart records are not available for welds made at region 3 (R3) and for one weld at region 1 (R1). Weld time was typically 9.5 min for 25-mm-thick welds, 15 min for 50-mm-thick welds, and 14 min for 76-mm-thick welds. The welding time includes the 72-mm run-in length, 457-mm weld plate length, and 50-mm weld run-out for a total of 584-mm weld length.

RADIOGRAPHY

Every weld was radiographed by a commercial testing laboratory. Seven welds had indications, all of which were verified by sectioning. Three of the indications were clearly visible from the surface. Weld "K" had noncritical undercut on the 50-mm side of the 50- to 76-mm transition welds. Weld "B," region 2 (R2), had slag inclusions resulting from a weld restart 130 mm from the weld plate starting edge that was detectable by visual examination and was confirmed by radiography to be 25 by 38 mm in area. Weld "M" (R3) had visible incomplete fusion over much of the weld length due to improper weld joint spacing.

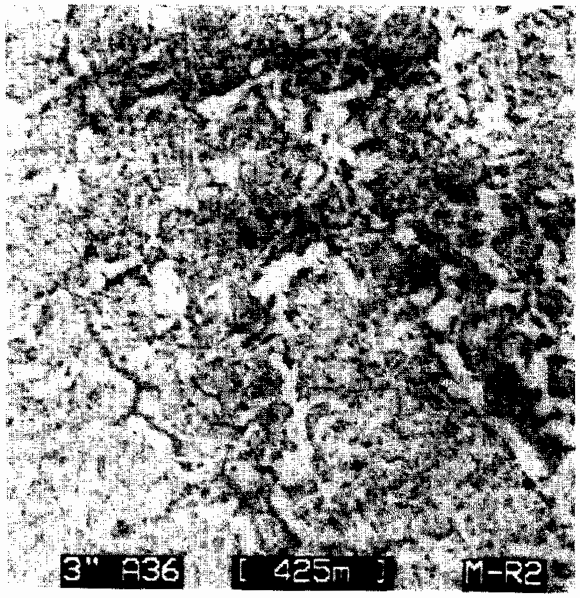
Radiographs of weld "o" and weld "O" (R3), both 76-mm butt weld in A588 alloy, exhibited porosity that appeared to start near the fusion boundary and curve upward to the weld center line. Weld "o" had two indications, both approximately 6 mm wide and 19 mm long, at 190 and 350 mm above the starting end of the weld plate. Weld "O," region 4 (R4), had a cluster of five porosity indications, each about 2 mm in diameter, clustered in a 10-mm-diameter area, 15 mm below the top end of the weld plate. A transverse macrograph of the cluster porosity in weld "O" (R4) and a longitudinal macrosection of the upper inclusion in weld "o" are shown in figure 7.

Hot cracking was clearly evident in weld "M" (R2) and only slightly evident in weld "n". The slight indication on weld "n" was partly due to a poor quality radiograph. Transverse and longitudinal macrographs of both welds are shown in figures 8 and 9, respectively. A longitudinal section of weld "n" appears in figure 9(c), where the 1.0 form factor of the weld pool is revealed by the solute banding lines.

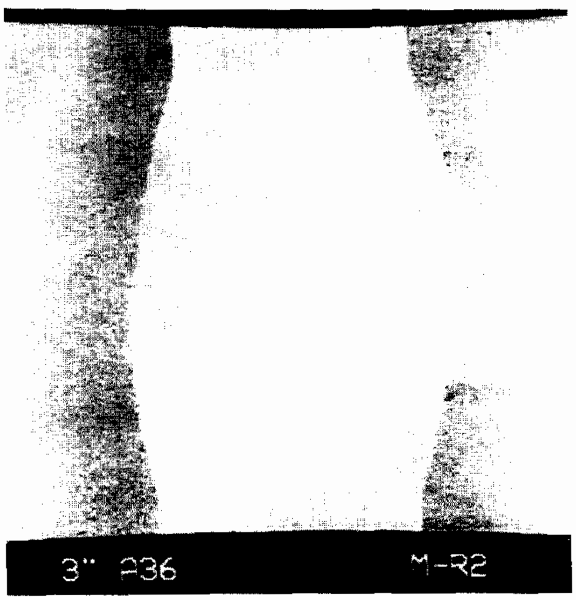
Transverse Section of Weld "O" (R4)

Longitudinal Section of Weld "o" (OGI)

Figure 7. Porosity evolved from HAZ at the plate centerline.



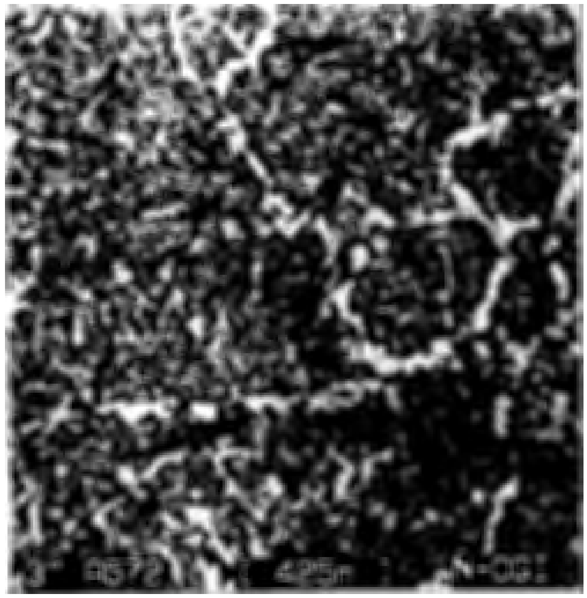
(a)
Weld Center (μm) x 50



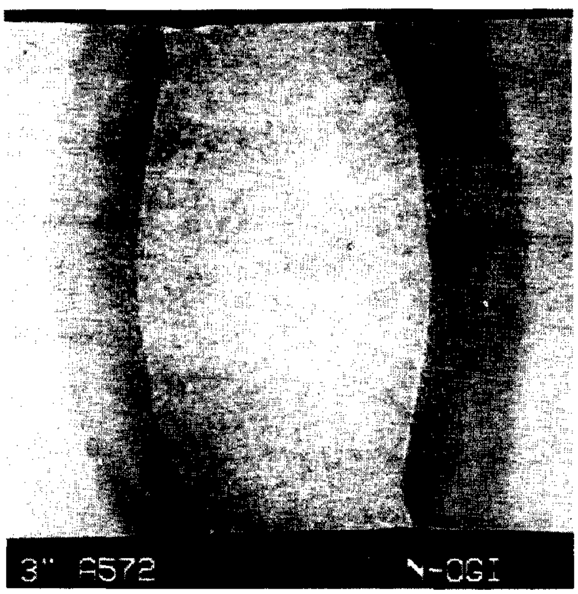
(b)
Transverse Weld Section

(c)
Longitudinal Weld Section

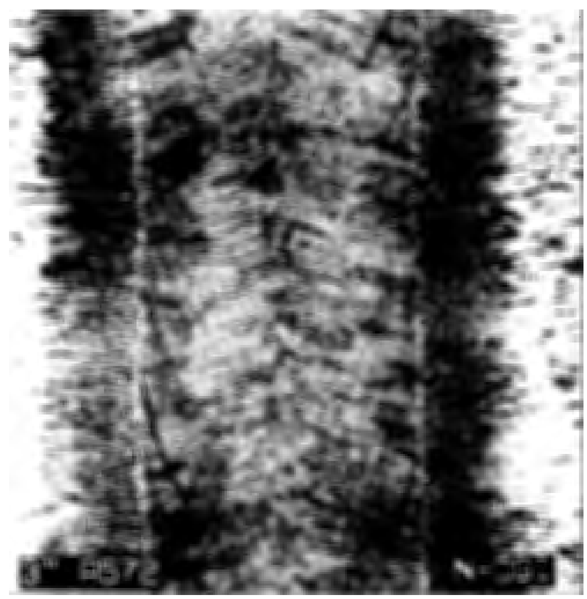
Figure 8. Micrograph (a) and macro [(b) and (c)] of ESW M-R2 with hot cracking.



(a)
Weld Center (μm) x 50



(b)
Transverse Weld Section



(c)
Longitudinal Weld Section

Figure 9. Micrograph (a) and macro [(b) and (c)] of ESW N-OGI with hot cracking.

MICROSTRUCTURE

Transverse sections of all but the redundant 76-mm welds are shown in figures 10 through 23. The fabricator weld is at the top of each figure and the corresponding weld is at the bottom. The percent of base metal dilution was measured from these weld cross sections, assuming a constant 19-mm weld joint spacing (the results are included in table 6).

Micrographs taken at the weld center are shown to the right of each weld cross section in figures 10 through 23. Every weld contains a predominant acicular ferrite microstructure and generally, increasing volumes of proeutectoid ferrite on thicker weldments.

Chemistry derived through spark spectrographic analysis is provided for each weld in table 6, and includes percentage of base metal dilution. Chemistry data is not shown for the duplicate 76-mm A36 welds identified as "M" (R1-3) since they are duplicate values. Weld "M" (A2) was analyzed because of its hot cracking condition and it contained 0.12 percent C, 0.92 percent Mn, 0.23 percent S, 0.018 percent Cr, 0.90 percent Ni, 0.163 percent Mo, and 46 percent dilution.

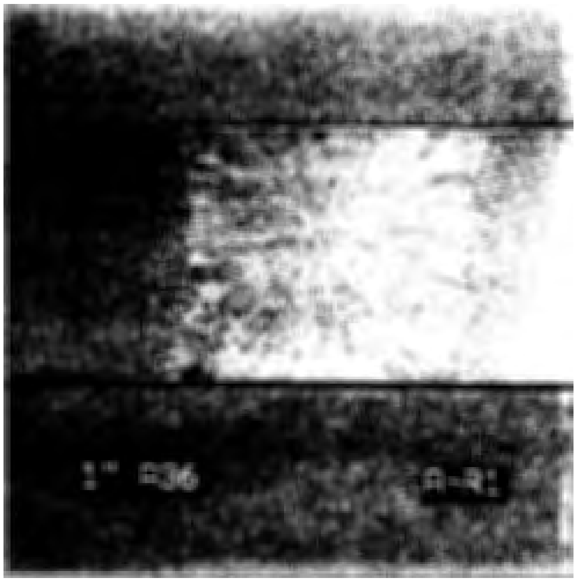
The chemistry for each base metal alloy and thickness is provided in table 7, and is from spark spectrographic analysis rather than from the manufacturers certification sheets. Carbon levels at the high end of the allowable range are shown for all thicknesses of A588 and A572 alloys.

HARDNESS

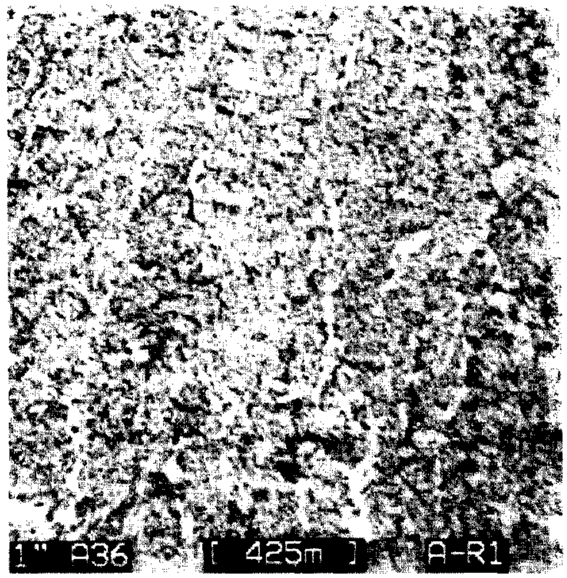
Weld and base metal hardness values from the Rockwell B scale 1.58-mm ball indentor are shown in table 8 for each weld, HAZ, and unaffected base metal at the midplate thickness. The weld and HAZ range for all three alloys was 80 to 95 Rockwell B. The A36, 25-mm plate had a range of 72 to 79 Rockwell B as received that increased to a more uniform 86 to 87 Rockwell B in the weld HAZ, and 91 to 93 Rockwell B across the weld. The A572 alloy weld and HAZ hardness is nearly identical to the as-received material.

IMPACT TOUGHNESS

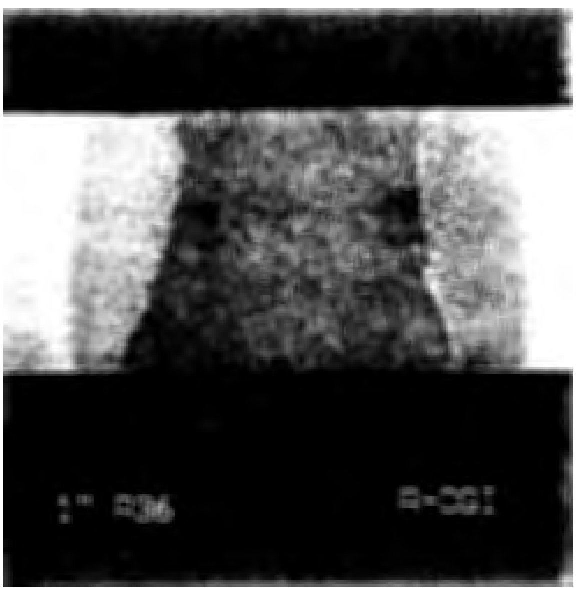
Average CVN impact data for each weld, HAZ, and as-received alloy is presented in table 9. Values for individual CVN bars are presented in table 10. The base metal alloy CVN bars were machined from the plate midthickness to compare with the location of weld and HAZ samples. Only two samples were tested for 25-mm A588 base metal as



Fabricator Weld "A"



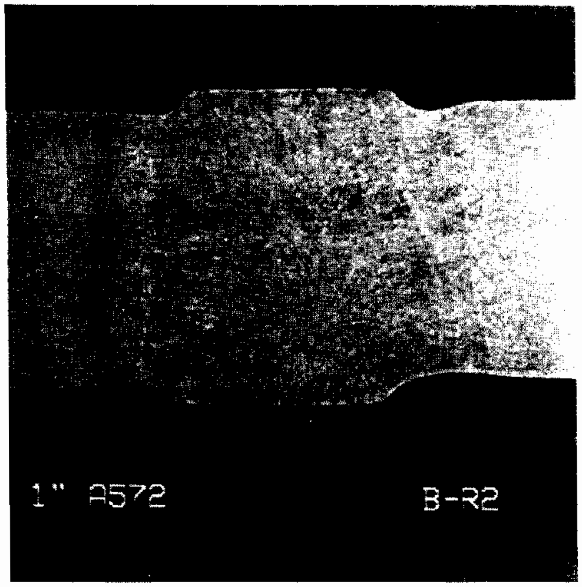
Weld Center X 50



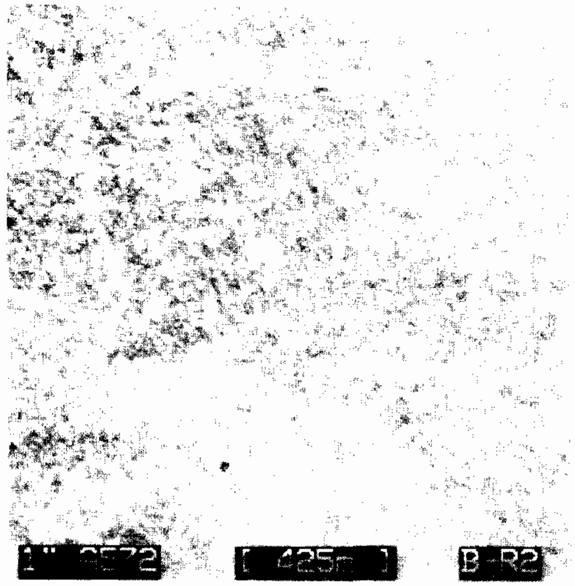
Weld "B"

Weld Center X 50

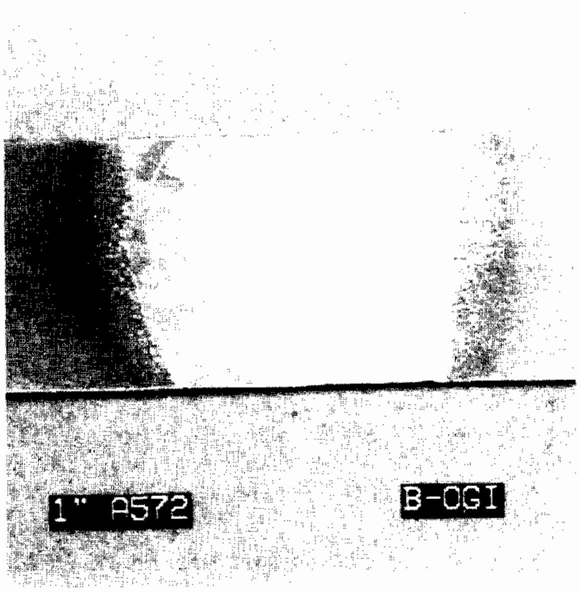
Figure 10. Macro and micrographs of 25-mm A36 ESW.



Fabricator Weld "B"



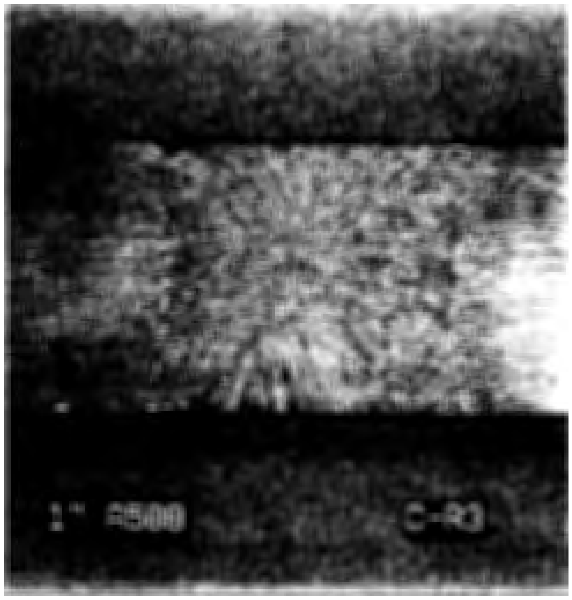
Weld Center X 50



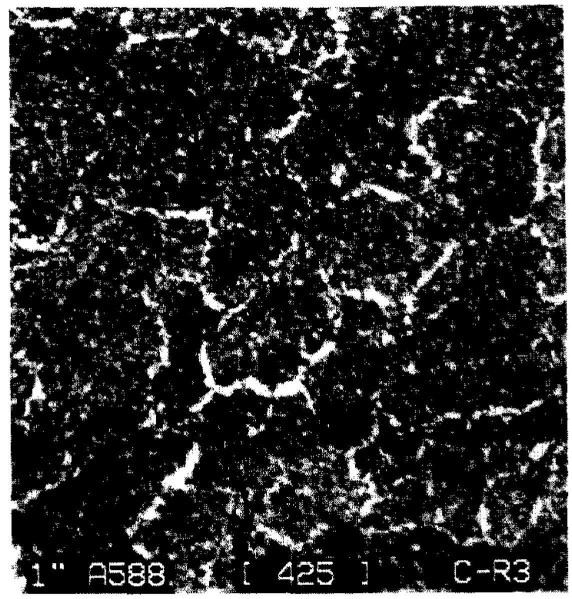
Weld "b"

Weld Center X 50

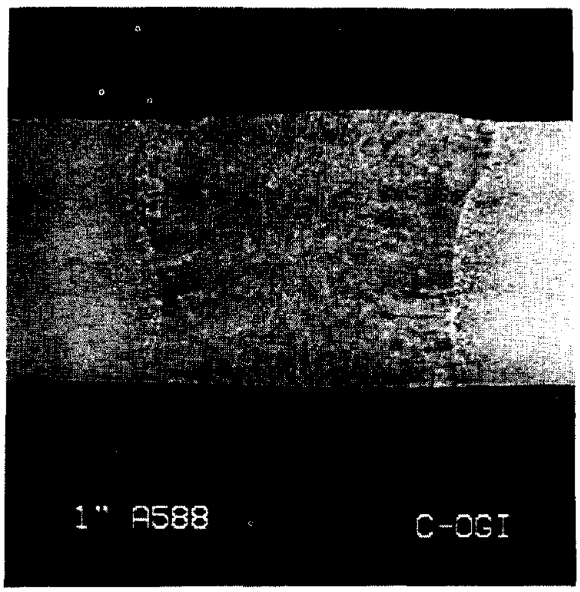
Figure 11. Macro and micrograph of 25-mm A572-50 ESW.



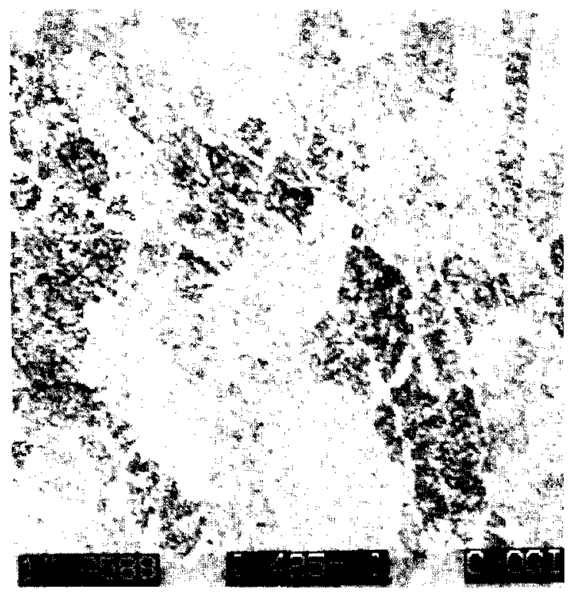
Fabricator Weld "C"



Weld Center X 50

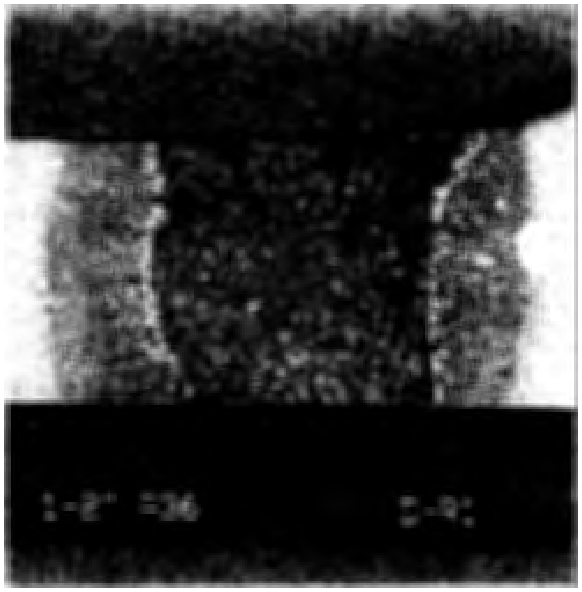


Weld "c"

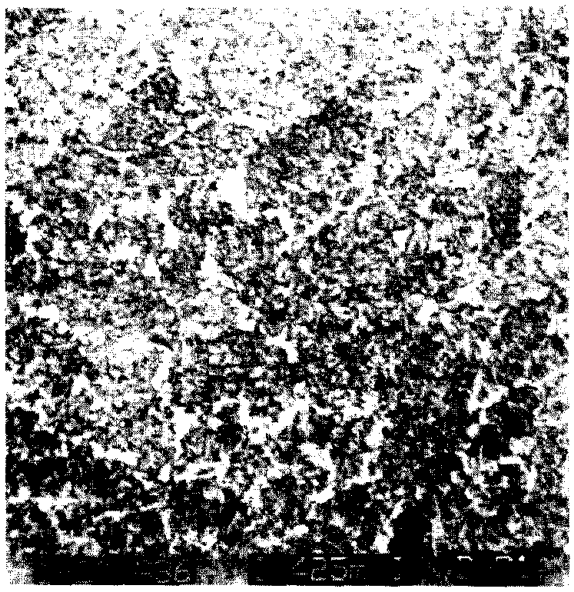


Weld Center X 50

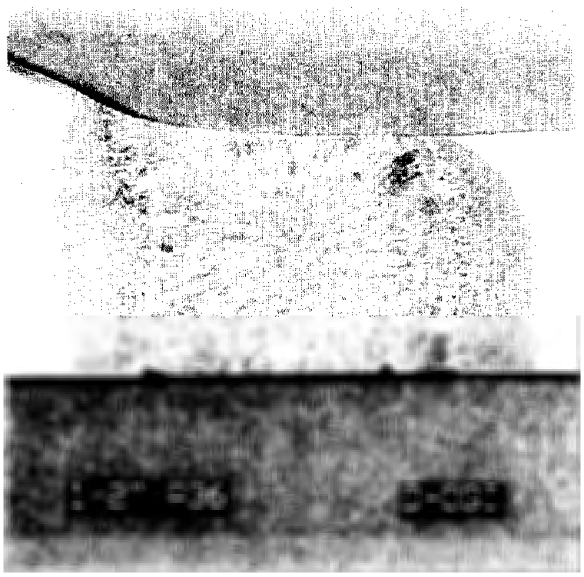
Figure 12. Macro and micrograph of 25-mm A588 ESW.



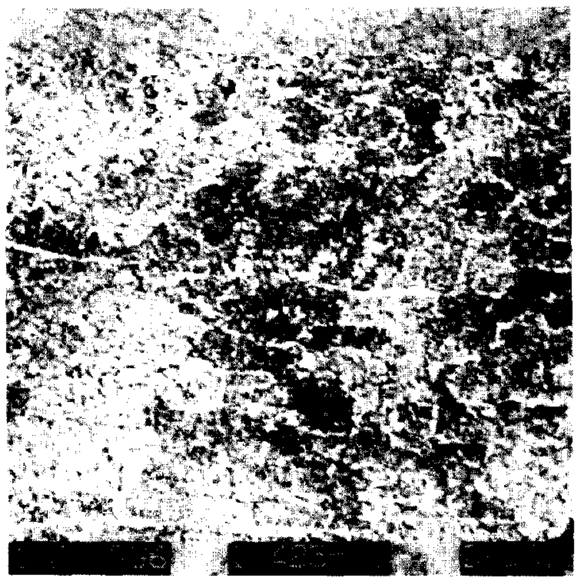
Fabricator Weld "D"



Weld Center X 50

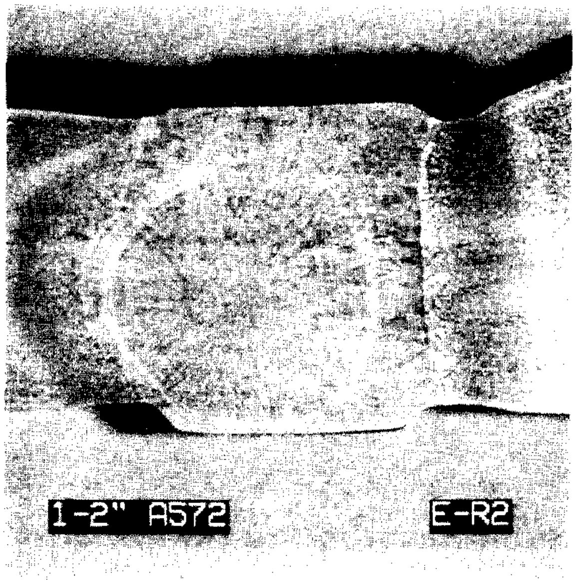


Weld "d"

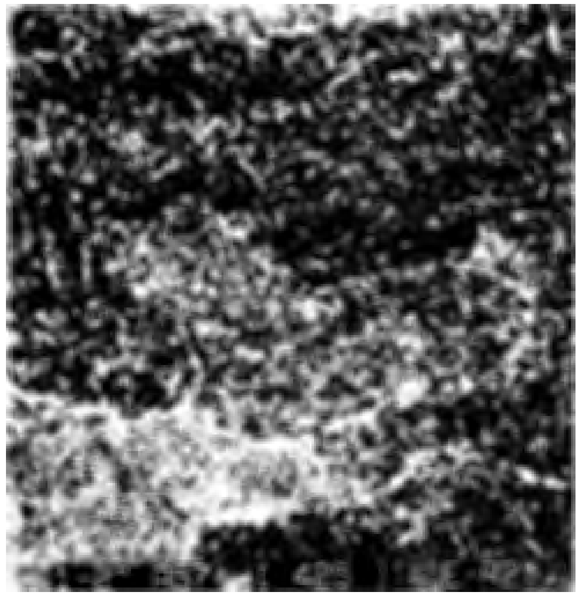


Weld Center X 50

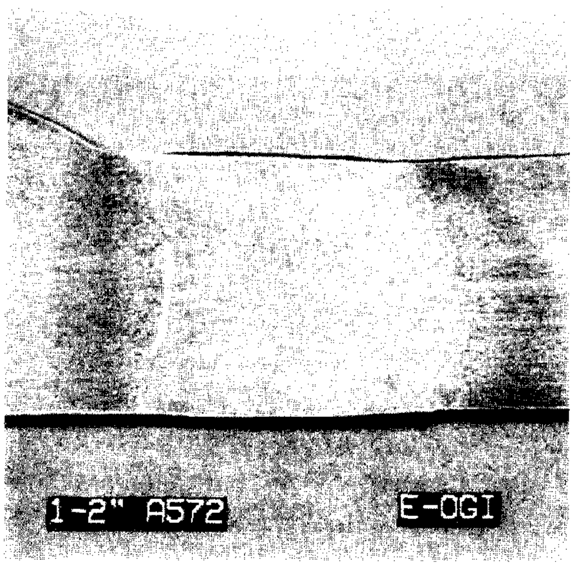
Figure 13. Macro and micrograph of 25-mm A36 ESW.



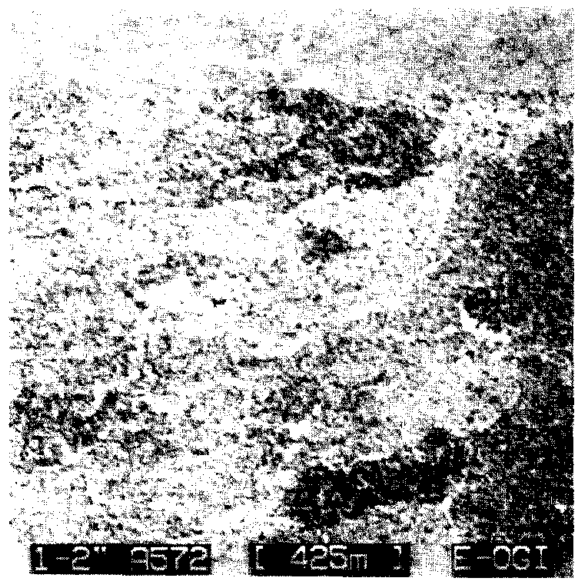
Fabricator Weld "E"



Weld Center X 50

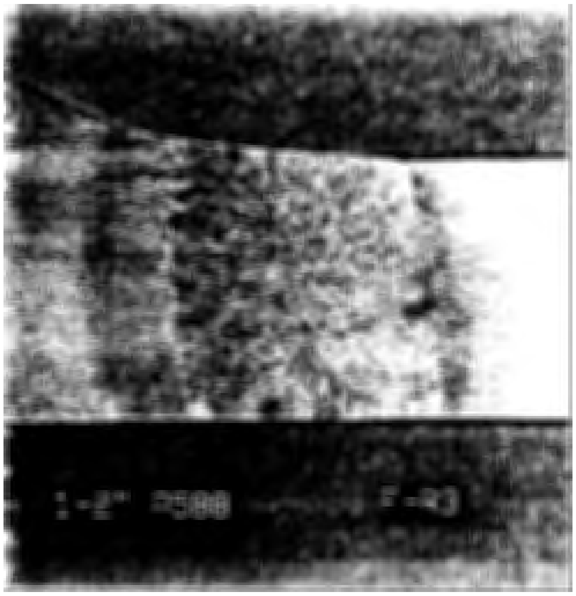


Weld "E"

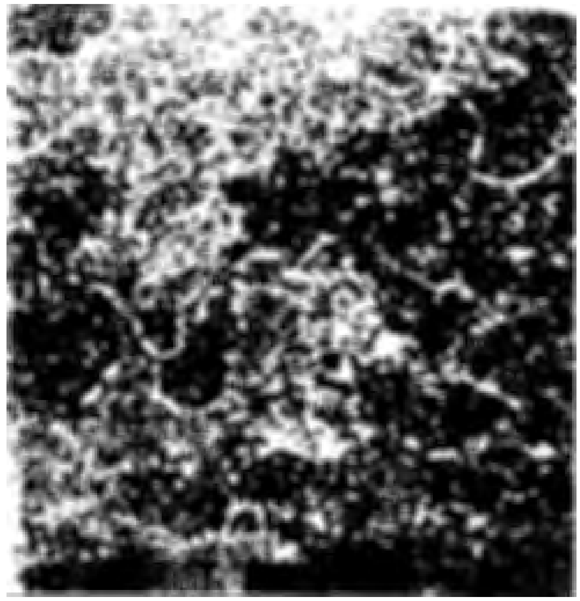


Weld Center X 50

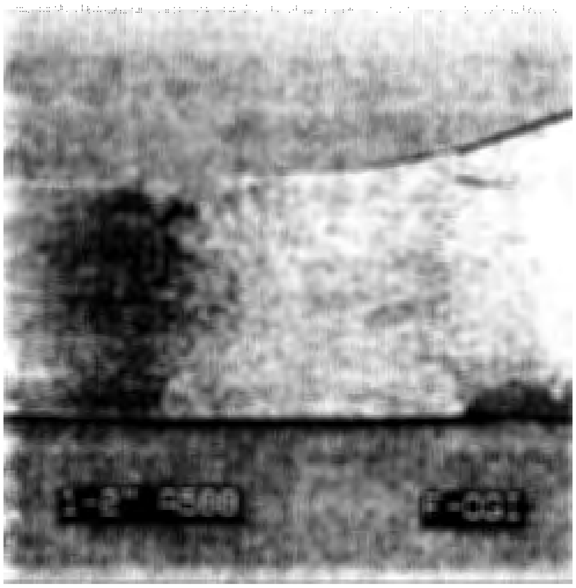
Figure 14. Macro and micrograph of 25- to 50-mm A572-50 ESW.



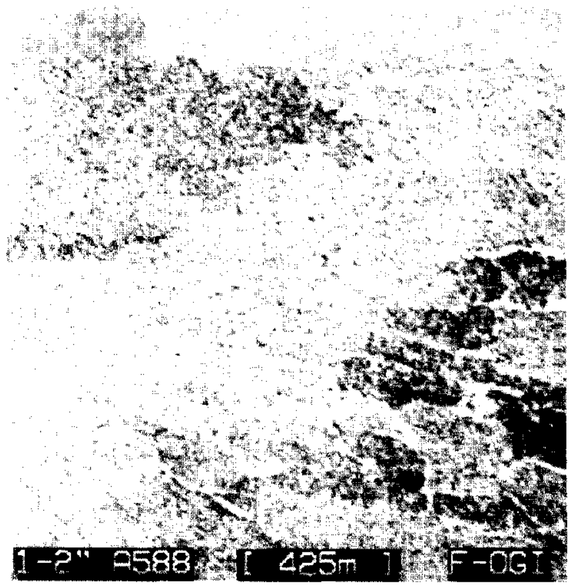
Fabricator Weld "F"



Weld Center X 50

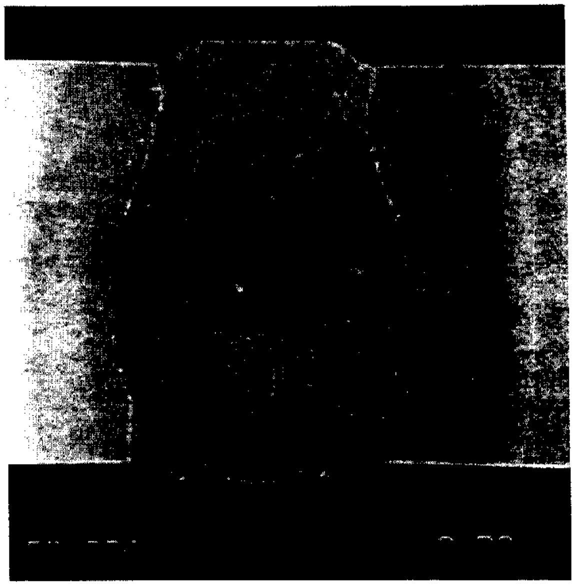


Weld "f"

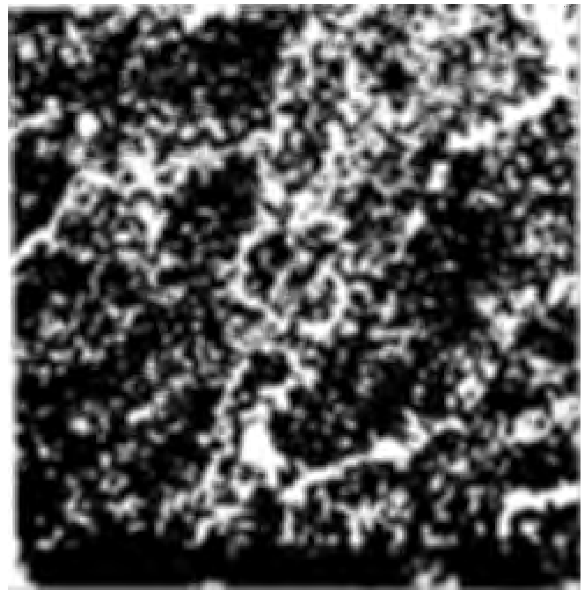


Weld Center X 50

Figure 15. Macro and micrograph of 25- [illegible] mm A588 [illegible].

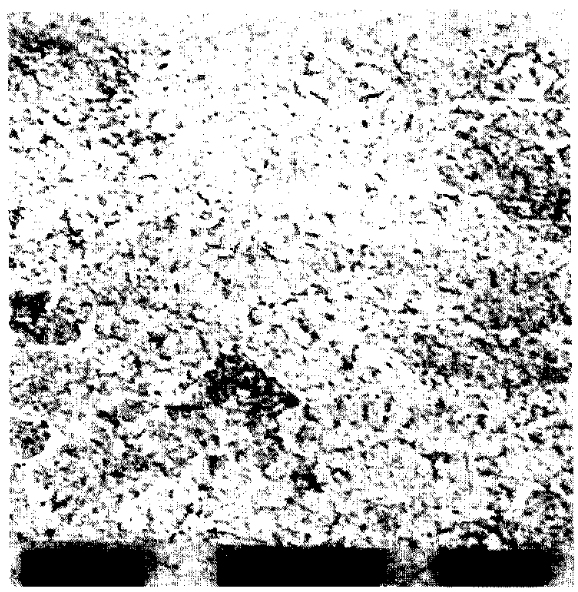


Fabricator Weld "G"



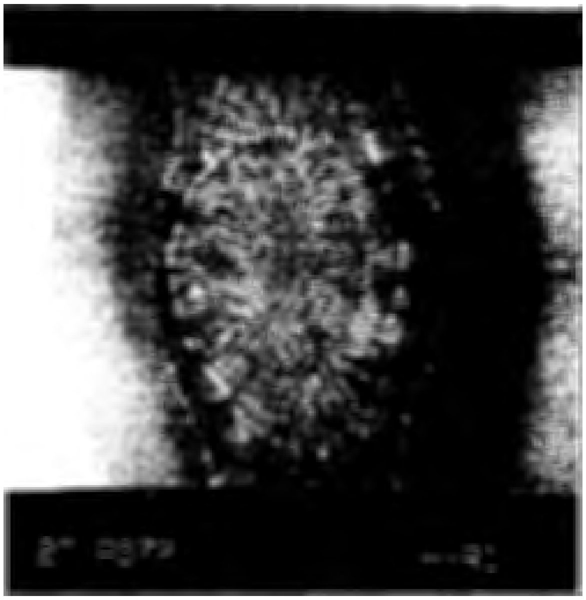
Weld Center X 50

Weld "g"



Weld Center X 50

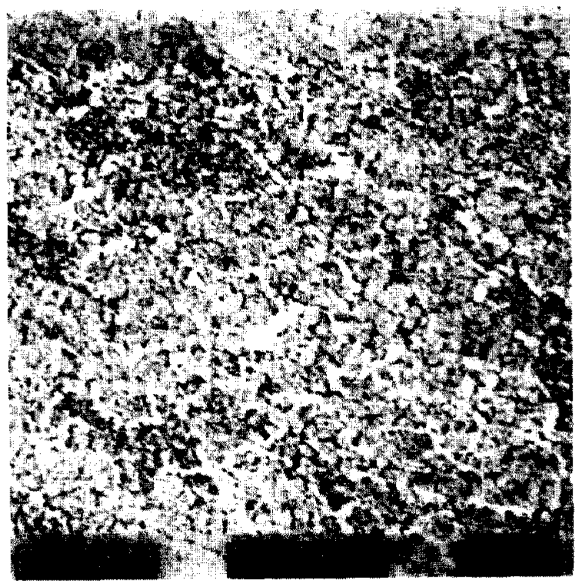
Figure 16. Macro and micrograph of 50-mm A36 ESW.



Fabricator Weld "H"

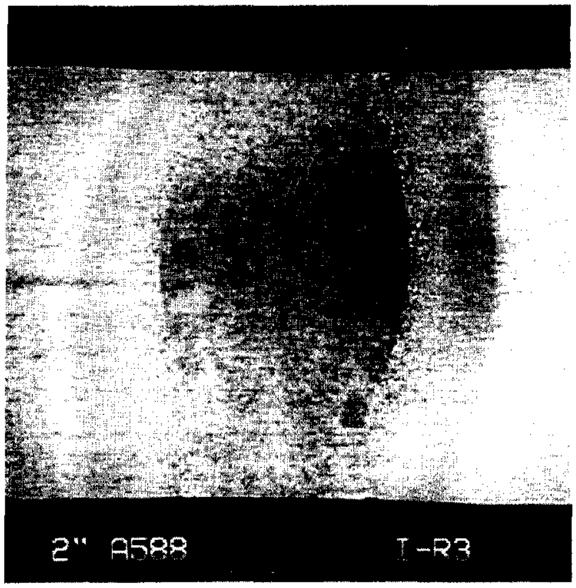
Weld Center X 50

Weld "h"

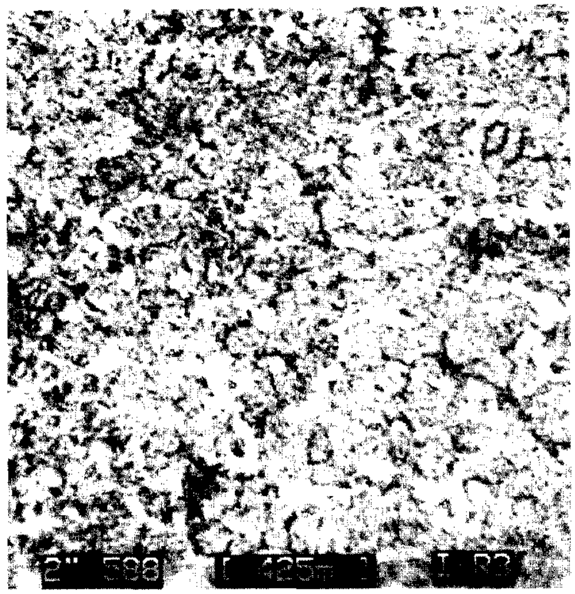


Weld Center X 50

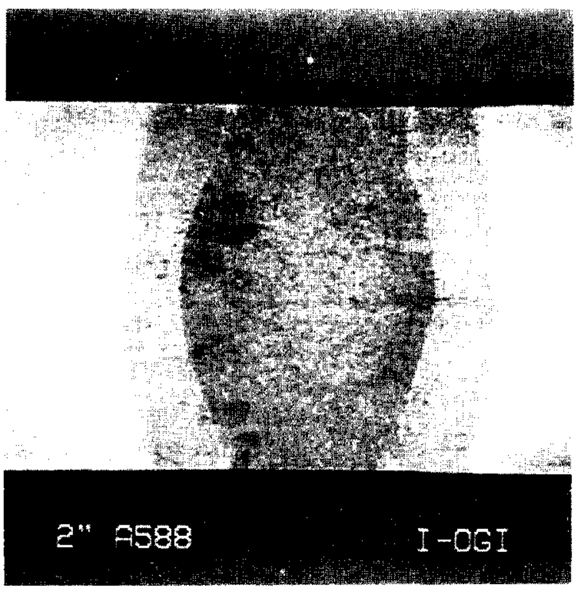
Figure 17. Macro and micrograph of 50-mm A572-50 ESW.



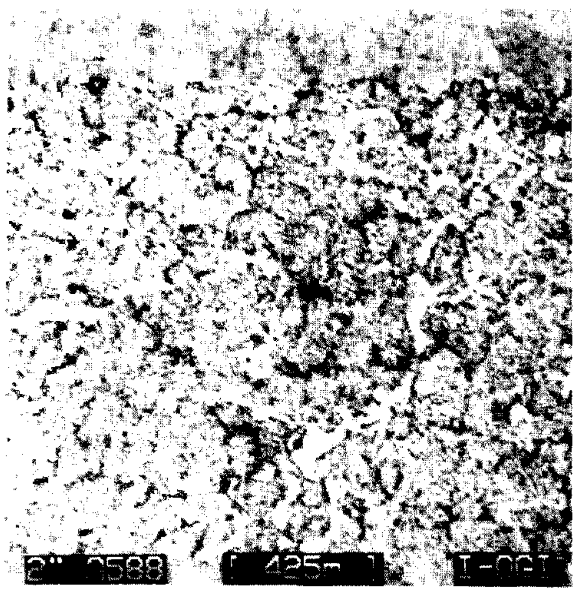
Fabricator Weld "I"



Weld Center X 50



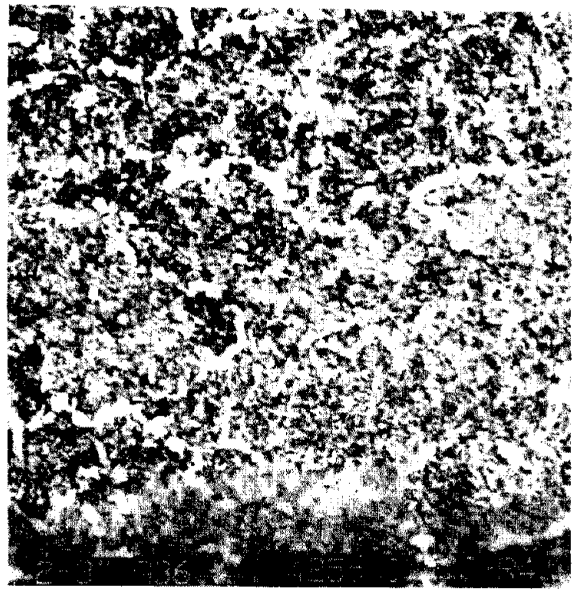
Weld "i"



Weld Center X 50

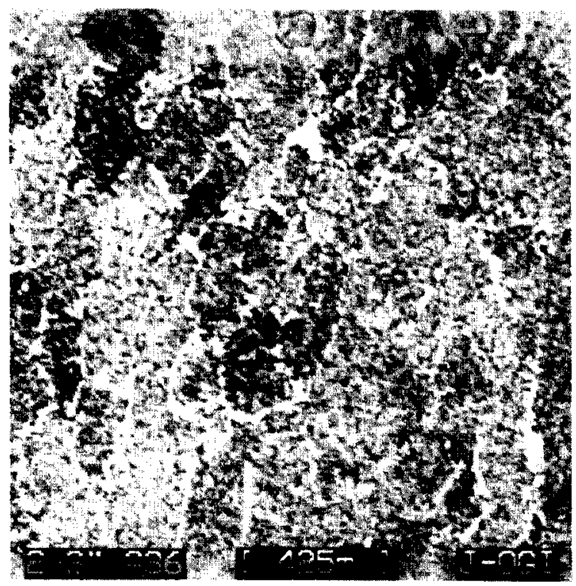
Figure 18. Macro and micrograph of 50-mm A588 ESW.

Fabricator Weld "J"



Weld Center X 50

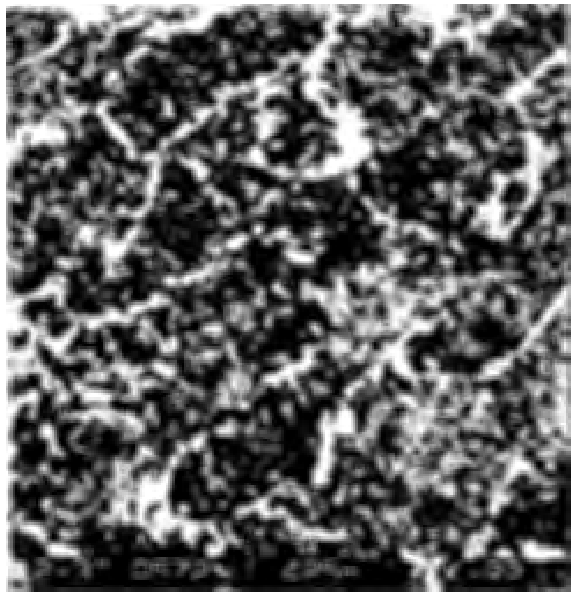
Weld "j"



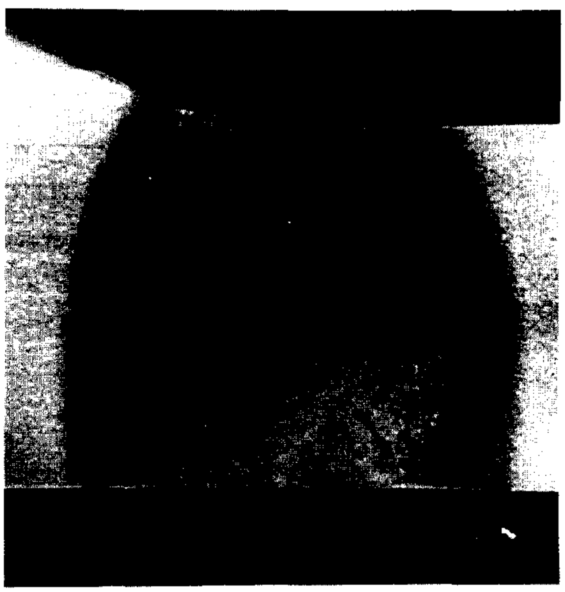
Weld Center X 50

Figure 19. Macro and micrograph of 50- to 76-mm A36 ESW.

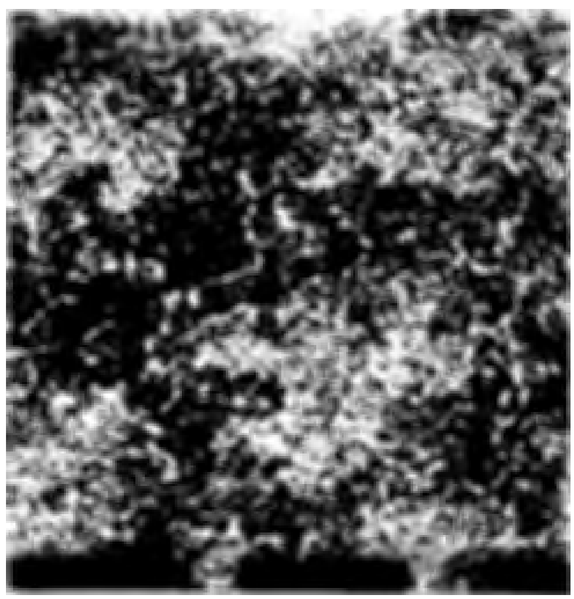
Fabricator Weld "K"



Weld Center X 50



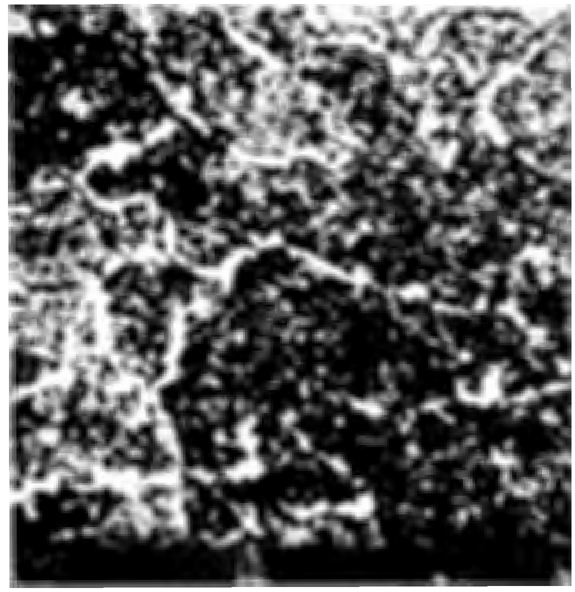
Weld "k"



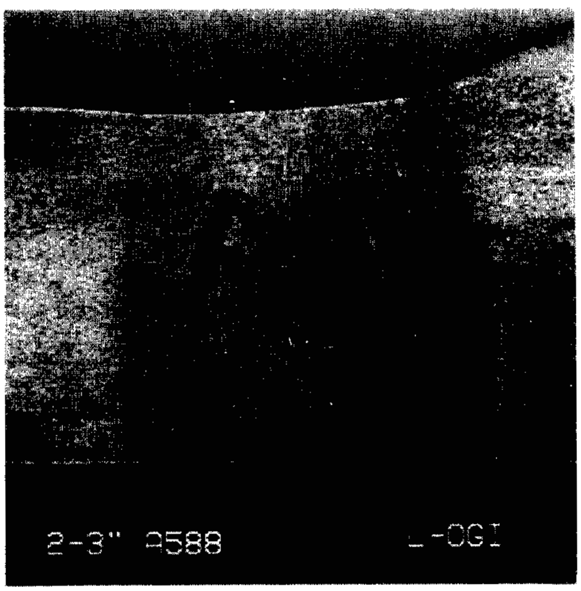
Weld Center X 50

Figure 20. Macro and micrograph of 50- to 76-mm A572-50 ESW.

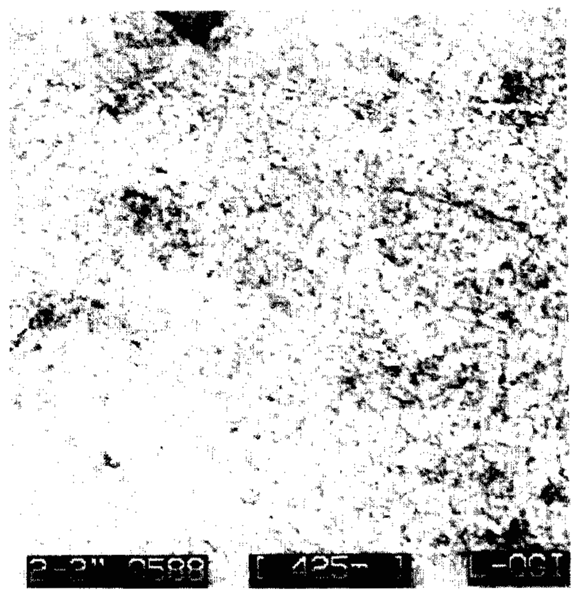
Fabricator Weld "L"



Weld Center X 50



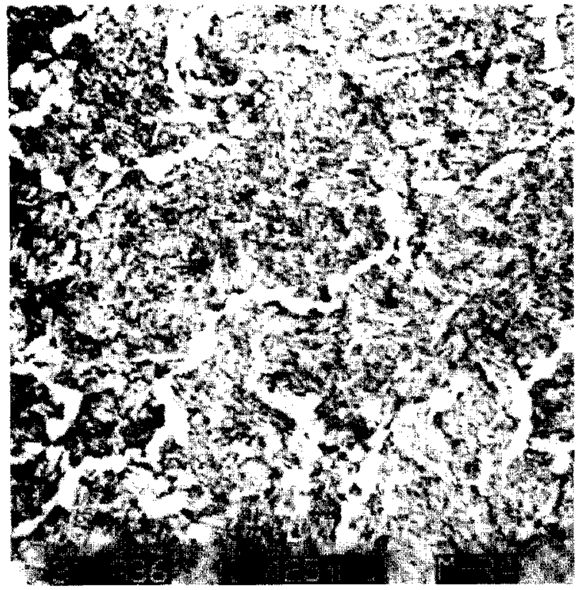
Weld "1"



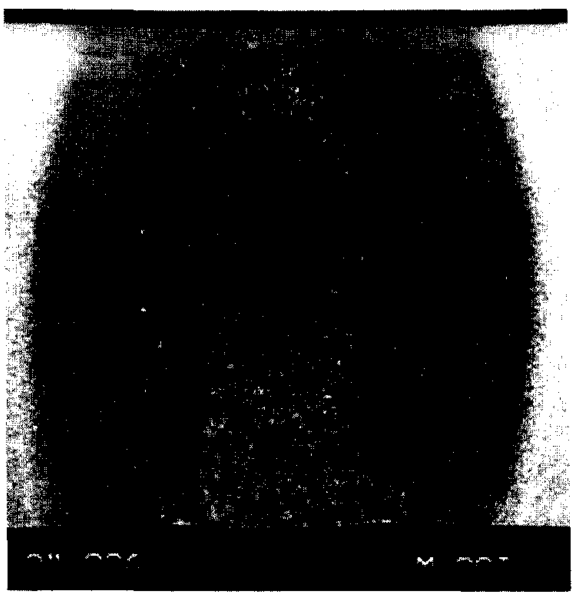
Weld Center X 50

Figure 21. Macro and micrograph of 50- to 76-mm A588 ESW.

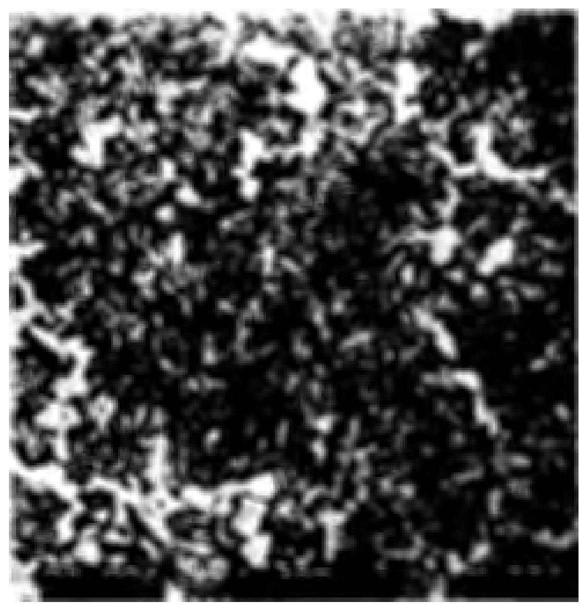
Fabricator Weld "M"



Weld Center X 50

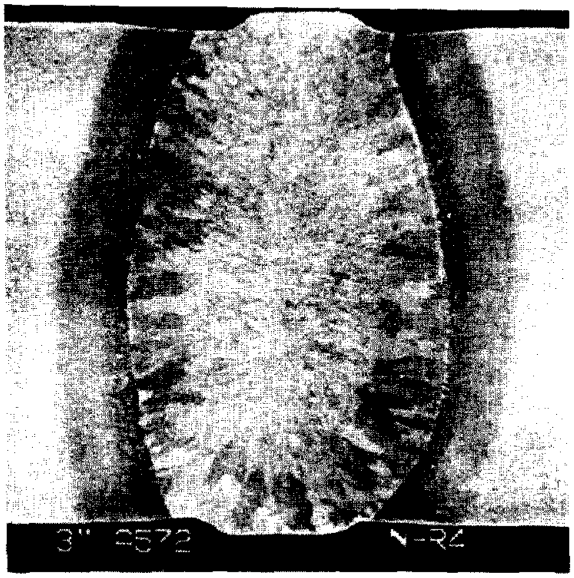


Weld "m"

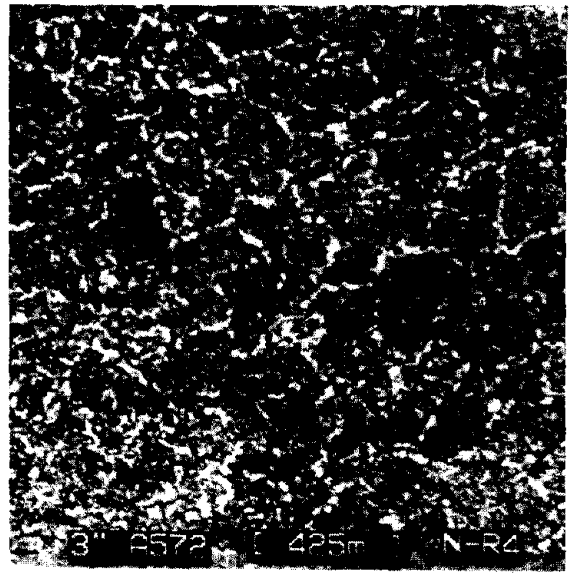


Weld Center X 50

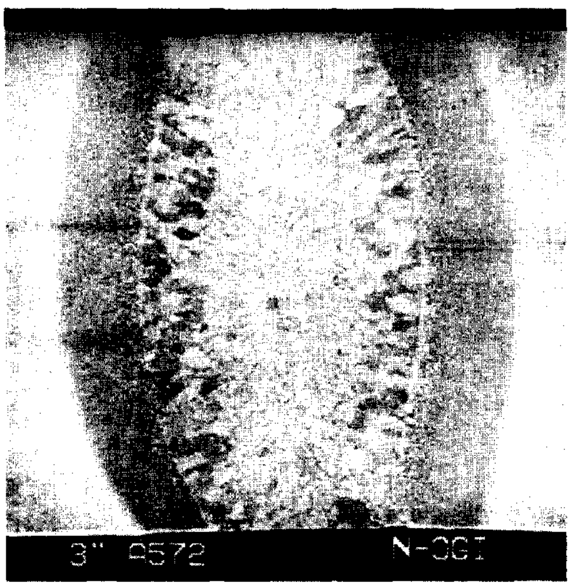
Figure 22. Macro and micrograph of 76-mm A36 ESW.



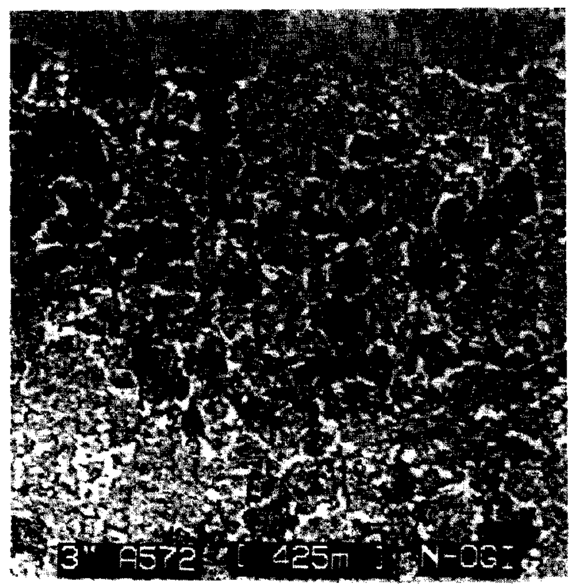
Fabricator Weld "N"



Weld Center X 50

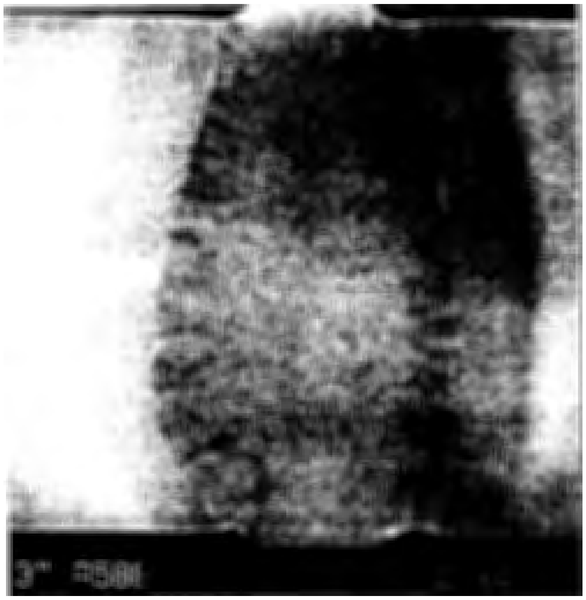


Weld "n"

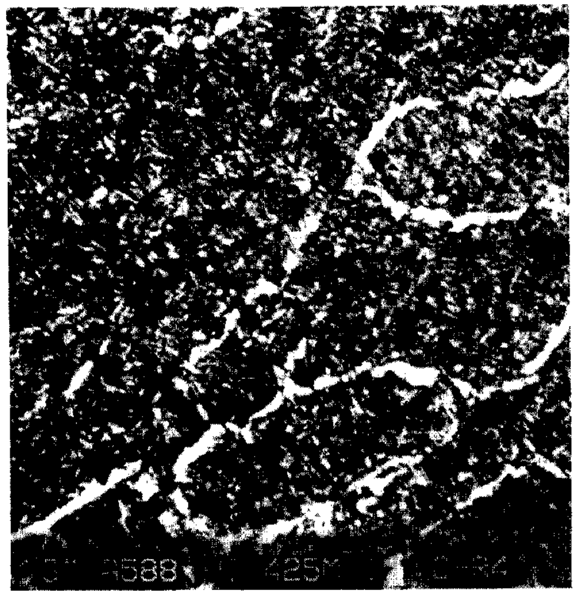


Weld Center X 50

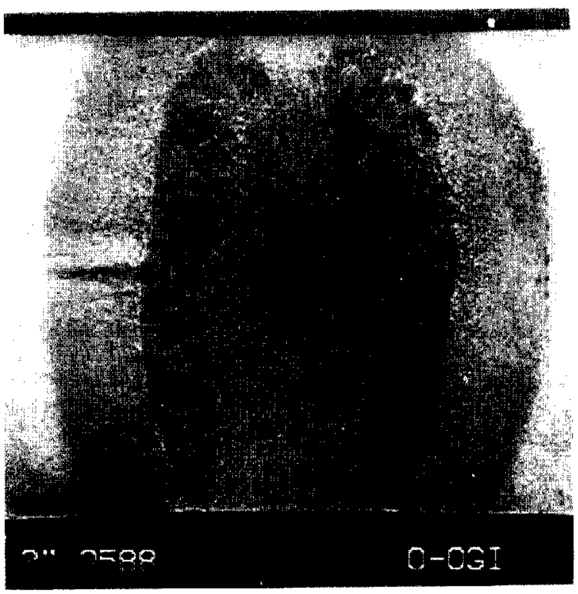
Figure 23. Macro and micrograph of 76-mm A572-50 ESW.



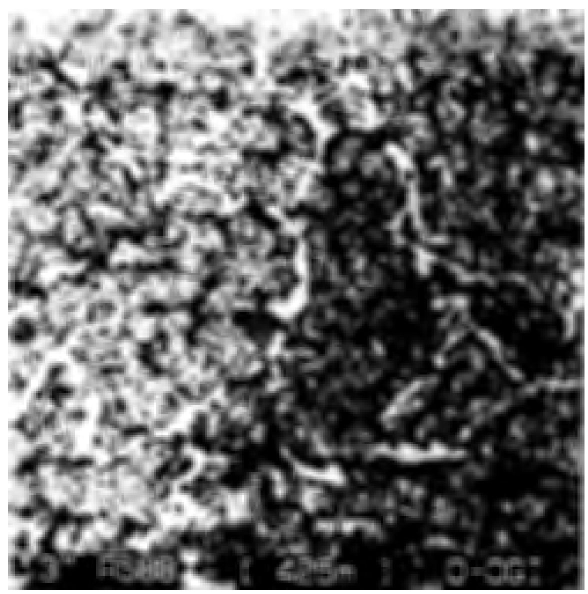
Fabricator Weld "O"



Weld Center X 50



Weld "o"



Weld Center X 50

Figure 24. Macro and micrograph of 76-mm A588 ESW.

Table 6. Weld metal composition.

Balance Fe

Weld ID Field	C	Mn	Si	Cr	Ni	Mo	% Dilution[1]	Alloy	Joint Type
A/a	0.10/0.09	1.10/1.02	0.30/0.24	0.00/0.00	1.52/1.39	0.27/0.25	19/13	A36	25-mm Butt
B/b	0.10/0.08	1.22/1.15	0.30/0.30	0.00/0.00	1.47/1.69	0.25/0.29	33/34	A572	25-mm Butt
C/c	0.07/0.08	1.00/1.19	0.32/0.35	0.21/0.21	1.35/1.33	0.25/0.25	11/26	A588	25-mm Butt
D/d	0.09/0.10	1.03/1.03	0.27/0.26	0.00/0.00	1.41/1.25	0.25/0.22	11/33	A36	25- to 50-mm Transition
E/e	0.07/0.08	1.13/1.15	0.35/0.31	0.00/0.01	1.82/1.61	0.31/0.29	21/26	A572	25- to 50-mm Transition
F/f	0.07/0.05	1.24/1.13	0.33/0.34	0.13/0.08	1.62/1.88	0.29/0.33	17/23	A588	25- to 50-mm Transition
G/g	0.08/0.10	1.09/1.03	0.28/0.27	0.01/0.00	1.60/1.31	0.27/0.23	40/33	A36	50-mm Butt
H/h	0.11/0.10	1.08/1.07	0.26/0.26	0.01/0.01	1.09/1.33	0.33/0.23	28/38	A572	50-mm Butt
I/i	0.08/0.11	1.07/1.11	0.27/0.26	0.16/0.26	1.46/0.82	0.25/0.16	19/29	A588	50-mm Butt
J/j	0.11/0.10	1.06/1.01	0.27/0.26	0.00/0.00	1.27/1.37	0.22/0.24	36/36	A36	50- to 76-mm Transition
K/k	0.10/0.11	1.06/1.18	0.25/0.30	0.02/0.02	1.37/1.34	0.24/0.23	36/36	A572	50- to 76-mm Transition
L/l	0.09/0.00	1.09/1.22	0.29/0.32	0.21/0.21	1.23/1.14	0.22/0.20	42/29	A588	50- to 76-mm Transition
M/m	0.14/0.13	1.11/0.97	0.31/0.24	0.01/0.01	0.97/0.95	0.18/0.17	46/47	A36	76-mm Butt
N/n	0.14/0.13	1.16/1.02	0.28/0.24	0.07/0.03	0.91/0.81	0.18/0.15	53/47	A572	76-mm Butt
O/o	0.10/0.11	0.12/1.09	0.32/0.30	0.22/0.28	1.23/0.98	0.22/0.18	47/51	A588	76-mm Butt

[1] Dilution calculations assumed proper 19-mm joint spacing.

Table 7. Base metal composition and Charpy impact values.

Alloy	Thickness (mm)	Impact Energy at 4 °C: Plate CL[1] (joules)	Impact Energy at 4 °C: Plate CL[1] (ft/lb)	Impact Energy at 4 °C: 1/4t[2] (joules)	Impact Energy at 4 °C: 1/4t[2] (ft/lb)	Composition: C	Composition: Mn	Composition: Si	Composition: Cr	Composition: Ni	Composition: Mo
A36	25.4	31	23	103	77	0.240	1.086	0.070	0.001	0.015	0.000
A572	25.4	24	18	27	20	0.225	1.043	0.186	0.012	0.007	0.000
A588	25.4	>311	>230	NT	NT	0.119	0.881	0.372	0.507	0.129	0.027
A36	50.8	33	25	27	20	0.228	0.995	0.198	0.012	0.015	0.000
A572	50.8	31	25	27	19	0.241	1.200	0.168	0.024	0.030	0.000
A588	50.8	100	74	143	107	0.177	1.159	0.254	0.448	0.100	0.015
A36	76.2	29	22	19	14	0.233	0.982	0.208	0.006	0.001	0.000
A572	76.2	28	21	27	20	0.241	1.285	0.206	0.090	0.073	0.016
A588	76.2	32	24	63	47	0.179	1.184	0.278	0.486	0.013	0.015

[1] Plate centerline impact values provided to compare with ESW and HAZ impact sample location.

[2] Impact values from 1/4t represent AASHTO Zone 2 location for plate impact requirements rather than the 1/4W location for ESW.

Table 8. Electroslag welding hardness (plate centerline)
Rockwell B 1.58-mm ball, 100 kg.

Weld ID Field/Lab	Weld CL	Weld 1/4W	HAZ	Base	Alloy	Joint Type
A/a	91/91	92/93	86/86	77/79	A36	25-mm Butt
B/b	94/94	94/94	94/95	91/91	A572	25-mm Butt
C/c	93/90	94/91	94/89	89/85	A588	25-mm Butt
D/d	88/90	94/91	94/87	72/75	A36	25- to 50-mm Transition
E/e	94/94	94/94	90/93	83/84	A572	25- to 50-mm Transition
F/f	89/92	94/92	96/92	85/84	A588	25- to 50-mm Transition
G/g	90/90	91/90	82/86	76/76	A36	50-mm Butt
H/h	87/89	89/92	90/92	85/88	A572	50-mm Butt
I/i	90/91	92/93	89/91	83/85	A588	50-mm Butt
J/j	92/89	92/90	84/87	76/77	A36	50- to 76-mm Transition
K/k	91/91	92/93	95/95	91/90	A572	50- to 76-mm Transition
L/l	92/91	92/92	93/90	87/82	A588	50- to 76-mm Transition
M/m	88/84	88/87	81/81	75/74	A36	76-mm Butt
N/n	89/90	80/90	97/97	90/93	A572	76-mm Butt
O/o	89/91	91/92	93/91	89/83	A588	76-mm Butt

Table 9. Plate centerline Charpy impact comparison (Joules).

Averages are based upon three data points

Weld ID Field/Lab	Weld CL -12°C	Weld 1/4W[1] -12°C	HAZ[2,3,4] -12 °C	HAZ[2,3,4] 4 °C	Plate 4 °C	Alloy	Joint Type
A/a	39/39	54/62	19/11	18/53	31	A36	25-mm Butt
B/b	42/53	96/19	15/7	27/42	24	A572	25-mm Butt
C/c	68/49	98/107	20/26	31/30	311	A588	25-mm Butt
D/d	38/34	56/61	2216	24/40	33	A36	25 to 50-mm Transition
E/e	62/56	94/79	8/16	24/24	31	A572	25 to 50-mm Transition
F/f	98/47	118/79	20/24	24/20	100	A588	25 to 50-mm Transition
G/g	62/61	62/60	15/15	25/24	33	A36	50-mm Butt
H/h	22/49	72/92	37/15	29/35	31	A572	50-mm Butt
I/i	57/56	66/100	28/30	32/23	100	A588	50-mm Butt
J/j	35/45	47/60	12/12	19/61	29	A36	50 to 76-mm Transition
K/k	31/58	61/87	23/23	34/14	28	A572	50 to 76-mm Transition
L/l	43/49	73/96	22/23	23/23	32	A588	50 to 76-mm Transition
M/m	18/23	41/28	11/11	26/26	29	A36	76-mm Butt
N/n	28/26	43/39	11/15	24/19	31	A572	76-mm Butt
O/o	24/22	50/37	12/12	18/20	32	A588	76-mm Butt

[1] 1/4 W represents sections taken halfway between weld centerline and fusion boundary.
[2] HAZ values include only those with coarse grain brittle fracture surfaces.
[3] HAZ Charpy bars on transition welds were all taken from the thicker member.
[4] HAZ values are normally compared to as-received plate requirements at 4.4 °C.

Table 10. ESW Charpy impact results (ft/lb).

(Foot/Pounds)

Weld ID	Weld CL -12 °C				Weld 1/4W -12 °C				HAZ -12 °C				HAZ 4 °C			
	Bar No. 1	2	3	Ave	Bar No. 21	22	23	Ave	Bar No. 31	32	33	Ave	Bar No. 34	35	36	Ave
A	24	34	29	29	37	41	41	40	19	14	9	14	12	10	17	13
B	30	32	30	34	78	61	74	71	11	15	7	11	16	22	20	20
C	51	50	48	50	74	68	74	72	12	18	13	15	20	36	22	26
D	24	24	34	28	48	39	36	41	14	10	22	16	11	10	34	18
E	40	46	21	46	70	67	69	69	5	7	6	6	20	17	16	18
F	68	70	76	72	80	93	89	87	20	20	10	17	17	17	20	18
G	44	51	43	46	40	54	42	46	8	15	9	11	17	23	16	19
H	18	17	13	16	42	75	41	53	26	28	X	27	22	22	19	21
I	54	34	36	42	50	51	44	49	19	24	20	21	19	27	26	24
J	26	24	26	26	48	23	33	35	9	9	10	9	12	14	14	14
K	25	26	20	23	68	48	47	45	16	15	18	17	22	28	24	25
L	32	29	34	32	55	90	49	54	6	15	18	13	22	15	15	17
M	11	15	13	13	36	31	22	30	7	7	9	8	16	17	20	19
N	24	21	17	21	33	32	31	32	10	6	9	8	12	24	X	18
O	20	18	14	18	40	35	35	37	8	10	8	9	15	15	9	13
a	30	28	30	29	52	47	37	46	8	7	8	8	42	32	42	39
b	40	36	40	39	58	61	59	59	5	6	5	6	10	23	20	17
c	40	30	39	36	85	80	73	79	19	10	11	13	15	31	19	21
d	30	22	23	25	45	39	51	45	X	12	26	19	18	30	42	30
e	37	39	47	41	57	58	60	58	14	6	X	10	15	17	21	18
f	35	32	36	35	54	59	59	58	21	18	15	18	13	17	16	15
g	44	56	33	45	44	41	48	44	8	12	12	11	16	20	15	17
h	30	38	39	36	53	76	76	68	15	11	8	12	29	20	30	26
i	40	44	38	41	79	66	75	74	9	6	10	8	11	25	16	17
j	34	26	39	33	48	42	40	44	28	9	15	17	44	50	41	45
k	45	46	39	43	64	64	X	64	12	18	21	17	12	10	10	11
l	35	37	34	36	65	77	70	71	10	9	8	9	21	15	15	17
m	18	15	17	17	20	24	20	21	8	7	8	8	24	17	16	19
n	21	22	14	19	30	26	31	29	11	11	10	11	18	11	12	13
o	17	17	13	16	27	26	X	27	11	6	9	9	13	15	16	15

NOTE: Fractional values not shown here were used in determining averages.

the first bar produced 311 J and the second nearly stopped the pendulum. Only values for HAZ samples that exhibit a predominantly brittle coarse-grained fracture surface were included in this data.

Two groups of CVN data and two individual cases are below the target 27 J. The two groups include all of the 76-mm-thick weld centerline samples, and most of the 76-mm-thick weld HAZ 4.4 °C samples. The individual cases are weld "H" (R2) at the weld center line (16 J), and weld "A" (R1) at the weld HAZ (13 J).

DISCUSSION

FABRICATOR OBSERVATIONS

Each of the fabricators made an impressive effort in the narrow gap ESW field trial project. Since each had some experience with conventional consumable guide electroslag welding, the observations expressed by the welders regarding both processes were very important. The increased welding speed was by far the most appreciated difference. The next most frequent observation concerned the greater accuracy required for joint spacing, flux addition, and welding power conditions for the narrow gap ESW. Each fabricator had been performing conventional ESW within prescribed practices, but none had required the accuracy needed for narrow gap ESW.

It was pointed out that weld setup was easier with a wider joint spacing. Wider joint spacing can be used and still produce welds with good appearance and nondestructive testing results, but the wider joint spacing increases welding time, dilution, and heat input. Each contributes to low weld metal and HAZ impact toughness.

WELD MONITORING

Welding time with the narrow gap ESW process is very consistent when proper joint spacing and electrode wire feed speed are provided. It may be advisable to record both electrode wire feed rate and welding time to insure that proper weld setup was followed. Amperage traces from weld strip chart records are shown in figure 25. Strip chart, figure 25 (a), demonstrates a variation in amperage due to slag loss that was corrected adjusting the automatic flux feed rate. Most amperage variations are corrected by adjusting the slag level rather than the electrode wire feed rate. Strip chart, figure 25 (b), shows low amperage in the weld run-in area due to high electrical resistance at the run-in tack welds. In this case, the amperage level improved as the slag pool made contact with the main weld plates. No adjustment was made in electrode feed speed as the specified rate had already been established and amperage variations are not unusual in run-in or run-out areas.

As expected, a wide range of equipment and working conditions was encountered among the four fabricators. If the wire feed controller provided by the contractor had been compatible with the fabricator power supplies, both voltage and wire feed speed would have been controlled by one unit. As it was, the voltage control was on the fabricator power supply and voltage was monitored with a digital volt meter measuring between the guide tube holder and welding ground cable clamp. In two cases, the welding power supply condition was such that voltage had to be adjusted occasionally and at some inconvenience because of the voltage control location.

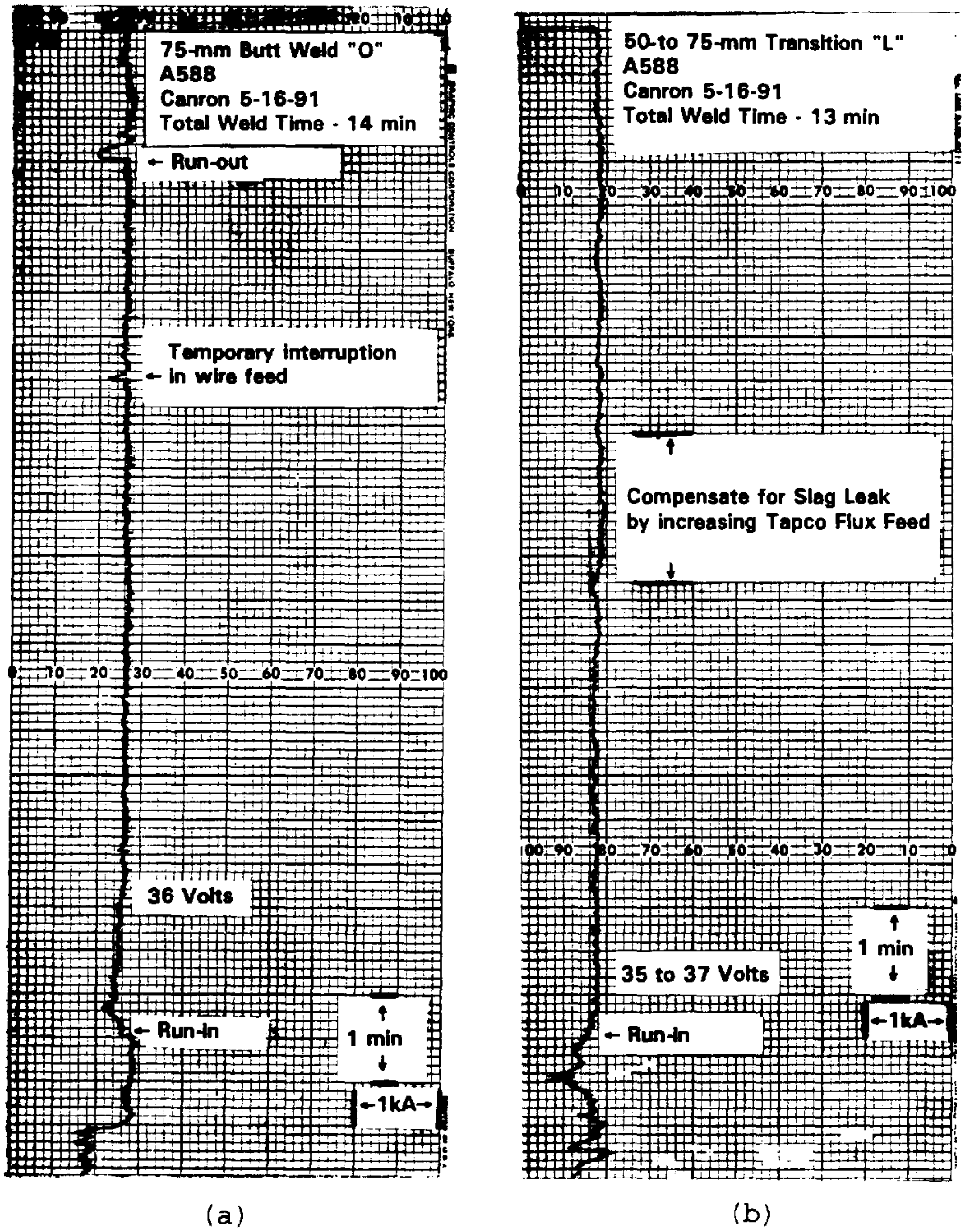


Figure 25. Amperage chart recording.

Equipment used in this project clearly demonstrated that a variety of power supplies can be used for ESW, provided that process controls and monitoring systems are configured to allow compliance with the specified voltage, current, and electrode feed rates of the procedure.

DEFECTS

In two cases, welds had to be stopped prematurely. During weld "B" (R2) an unidentified piece of material fell into the weld joint that created arcing and damage to the side of the guide tube. Because of time constraints, the weld was restarted after removing the slag layer and replacing the guide tube rather than cutting the weld out and repeating the entire procedure. The radiograph of this weld indicated a 25- by 38-mm restart 130-mm from the bottom edge of the weld plates.

On one training weld, the cooling water was inadvertently turned off by someone not involved in the project. By the time the situation was discovered, one cooling shoe had a hole melted through the copper. The cooling shoe was repaired and within 24 h, the weld procedure completely repeated with guaranteed water flow.

In weld "O," large-scale porosity was found as shown in figure 7. In both cases the source of porosity was an inclusion in the base metal HAZ that also appeared on the radiograph.

In field trial "M," hot cracking occurred in the 76-mm-thick A36 weld. Similarly, hot cracking was reproduced in a 76-mm-thick A572 weld "n" in the laboratory. The reason for the hot cracking was due to the increased weld metal carbon content in these weldments. Weld metal carbon content is the result of the combined carbon present in the filler wire, guide tube, and base metal alloy. The combination of 1018 guide tube rather than lower carbon 1010 and high base metal carbon contents, 0.23%, together with the increased dilution for electroslag welded 76-mm-thick plate material, resulted in hot cracking susceptibility. In the following equation developed by Bailey and Jones in their work at The Welding Institute,

$$UCS = 230C + 190S + 75P + 45Nb - 12.3Si - 5.4Mn - 1$$

the units of crack susceptibility (UCS) are extremely dependent upon the percentage of carbon in the weld deposit, and if the value of UCS exceeds 25, the possibility of weld metal hot cracking must be considered. The UCS values for the 76-mm-thick plates of A36 and A572 range between 49 and 52. The amount of dilution of base metal melted into the weld pool increases with plate thickness (up to 60 percent for 76-mm-thick plate). The filler metal provides excellent resistance to hot cracking since its UCS value is only 11. While 1010 material has a UCS value of 16, 1018 with a UCS value of 32 was used in these trials due to availability. The weld metal UCS values for 76-mm-thick ESW A36 and A572 averaged 27. Since control of weld metal composition at a UCS value of less than 25 is important, using 1010 guide tube material helps minimize the UCS value. This becomes increasingly important as base metal carbon content increases, and as thickness increases due to increased dilution.

Comparison between weld "H" and the 76-mm-thick welds was the low (1.09 percent) Ni content. This is not a singularly conclusive reason for the high volume of proeutectoid ferrite, but when combined with the Charpy impact toughness data that follows, there is a strong case for requiring greater than 1.0-percent Ni in the weld metal.

MICROSTRUCTURE

All of the weld centerline micrographs revealed a high percentage of acicular ferrite, indicating that the alloying of the electrode wire is an effective means of controlling the microstructure in ESW. The high volume of proeutectoid ferrite in the group of 76-mm-thick welds is directly associated with the high percentage of base metal dilution. Weld "H" (R1) also contains a similar proeutectoid ferrite level, but without high volume base metal dilution. The Ni content in weld "H" (R1) is 1.09 percent compared to 1.33 percent Ni in weld "h" having even higher dilution. The cause of this discrepancy is not clear; however, the difference in proeutectoid ferrite volume is evident.

CHARPY IMPACT TOUGHNESS

The contrasting 22 and 49 J of Charpy impact energy between welds "H" and "h" properly reflect the influence of high proeuctectoid ferrite volume in reducing weld metal toughness. All of the 76-mm-thick welds have a microstructure similar to weld "H" as well as similar Charpy impact values in the range of 17 to 28 J for all three alloys. Weld metal CVN toughness from the 1/4W position tested at -12 °C is very high and compares well with previous research.

Some comparison can be drawn between the HAZ results in this project and those of a special weld study for FHWA entitled "Heat-Affected Zone Toughness of Electroslag Weldments," CY 1990. Only 50- and 76-mm-thick welds of Alloy A36 and A588 were included in the 1990 HAZ special study. Comparison of HAZ data in these two projects, including the unaffected base metal, are shown in table 11.

It is important to note that with the exception of the 100-J 50-mm A588, all of the base materials for this project are significantly lower in CVN impact energy than were

Table 11. HAZ Charpy impact comparison[1] (joules and ft/lb at 4 °C).

		RESEARCH[2]				DEMONSTRATION[3]			
		HAZ		BASE		HAZ		BASE	
Alloy	Thickness	(joules)	(ft/lb)	(joules)	(ft/lb)	(joules)	(ft/lb)	(joules)	(ft/lb)
A36	50 mm	48	36	83	62	24	18	33	25
A36	76 mm	19	14	83	62	24	18	33	25
A588	50 mm	31	23	50	37	27	20	100	75
A588	76 mm	25	19	60	45	19	14	32	24

[1] In all cases only Charpy impact tests exhibiting course grain brittle fracture surface condition were included.

[2] Data from "Heat-Affected Zone Toughness of Electroslag Weldments," an FHWA Project CY 1990.

[3] The average CVN value of the welds are used for comparison.

the materials from the 1990 HAZ special study. Even with lower base material toughness, the demonstration weld group CVN results are not substantially lower than those of the HAZ special weld study.

CONCLUSIONS

In conclusion, it has been demonstrated that the modified ESW practices can be successfully used in commercial fabrication facilities. Specialized training in the workplace will be needed to emphasize the importance of proper setup and operating conditions, since welds with good appearance can be made outside of the specified range of welding conditions. For welds greater than 50 mm in thickness, factors influencing cracking susceptibility must be considered and controlled.

The ESW process lends itself well to quality assurance methods in that the single-pass process with a permanent record of voltage, amperage, and welding time can easily verify proper setup and weld performance. If electrode wire feed rate is also recorded, quality assurance is further enhanced at very little extra cost.

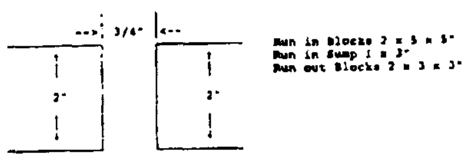
APPENDIX A - Electroslag welding procedure, 50-mm (2-in) butt weld.

Catalogue number 8	ECHO is off 1. Procedure details	Test record(PQR) number

Manufacturers name OREGON GRADUATE INSTITUTE
Procedure (WPS) no. NA
Revision no. NA

Welding process	Electroslag	PARENT MATERIAL Thickness 2 to 2
Root run process	Electroslag	Type C-Mn steel
Joint type	Butt-2 sided	Alloy STRUCTURAL STEEL
Welding position	Vertical	Standard Grade
Test piece posn.	VERTICAL	Material group(s) A-36, A-572, A-588
Welding technique	WING GUIDE	Dimensions of test piece 12" BY 18"

WELD PREPARATION



Bevel angles left right
1st side - major
root
2nd side - major
root
Backing material

Side 1 groove depth
Root face
Side 2 groove depth
Gap
Land
Radius

RUN SEQUENCE

Number of runs
1st side
2nd side
1st side
2nd side
1st side
Sealing run

Method of preparation and cleaning FLAME CUT OXYACETYLENE AND HAND GRIND

POST-WELD HEAT TREATMENT
Specification NA
Method
Control
Soak temp
Soak time

WELDING CONSUMABLES

Filler material
Make/type OGI CUSTOM
Specific. TUBULAR ALLOY
Size(s) 3/32"
Shielding gas/flux
Make/type HOBART PF 201 (200gm)
Composition

Baking treatment
STORE FLUX AT 250F UNTIL USE

Side 2 treatment

	Preheat	Interpass
Temp Method Control	AMBIENT	NA

WELDING CONDITIONS	Units
Run number(s)	
Electrode polarity	DCEP
Consumable diameter	2/32"
Current	950 AMP
Voltage/Arc length	36-37 V
Gas flow rate(s) (Shielding/Purging)	NA
Travel speed	NA
Wire feed rate	365-370 IN/MIN

Other information AFTER THE INITIAL 200 GRAMS OF FLUX HAS BEEN ADDED, CONTINUE TO ADD FLUX WITH THE TAPCO POWDER FEEDER AT 1.7 CONTRL SETTING AND THE NUMBER 20 WHEEL FOR DURATION OF THE WELD. WING GUIDE CROSS SECTION DIMENSIONS ARE 1/4 in. BY 1 1/2 in.

Originator Date Welder

EXTENT OF APPROVAL
Range of materials A-36, A-572, A-588
Range of thickness 2 in. TO 2 in. ONLY
Range of diameters

Code(s)

WELDSPEC software by The Welding Institute, Cambridge. Telephone (0223)891162

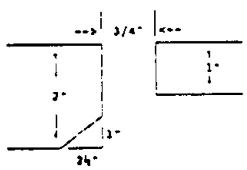
Electroslag welding procedure, 50-to 25-mm (2-to 1-in) transition butt weld.

Catalogue number 9	ECHO is off 1. Procedure details	Test record(PQR number

Manufacturers name OREGON GRADUATE INSTITUTE	Procedure (WPS) no. NA	Revision no. NA

Welding process	Electroslag	PARENT MATERIAL Thickness 1 to 2
Root run process	Electroslag	Type C-Mn steel
Joint type	Butt-2 sided	Alloy STRUCTURAL STEEL
Welding position	Vertical	Standard Grade
Test piece posn.	VERTICAL	Material group(s) A-36, A-572, A-588
Welding technique	WING GUIDE	Dimensions of test piece 12" BY 18"

WELD PREPARATION



Run in Blocks 1 x 5 x 5": Blocks
Must Match Transition
Run in Sump 1 x 3"
Run out Blocks 1 x 3 x 3": Blocks
Must Match Transition

Bevel angles left right
1st side - major
root
2nd side - major
root
Backing material

Side 1 groove depth
Root face
Side 2 groove depth
Gap
Land
Radius

RUN SEQUENCE

Number of runs
1st side
2nd side
1st side
2nd side
1st side
Sealing run

Method of preparation and cleaning FLAME CUT OXYACETYLENE AND HAND GRIND

WELDING CONSUMABLES

Filler material
Make/type OGI CUSTOM
Specific. TUBULAR ALLOY
Size(s) 3/32"
Shielding gas/flux
Make/type HOBART PF 201 (125gm)
Composition

POST-WELD HEAT TREATMENT

Specification NA
Method
Control
Soak temp
Soak time

Baking treatment
STORE FLUX AT 250F UNTIL USE

Side 2 treatment

	Preheat	Interpass
Temp Method Control	AMBIENT	NA

WELDING CONDITIONS	Units
Run number(s)	
Electrode polarity	DCEP
Consumable diameter	2/32"
Current	650 AMP
Voltage/Arc length	36-37 V
Gas flow rate(s) (Shielding/Purging)	NA
Travel speed	NA
Wire feed rate	260 in/min

Other information AFTER THE INITIAL 125 GRAMS OF FLUX HAS BEEN ADDED, CONTINUE TO ADD FLUX WITH THE TAPCO POWDER FEEDER AT 1.7 CONTRL SETTING AND THE NUMBER 20 WHEEL FOR THE DURATION OF THE WELD. WING GUIDE TUBE CROSS SECTION DIMENSIONS ARE 1/4 in. BY 3/4 in.

Originator Date Welder

EXTENT OF APPROVAL
Range of materials A-36, A-572, A-588
Range of thickness 2 in. TO 1 in.
Range of diameters TRANSITION JOINT ONLY

Code(s)

WELDSPEC software by The Welding Institute, Cambridge. Telephone (0223)891162

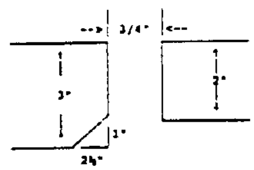
Electroslag welding procedure, 76-to 50-mm (3-to 2-in) transition butt weld.

Catalogue number 10	ECHO is off 1. Procedure details	Test record(PQR) number

Manufacturers name OREGON GRADUATE INSTITUTE	Procedure (WPS) no. NA	Revision no. NA

Welding process	Electroslag	PARENT MATERIAL Thickness 2 to 3
Root run process	Electroslag	Type C-Mn steel
Joint type	Butt-2 sided	Alloy STRUCTURAL STEEL
Welding position	Vertical	Standard Grade
Test piece posn.	VERTICAL	Material group(s) A-36, A-572, A-588
Welding technique	WING GUIDE	Dimensions of test piece 12" BY 18"

WELD PREPARATION



Run in Blocks 2 x 3 x 5": Blocks
Must Match Transition
Run in Sump 3 x 3"
Run out Blocks 2 x 3 x 3": Blocks
Must Match Transition

RUN SEQUENCE

Bevel angles left right
1st side - major
root
2nd side - major
root
Backing material

Side 1 groove depth
Root face
Side 2 groove depth
Gap
Land
Radius

Number of runs
1st side
2nd side
1st side
2nd side
1st side
Sealing run

Method of preparation and cleaning FLAME CUT OXYACETYLENE AND HAND GRIND

POST-WELD HEAT TREATMENT

Specification NA
Method
Control
Soak temp
Soak time

WELDING CONSUMABLES

Filler material
Make/type OGI CUSTOM
Specific. TUBULAR ALLOY
Size(s) 3/32"
Shielding gas/flux
Make/type HOBART PF 201 (200gm)
Composition

Baking treatment
STORE FLUX AT 250F UNTIL USE

	Preheat	Interpass
Temp Method Control	AMBIENT	NA

Side 2 treatment

WELDING CONDITIONS	Units
Run number(s)	
Electrode polarity	DCEP
Consumable diameter	2/32"
Current	950 AMP
Voltage/Arc length	36-37 V
Gas flow rate(s) (Shielding/Purging)	NA
Travel speed	NA
Wire feed rate	365-370 in/min

Other information AFTER THE INITIAL 200 GRAMS OF FLUX HAS BEEN ADDED, CONTINUE TO ADD FLUX WITH THE TAPCO POWDER FEEDER AT 1.7 CONTRL SETTING AND THE NUMBER 20 WHEEL FOR DURATION OF THE WELD. WING GUIDE CROSS SECTION DIMENSIONS ARE 1/4 in. BY 1 1/2 in.

Originator	Date	Welder

EXTENT OF APPROVAL
Range of materials A-36, A-572, A-588
Range of thickness 2 in. TO 3 in.
Range of diameters TRANSITION JOINT ONLY

Code(s)

WELDSPEC software by The Welding Institute, Cambridge. Telephone (0223)891162

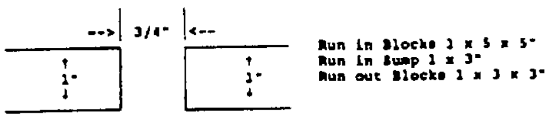
Electroslag welding procedure, 25-mm (1-in) butt weld.

Catalogue number 11	ECHO is off 1. Procedure details	Test record(PQR) number

Manufacturers name OREGON GRADUATE INSTITUTE	Procedure (WPS) no. NA	Revision no. NA

Welding process	Electroslag	PARENT MATERIAL Thickness 1 to 1
Root run process	Electroslag	Type C-Mn steel
Joint type	Butt-2 sided	Alloy STRUCTURAL STEEL
Welding position	Vertical	Standard Grade
Test piece posn.	VERTICAL	Material group(s) A-36, A-572, A-588
Welding technique	WING GUIDE	Dimensions of test piece 12" BY 18"

WELD PREPARATION



RUN SEQUENCE

Bevel angles left right
1st side - major
root
2nd side - major
root
Backing material

Side 1 groove depth
Root face
Side 2 groove depth
Gap
Land
Radius

Number of runs
1st side
2nd side
1st side
2nd side
1st side
Sealing run

Method of preparation and cleaning FLAME CUT OXYACETYLENE AND HAND GRIND

POST-WELD HEAT TREATMENT

Specification NA
Method
Control
Soak temp
Soak time

WELDING CONSUMABLES

Filler material
Make/type OGI CUSTOM
Specific. TUBULAR ALLOY
Size(s) 3/32"
Shielding gas/flux
Make/type HOBART PF 201 (125gm)
Composition

Baking treatment
STORE FLUX AT 250F UNTIL USE

Side 2 treatment

	Preheat	Interpass
Temp Method Control	AMBIENT	NA

WELDING CONDITIONS Units

Run number(s)	
Electrode polarity	DCEP
Consumable diameter	2/32"
Current	650 AMP
Voltage/Arc length	36-37 V
Gas flow rate(s) (Shielding/Purging)	NA
Travel speed	NA
Wire feed rate	260 in/min

Other information AFTER THE INITIAL 125 GRAMS OF FLUX HAS BEEN ADDED, CONTINUE TO ADD FLUX WITH THE TAPCO POWDER FEEDER AT 1.7 CONTRL SETTING AND THE NUMBER 20 WHEEL FOR THE DURATION OF THE WELD. WING GUIDE CROSS SECTION DIMENSIONS ARE 1/4 in. BY 3/4 in.

Originator Date Welder

EXTENT OF APPROVAL
Range of materials A-36, A-572, A-588
Range of thickness 1 in. TO 1 in. ONLY
Range of diameters

Code(s)

WELDSPEC software by The Welding Institute, Cambridge. Telephone (0223)891162

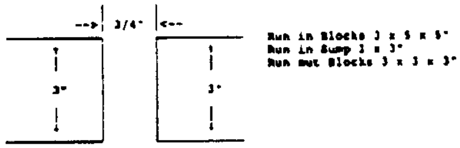
Electroslag welding procedure, 76-mm (3-in) butt weld.

Catalogue number 12	ECHO is off 1. Procedure details	Test record(PQR) number

Manufacturers name	Procedure (WPS) no.	Revision no.
OREGON GRADUATE INSTITUTE	NA	NA

Welding process	Electroslag	PARENT MATERIAL	Thickness 3 to 3
Root run process	Electroslag	Type	C-Mn steel
Joint type	Butt-2 sided	Alloy	STRUCTURAL STEEL
Welding position	Vertical	Standard	Grade
Test piece posn.	VERTICAL	Material group(s)	A-36, A-572, A-588
Welding technique	WEB GUIDE	Dimensions of test piece	12" BY 18"

WELD PREPARATION



Bevel angles — left right
1st side - major
root
2nd side - major
root
Backing material

Side 1 groove depth
Root face
Side 2 groove depth
Gap
Land
Radius

RUN SEQUENCE

Number of runs
1st side
2nd side
1st side
2nd side
1st side
Sealing run

Method of preparation and cleaning FLAME CUT OXYACETYLENE AND HAND GRIND

POST-WELD HEAT TREATMENT

Specification NA
Method
Control
Soak temp
Soak time

Baking treatment
STORE FLUX AT 250F UNTIL USE

WELDING CONSUMABLES

Filler material
Make/type OGI CUSTOM
Specific. TUBULAR ALLOY
Size(s) 3/32"
Shielding gas/flux
Make/type HOBART PF 201 (300gm)
Composition

Side 2 treatment

	Preheat	Interpass
Temp Method Control	AMBIENT	NA

WELDING CONDITIONS Units

Run number(s)	
Electrode polarity	DCEP
Consumable diameter	3/32"
Current	1300AMP
Voltage/Arc length	36-37 V
Gas flow rate(s) (Shielding/Purging)	NA
Travel speed	NA
Wire feed rate	180-190 IN/MIN EACH WIRE - (2 WIRE SYSTEM)

Other information AFTER THE INITIAL 300 GRAMS OF FLUX HAS BEEN ADDED, CONTINUE TO ADD FLUX WITH THE TAPCO POWDER FEEDER AT 1.7 CONTRL SETTING AND THE NUMBER 20 WHEEL FOR DURATION OF THE WELD. WEB GUIDE CROSS SECTION DIMENSIONS ARE 1/4 in. BY 1 3/4 in.

Originator	Date	Welder

EXTENT OF APPROVAL
Range of materials A-36, A-572, A-588
Range of thickness 3 in. TO 3 in. ONLY
Range of diameters

Code(s)

WELDSPEC software by The Welding Institute, Cambridge. Telephone (0223)891162

APPENDIX B. ESW PRACTICE

WELD SETUP

1. Flame-cut square edges on plates and grind to remove oxides or other contaminants.

2. Using a fixture or braces, clamp the plates in position to provide a uniform 19-mm joint space in the vertical position.

3. With SMAW or GMAW processes, weld the run-in and run-out blocks to the plates with all welds inside the ESW joint area. Be sure all blocks are parallel to the plate surfaces and tightly fit to the plate edges. This will avoid slag loss.

4. Position the wire feeder so the guide tube is centered on the weld joint.

5. Cut the guide tube or adjust the feeder position to produce 19-mm space between the end of the guide tube and starting sump. The sump may be cut deeper or space blocks of matching chemistry added when conditions make such adjustments more practical.

6. Place insulators around the guide tube to hold it in the center of the joint during welding. If the guide tube is close enough to the plate edge to arc or short out, the weld must be terminated.

7. Extend the electrode wire through the guide to be sure it feeds freely.

8. Position the cooling shoes so that the reinforcing groove is centered over the weld joint. Use alumina ceramic tape to fill the reinforcing groove below the runin sump (starting sump) or where fit up between the cooling shoe and the plate surface cannot be adjusted to provide good contact.

9. Attach one ground lead near the bottom of each plate after removing mill scale or any material that may prevent good contact.

10. Position the flux feeder tube as near to the top of the weld joint as possible without obstructing the area for starting flux addition, or without allowing it to be within arcing distance of the run-out block and cooling shoes.

WELD OPERATION

1. Turn the cooling water on for the copper shoes just before the weld start. To avoid condensation on the shoe face, do not turn the cooling water on until the weld is ready to start.

2. Close contactor and check for open circuit voltage (a short exists if there is no open circuit reading and/or if there is a current reading immediately after closing the contactor).

3. Start the wire feed at a midrange setting (i.e., 4590 mm/min, 180 in/min).

4. Add the initial flux volume as the arc starts. Add it at a gradual rate, taking about 1 min to add the specified amount. If flux addition is rushed, a large percentage may be lost because of insufficient melting.

5. As soon as the starting flux volume has been added, increase the wire feed rate to the level specified in the procedure. This should be completed before the slag pool has advanced more than 20 mm above the run-in.

6. Start the metered flux addition when the original flux addition is completed.

7. Monitor the current level for a stable meter and chart record after the slag pool progresses out of the run-in. If the band width on the recorder continues to be erratic, the slag volume is low. The metered flux should be increased until amperage becomes stable. If a visible slag leak occurs, a gradual manual flux addition may be required. Be sure it is slow enough to allow complete flux melting in order to avoid slag entrapment. Current variations may be exaggerated if the run-in and run-out width is greater than the joint spacing.

8. As the slag pool reaches the top of the run-out blocks, turn off the wire feed and contactor at the same time to avoid arcing or molten slag spill.

9. The cooling shoe may be removed as soon as the slag pool becomes solid. Caution must be taken to avoid hot slag that pops off the weld face as it cools. The final slag depth should be a minimum of 19 mm and a maximum of 41 mm at the top of the runout.

Caution: Slag chips may be very sharp.