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Repair of Process-Related Defects in Electroslag Welding

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

FOREWORD

The purpose of this report is to provide a welding procedure for weld repair of electroslag weldments and to document the fatigue properties of the resulting repaired electroslag weldments.

This report contains a description of the most common types of defects common to electroslag weldments, and weld repair procedures that can be used to repair each type of defect. The report also contains information about the fatigue properties of the repaired electroslag weldments relative to electroslag weldments without repair welds. An appendix details a welding procedure for manual shielded arc weld repair.

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

Thomas J. Pasko

Director, Office of Advanced Research

NOTICE

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16. Abstract

The primary objectives of this program were to develop a welding procedure for repair of electroslag weldments (ESW) and to determine if repair welding influenced the fatigue strength of electroslag weldments. Integral to this effort was the identification of the most likely types of defects, their causes, and the potential for effective repair.

The electroslag welding process is capable of producing a higher volume of defect-free weld deposit than other processes used for joining structural steel. When defects do occur, however, ESW is not well-suited for use as a repair process since it is limited to vertical position, single-pass, full-thickness welding.

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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.				
		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

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* 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 ABBREVIATIONS

ESW	Electroslag Weldments
SMAW	Shielded Metal Arc Welding
OGI	Oregon Graduate Institute
RT	Radiographically Tested
UT	Ultrasonically Tested

INTRODUCTION

The primary objectives of this program were to develop a welding procedure for repair of electroslag weldments (ESW) and to determine if repair welding influenced the fatigue strength of electroslag weldments. Integral to this effort was the identification of the most likely types of defects, their causes, and the potential for effective repair.

The electroslag welding process is capable of producing a higher volume of defect-free weld deposit than other processes used for joining structural steel. When defects do occur, however, ESW is not well suited for use as a repair process since it is limited to vertical position, single-pass, full-thickness welding.

SUMMARY

In this project, a shielded metal arc welding (SMAW) procedure was developed for the repair of ESW defects. Six ESW defects were defined and multiple examples of each were produced in 50-mm-thick A588 alloy steel plate. Three examples of each defect were repair welded then evaluated by ultrasonic, radiographic, and sectioning inspection methods to verify the SMAW repair procedure.

It was demonstrated that repaired electroslag welds maintain acceptable fatigue strength by full-scale beam fatigue tests. Four beams were tested, each containing two repaired ESW narrow gap welds in the 50-mm-thick tension flange, including two beams fatigued to 2 million cycles at a 124-MPa stress range prior to repair.

EXPERIMENTAL PROCEDURE

ELECTROSLAG WELDING PRACTICES

All laboratory welds for defect assessment were made on 50- by 300- by 600-mm A588 alloy plates with conventional fixed-position consumable single guide tube practice in a 31-mm joint spacing enclosed by water-cooled copper-sided shoes. Welding consumables were limited to the commercial 12-mm-round AISI-1018 consumable guide tube, 2.3-mm electrode wire, and electroslag welding flux. The four fatigue test beams were an exception to the ESW practice described above and were welded with the narrow gap (19-mm joint spacing) wing guide tube method and included two beams welded with electrode wire and two beams welded with tubular electrode wire.

Welding conditions for the standard practice ESW applications were 40 to 42V and 600 to 650 A. These conditions produced defect-free welds with good appearance and good fatigue strength as reported in the Federal Highway Administration, FHWA-RD-87-026, "Improved Fracture Toughness and Fatigue Characteristics of Electroslag Welds." Narrow gap welding conditions for the fatigue test beam ESW were 35 to 37V and 1000 to 1100 A.

WELD DEFECTS

Many typical ESW defects and their causes are described in a prior report, FHWA-RD-87-026. With the exceptions of cold cracking and porosity, each defect described in that report was produced in triplicate for this project to verify the defect description and to determine the extent of excavation required to complete repairs.

WELD INSPECTION

Electroslag welds were radiographically tested (RT) by a commercial testing lab, then ultrasonically tested (UT) with both straight and angle beam techniques to provide a more complete description of each defect. All repair weld reinforcement was removed by grinding to restore a smooth plate surface for ultrasonic and radiographic inspection. Magnetic particle or dye penetrant inspections were used to ensure that each defect had been completely removed prior to repair welding. All nondestructive testing was performed in compliance with American Welding Society D1.1 requirements.

REPAIR PROCEDURE DEVELOPMENT

The ANSI/AWS D1.1-86 "Structural Welding Code," the "New York State Steel Construction Manual," and other selected references were reviewed in preparation for the repair procedure. In addition, the individuals listed in table 1 were asked to provide

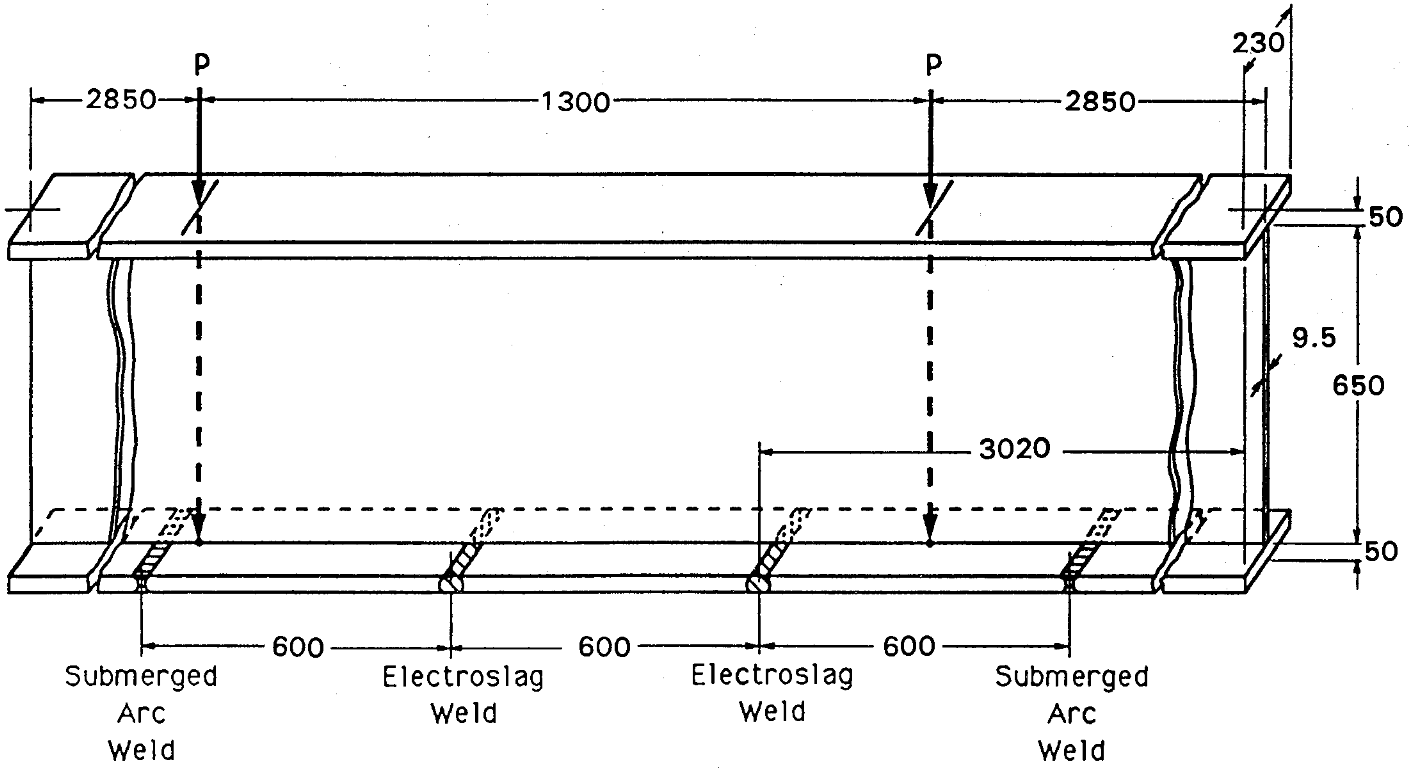
Table 1. Individuals who contributed information leading to the development of the ESW repair procedure.

Warren G. Alexander	State of New York, Department of Transportation, Office of Engineering Design and Construction Division, Private Consultant
Ian M. Friedland	Senior Program Officer of Cooperative Research Programs, Transportation Research Board, National Research Council
Gary Kasza	Federal Highway Administration Portland, Oregon
Bruce V. Johnson	Federal Highway Administration Portland, Oregon
Walt Hart	Oregon State Department of Transportation Salem, Oregon
Stuart Gloyd	Washington State Department of Transportation Olympia, Washington
Hasan Shatila	Washington State Department of Transportation Olympia, Washington
William F. Crozier	California State Department of Transportation Sacramento, California

repair welding procedures used by their department or agency and to contribute suggestions for developing a SMAW procedure applicable to repair of ESW on thick-section structural steel. The SMAW procedure was verified by performing repairs on three examples of each type of repairable ESW defect. All 18 repair samples were UT inspected and sectioned to confirm weld quality and compliance with weld preparation requirements.

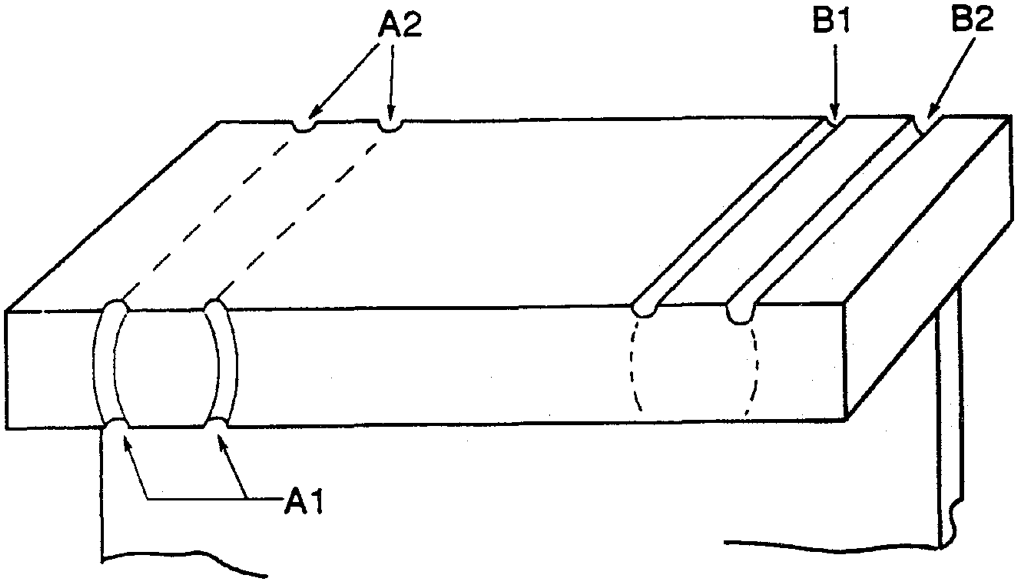
FATIGUE TESTING

Fatigue tests were conducted on four large I-beams as shown in figure 1. Two beams identified as nos. 4 and 6, had completed more than 2 million fatigue cycles at a 124-MPa stress level in earlier tests (report no. FHWA-RD-87-026). Two new beams, nos. 7 and 8, were fabricated to provide a direct comparison between the repair of new and of previously fatigued electroslag welded structures. Identical repairs were made on beams 4 and 7, and on beams 6 and 8 as shown in figures 2 and 3. Each excavation could represent the repair of more than one type of defect, since the distinction between repairs after excavation is simply one of shape and orientation. Possible defects for each excavation are listed with each diagram of the respective beam repair. The fatigue beams were repair welded. All repair work was monitored by an engineer and a quality assurance consultant with extensive ESW experience. After UT and RT inspection, the four beams were fatigue tested.



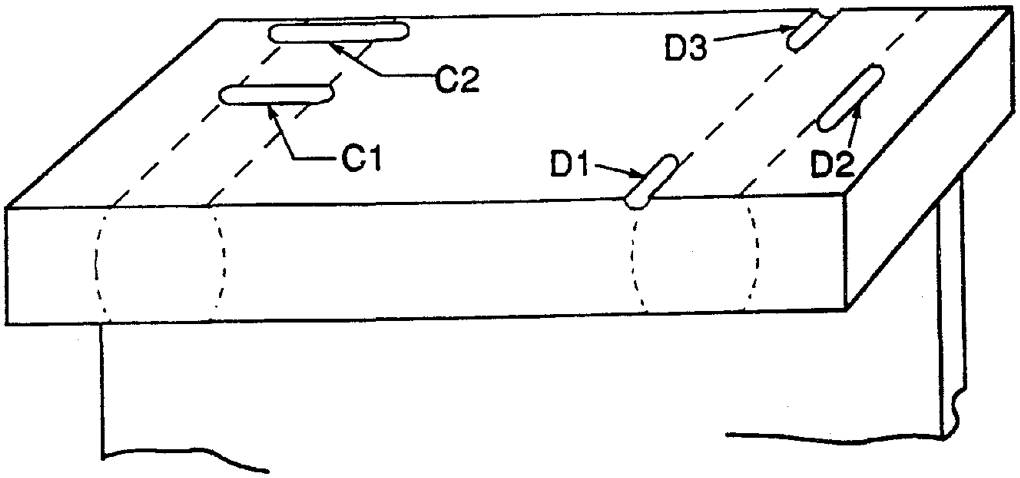
Units: Millimeters

Figure 1. Beam design for full-scale electroslag fatigue tests.



	Repair Excavations			Beam Nos. 4 and 7
	Depth (mm)	Width (mm)	Length (mm)	Simulated Repairs
A1	3	9	50	Cold Start, Undercut
A2	6	12	50	Cold Start, Undercut
B1	9	16	228	Undercut, Incomplete Fusion
B2	16	19	228	Incomplete Fusion, Slag Inclusion

Figure 2. Repair excavation in the electroslag weldments of full-scale fatigue test beams nos. 4 and 7.



	Repair Excavations			Beam Nos. 6 and 8
	Depth (mm)	Width (mm)	Length (mm)	Simulated Repairs
C1	15	19	46	Porosity, Slag Inclusion, Incomplete Fusion
C2	12	15	76	Porosity, Cold Start, Slag Inclusion
D1	12	16	100	Cold Start, Incomplete Fusion
D2	16	19	76	Slag Inclusion, Incomplete Fusion, Porosity
D3	9	16	25	Cold Start, Undercut, Incomplete Fusion

Figure 3. Repair excavation in the electroslag weldments of full-scale fatigue test beams nos. 6 and 8.

RESULTS

WELD DEFECT CONDITIONS

The eight electroslag weld defect conditions identified are described below. Weld sections showing each type of defect are shown in figures 4 through 10.

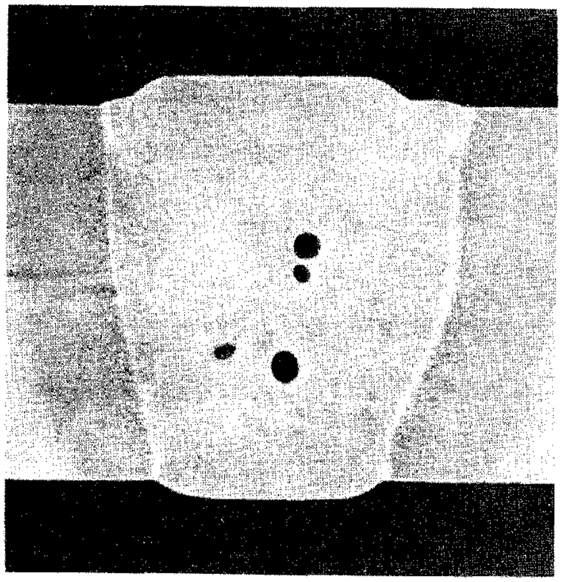
1. **Porosity** results from the use of improper or contaminated flux, outgassing from defects in the plate material near the weld fusion boundary, or in cases of extremely low slag pool depth (figure 4).

2. **Slag Inclusions** result when sudden variations in voltage or excessive flux addition occur, or where extreme weld joint surface variations are present. Each of these conditions create a sudden cooling of the slag pool that decreases weld penetration leaving a protrusion of solid base metal over molten slag. The protruding solid base metal obstructs upward movement of the slag pool, leaving a small deposit of slag trapped beneath it as seen in figure 5. The internal slag inclusions caused by a sudden voltage decrease tend to occur at both fusion boundaries of the weld and a discrete inconsistency may appear on the weld faces since the temperature is reduced uniformly across the slag pool.

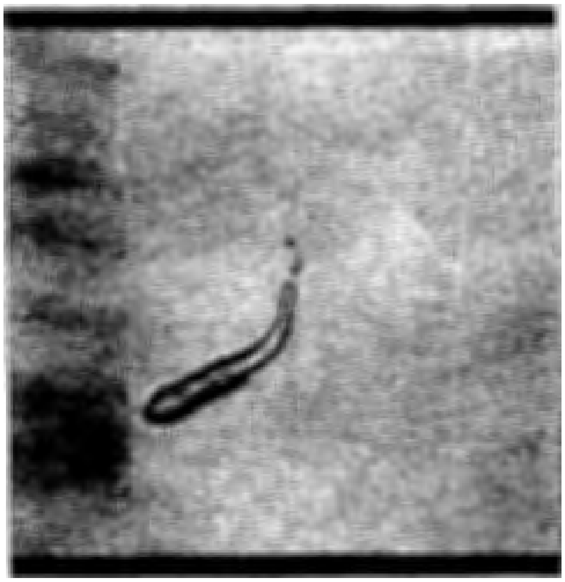
3. **Centerline Cracking** in ESW is usually a form of hot cracking. Hot cracking in other forms of welding is normally visible at the weld surface, but hot cracking may be present in electroslag welds with very good surface appearance. Hot cracking in ESW results when a susceptible weld metal chemistry is combined with rapid weld solidification and shrinkage rates. Excessive penetration due to high welding voltage dilutes the weld metal alloy content and if a high welding current/high deposition rate is also present, the resultant low alloy rapidly solidified weld is nearly guaranteed to produce centerline cracking (figure 6).

4. **Undercut or Underfill** results from high voltage, slow travel speed, improper positioning of the electrode, or cooling shoe conditions including poor fit-up, improper reinforcement groove geometry, or inadequate cooling (figure 7).

5. **Incomplete Fusion** is a result of low voltage, improper guide tube design, excessive current, or excessive slag depth. Areas of incomplete fusion will be filled with slag and are usually parallel to the weld joint. Extreme cases of incomplete fusion will produce exaggerated weld bead surface ripples that may be better described as cold laps lying transverse to the weld joint, and the cold laps may also entrap slag. Improper ground or guide tube position will also cause incomplete fusion at the weld edge, but the defect condition is identified as lack of weld symmetry (figure 8).



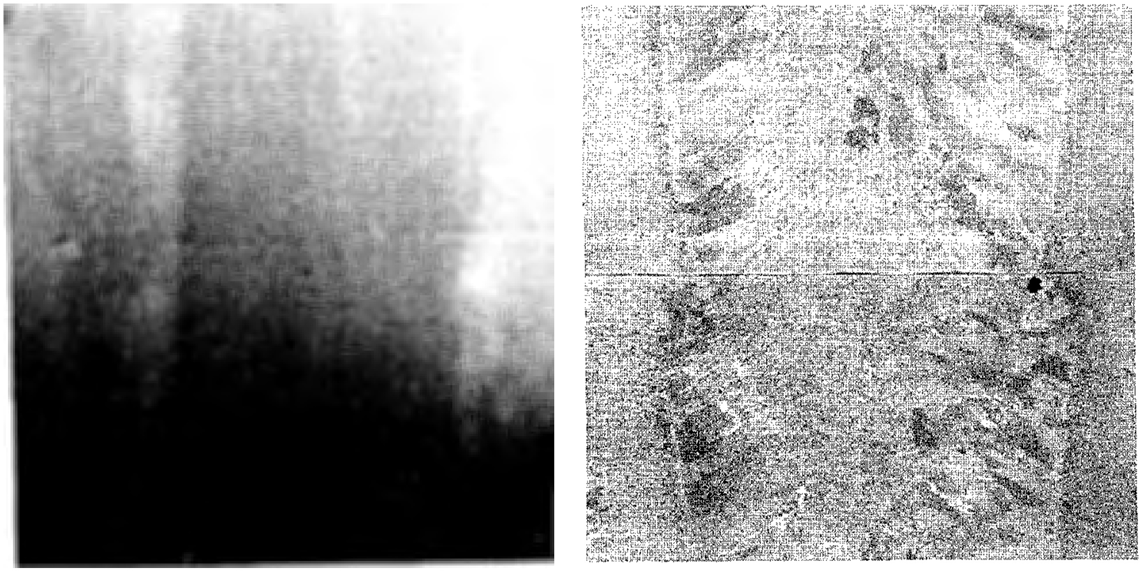
Transverse Weld Section
(a)



Longitudinal Weld Section
(b)

Figure 4. Porosity in electroslag welds from (a) very wet flux and (b) base metal inclusion at the weld fusion boundary.

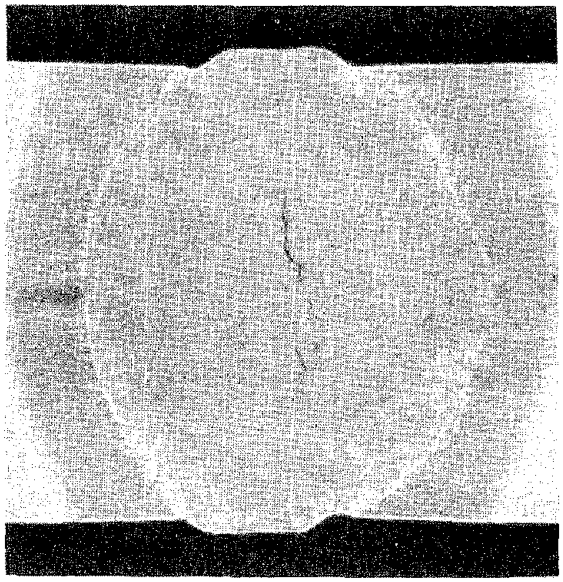
(a) Weld surface indication.



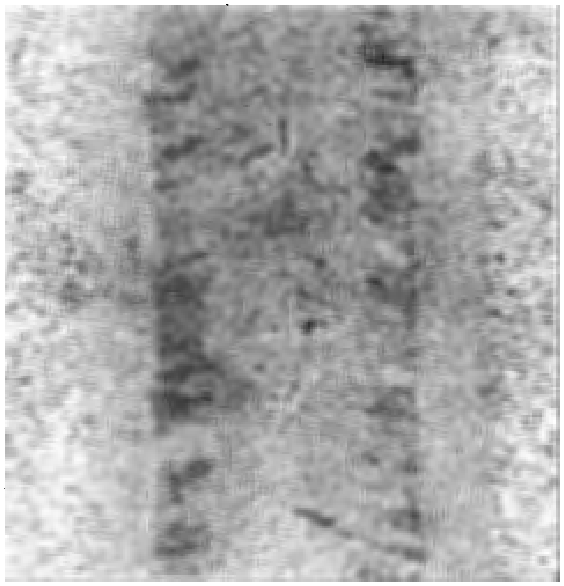
(b) Radiographic indication.

(c) Macro-section revealing
2-mm-diameter inclusion
9 mm below the plate surface.

Figure 5. Slag inclusion resulting from a sudden 5V decrease and gradual recovery to proper welding voltage.



Transverse Weld Section
(a)



Longitudinal Weld Section
(b)

Figure 6. Centerline cracking resulting from (a) high welding current and (b) improper alloy composition.

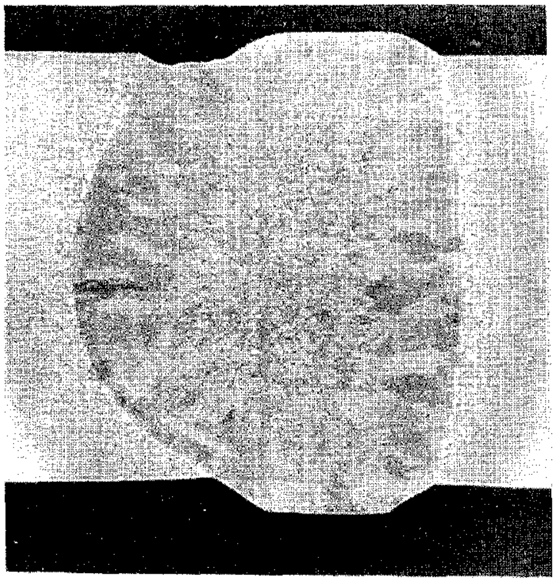


Figure 7. Underfill resulting from an excessive voltage and improper guide tube position nearer one side of the weld joint.

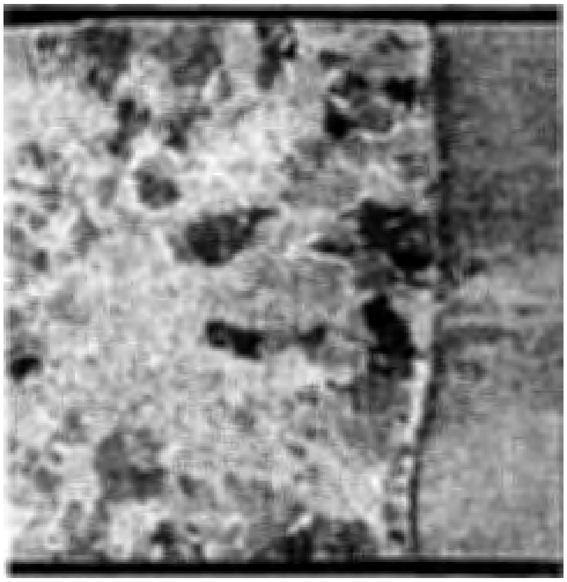


Figure 8. Incomplete fusion resulting from improper guide tube position nearer one side of the weld joint with otherwise proper welding conditions.

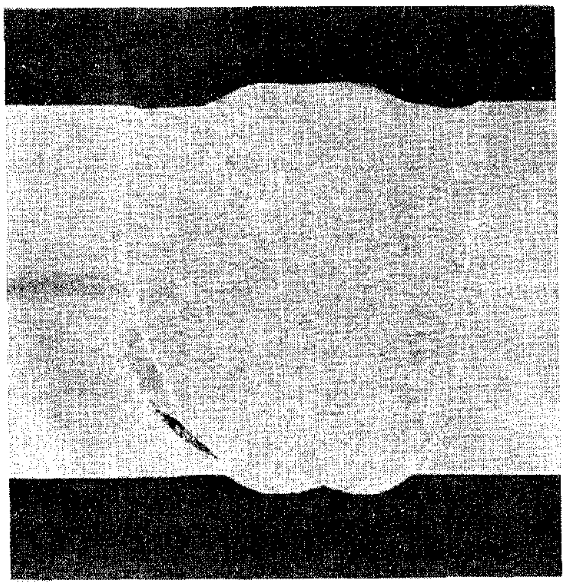


Figure 9. Lack of symmetry in a weld caused by positioning the guide tube nearer one plate surface resulting in a slag inclusion and minor underfill.

Figure 10. Weld centerline slag inclusion in a run-off block.

6. **Lack of Symmetry** in a weld results when the guide tube is not properly centered in the weld joint or when the ground connections are not properly positioned on each side of the weld joint. A nonsymmetrical weld setup produces a weld pattern that extends deeply into one weld member and produces incomplete fusion in the other, but the total weld volume is the same as found in a properly executed weld (figure 9).

7. **Restarting** an electroslag weld will produce incomplete fusion that may extend full thickness of the plate as well as small slag inclusions at the weld centerline just below the termination of the initial weld. The cause of a centerline slag inclusion at the end of a weld is similar to what is known as a shrinkage cavity in metal castings, and is found in most weld run-off tabs that are normally removed and discarded as shown in figure 10.

8. **Cold Starting** is incomplete fusion as the weld progresses from the run-in sump to the edge of the weld plates. The condition usually extends across the edge of the weld plates and may extend a short distance along the edge of the weld joint. Cold starting will occur if welding power conditions are not established quickly enough during the weld run-in or if the flux is added too fast to allow sufficient slag bath formation. Cold starts may also occur if the starting sump is not of sufficient length or if the run-in block is not adequately welded or clamped to the edge of the weld plates.

It was not possible to produce porosity on a dependable basis with conditions that would be encountered in industry. Porosity repair conditions would be nearly identical to those for slag inclusions, therefore repair of porosity samples was not pursued in this program.

Centerline cracking was also excluded from specific repair practices, since welds with centerline cracking should be completely removed and replaced. In order to perform SMAW repair of centerline cracking, the full thickness of the affected electroslag weld would have normally been removed.

INSPECTION

With the exception of centerline cracking, all evaluated defects were detectable with routine UT inspection. Centerline cracking was detectable with RT inspection, but it required an extra degree of attention by the inspector used in this program to identify smaller crack regions.

REPAIR WELDING PROCEDURE

The complete "Procedure Specification For Manual Shielded Metal Arc Welded Repair of Electroslag Weldments In Heavy Section Structural Steel" is presented in appendix A. The root radius and sidewall angle requirements for repair excavations are very important and must be observed. The angle limits for the groove end and sidewall are designed to reduce the potential for slag inclusion by forcing a cascading condition of the weld ends and overlap of the weld bead from layer to layer as shown in figure 11. The sidewall angle requirement also reduces sidewall undercut, which is a potential sight for slag inclusion or incomplete fusion.

The minimum 30-s arc time and 38-mm weld length are intended to provide sufficient heat input and weld pool size to avoid slag inclusions, incomplete fusion, or extreme hardness variations in the structure. Attachment of run-off blocks by clamping or prohibiting tack welds outside of the repair excavation is also intended to avoid new defects or unnecessary variations in material hardness or grain structure. The presence of these conditions may act as a fracture initiation site under fatigue loading. This situation was demonstrated by the failure of fatigue test beams nos. 1 and 2, reported in FHWA-RD-87-026, "Improved Fracture Toughness and Fatigue Characteristics of Electroslag Welds," where fatigue failure was initiated at starting block tack weld locations outside of the ESW weld joint.

FATIGUE TESTING

The results of the full-scale fatigue tests on electroslag-welded beams are presented in table 2. Each beam met the minimum fatigue required limit of 2 million cycles at a 124-MPa stress range, including beams 4 and 6 that had been fatigue tested to the minimum acceptance level prior to repair welding. The I-beam test results clearly indicate that sound-shielded metal arc repairs of electroslag defects are not detrimental to the fatigue strength of the weldment.

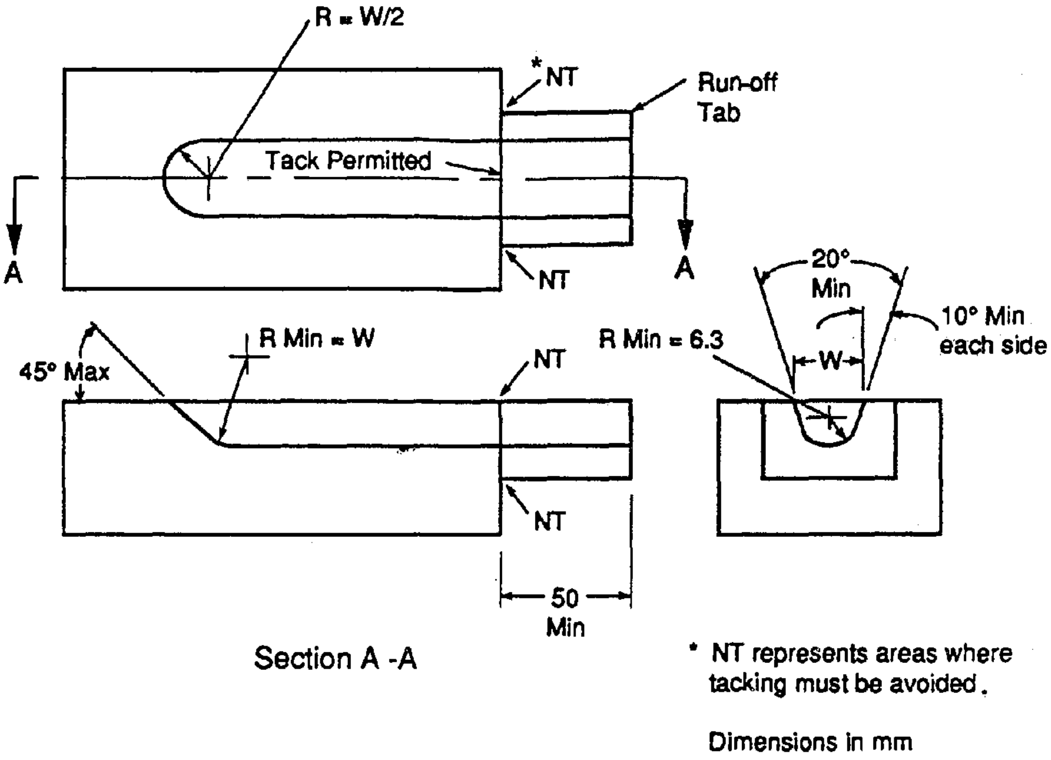


Figure 11. Repair weld groove requirements.

Table 2. Fatigue test beam results for shielded arc repair of electroslag weld defects.

			Million Cycles			Equivalent Stress Range (MPa)		
Beam No.	Weld No.	Electrode	Initial	Repair	Total	Initial	Repair	Failure
4	6 8	588 588	3.37	2.17	5.54	1.19	1.16	None
6	10 12	588 588	2.78	4.07	6.85	1.18	1.15	None
7	13 14	8544 8544	0	7.75	7.75	0	1.18	Subarc
8	15 16	8544 8544	0	2.3	2.3	0	1.14	Subarc

All eight welds were made with a narrow gap 19-mm joint space and 6.3- by 44-mm wing tube. Electrodes were used at 900 A, 40V and tubular electrodes were used at 1100 A, 35V.

CONCLUSIONS

1. Eight defect conditions were defined and dependably produced on 50-mm-thick A588 alloy structural steel.

2. A successful SMAW procedure was developed for repair welding of defects in electroslag-welded, heavy section, structural steel.

3. Due to the extent of excavation required and limited confidence in the ability to eliminate every incident of centerline cracking, it is recommended that electroslag welds with centerline cracks be completely removed and rewelded after correcting the process conditions that caused cracking.

4. Ultrasonic and radiographic inspection of electroslag welds require qualified evaluation due to the unique defect patterns encountered and the course grain structure of electroslag welds.

5. A continuous record of welding voltage, current, and deposition rate is recommended for each weld for quality assurance.

6. Fatigue testing on full-scale beams demonstrated that sound SMAW repair of electroslag welds is not detrimental to the fatigue strength of electroslag weldments.

APPENDIX A

OREGON GRADUATE INSTITUTE OF SCIENCE & TECHNOLOGY
DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING

WELDING PROCEDURE

PROCEDURE SPECIFICATION FOR MANUAL SHIELDED METAL ARC WELDED REPAIR OF ELECTROSLAG WELDMENTS IN HEAVY SECTION STRUCTURAL STEEL

Specification 81-452-3 August 03, 1990

Welding Process: Welding shall be done by the shielded metal arc process using manual equipment.

Base Metal: HSLA structural plate ASTM A588-85A Grade B, 50 mm or less in thickness.

Filler Metal: The filler metal shall conform to ASME Filler Metal Specification Number E-7018 (AWS A5.5). Electrodes will be provided in hermetically sealed containers and shall be dried for at least 2 h, but not to exceed 4 h, between 230 and 260 °C before use. After drying, electrodes shall immediately be placed in a storage oven held continuously at a temperature of at least 120 °C until used in the work. Electrodes not used within 4 h from the time they are removed from the drying or storage oven shall be redried for a minimum of 1 h at a temperature between 370 and 425 °C or shall be discarded and not used in the work.

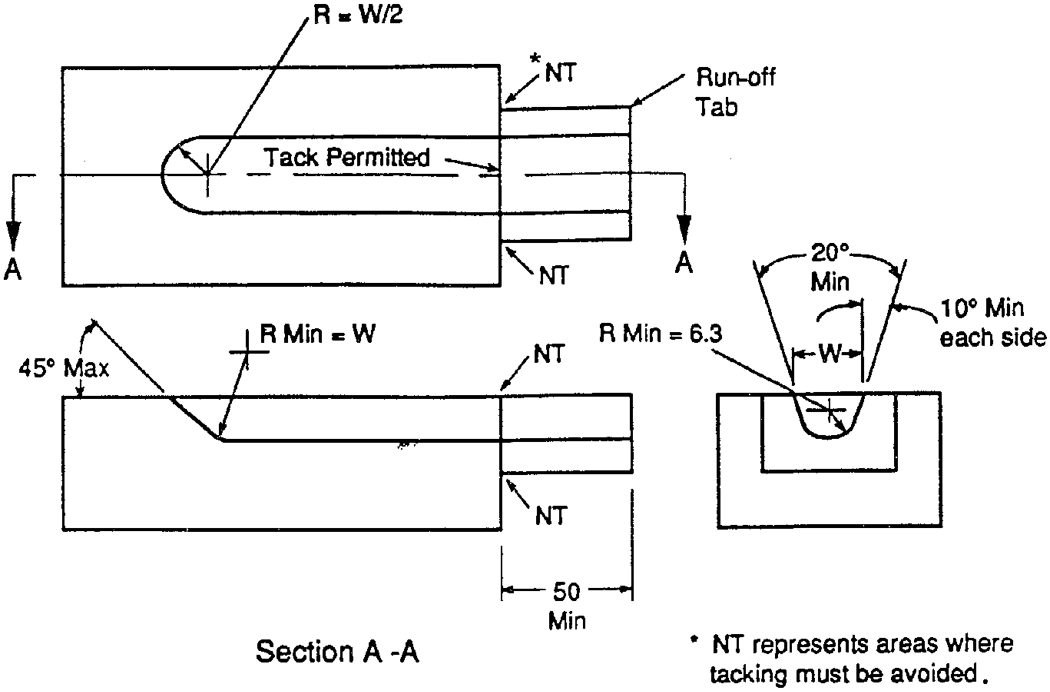
Position: The work shall be positioned for flat position welding.

Heat Treatment: A minimum preheat and interpass temperature of 120 °C shall be maintained through thickness and within 12 cm in any direction from the repair excavation. Post-weld heat treatment of 204 °C minimum and 260 °C maximum for 1 h/25.4 mm of thickness must be provided. Preheat interpass temperature maintenance and post-weld heat treatment shall be a contiguous process.

Preparation of Base Metal: Excavation of defects may be done by machining, grinding, or air carbon arc gouging. Air carbon arc gouging shall be done at a minimum preheat of 120 °C using direct current reverse polarity with a power supply rated at a minimum of 300 A. All gouging shall be followed by grinding to remove surface irregularities and carbon pickup. Grinding may be performed at ambient temperature.

Excavations shall have a minimum 6.3-mm root radius and minimum 10° sidewall angle on each side. Any closed-end excavation shall have a maximum 45° incline from the groove root to the plate surface to produce cascaded ends on multiple layer welds. The groove end shall be radiused to match the nominal groove width at any given depth.

Any open-ended excavation (groove at a plate edge) shall utilize run-off tabs with a minimum 150-mm weld length and groove geometry matching the repair excavation (figure 12). It is preferable to clamp run-off tabs into position. If tack welds must be made, they are only acceptable in the weld groove where they will be consumed by the repair weld. Tack welds will conform to repair weld preheat requirements.



* NT represents areas where tacking must be avoided.

Dimensions in mm

Figure 12. Minimum weld repair groove geometry and run-off tab requirements.

Repair excavations shall be inspected with magnetic particle testing to insure that defects have been completely removed prior to welding.

<u>Welding Procedures</u>: A 3.9-mm-diameter electrode must be used at 170 to 180 A direct current electrode positive with a power supply rated at a minimum of 300 A. All weld passes shall be done by the stringer-bead techniques. Weld start and terminations on multipass welds shall be arranged such that stacking does not occur. The minimum arc time shall be 30 s or the minimum weld length shall be 3.8 cm to ensure sufficient weld heating of the base metal. Aborted welds or arc strikes shall be completely removed by grinding before continuing the weld.

Repair welds shall provide an overfill of at least 3 mm to provide sufficient material for grinding back to a flush-plate surface. The last weld pass shall be placed so that it is deposited completely on repair weld metal and shall not be in contact with the base metal.

Appearance of Weld: The repair weld surface shall be reasonably smooth and even with no indication of undercut.

Weld Finishing: Upon completion of the work, all weld reinforcements shall be ground flat to match the original surface of the plate material being welded. Weld run-in and run-out blocks shall be removed by grinding and the edge of the plate ground to restore the original edge shape. All grinding marks shall run normal (parallel) to the lay of the beam.

Peening: Peening should not be used on this work.

Inspection: All repair welds shall be RT inspected no sooner than 48 h after repaired area has returned to ambient temperature in compliance with AWS D1.1-84 (Inspection Report on Electroslag Welds).

Agenda: Any area not addressed in this procedure is referred to AWS D1.1-86, section 3, as a minimum guideline.