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High-Speed Rail IDEA Program

Electroslag Field Welding of Railroad Rail

Final Report for High-Speed Rail IDEA Project 37

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January 2003

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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Electroslag Field Welding of Railroad Rail
IDEA Program Final Report
for the period September 2002 to November 2003
Contract Number HSR-37

Prepared for the IDEA Program
Transportation Research Board
National Research Council

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ACKNOWLEDGEMENTS

The authors would like to thank the Transportation Research Board, especially Mr. Chuck Taylor and Ms. Debra Irvin for their support and guidance. We also gratefully acknowledge the project's Advisory Board, Mr. Daniel Mesford and Mr. Bob Galloway, both of the Burlington Northern Santa Fe railroad, who provided invaluable direction and practicality. Finally, we would like to recognize the members of the industry and academia who have supported our numerous requests for information and technical assistance.

ABSTRACT

Research was conducted on the welding of railroad rail with the electroslag welding process. The work was sponsored by the Transportation Research Board (TRB) of the National Academies under contract HSR-37.

The work included a literature search, market survey and welding of 136 pound per yard rail varying voltage, current, electrode speed, chemistry, guide tube configuration, flux and cooling shoe geometry. The welds were tested by a combination of 4 point bend test, microstructure, macrostructure, chemical composition, hardness, strength and toughness.

The breaking strength of electroslag welded rail was increased from approximately 170,000 pounds to 375,000 pounds in the 4 point bend. This is approximately 5% less than AREMA rail weld specifications. The running surface and heat affected zone hardnesses were controlled to current AREMA requirements.

Key words: electroslag, welding, railroad rail, thermite, flashbutt

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EXECUTIVE SUMMARY

This report covers the Electroslag Field Welding of Railroad Rail project, HSR-37, sponsored by the Transportation Research Board (TRB) of the National Academies. The project started on September 10, 2002 and was concluded in November 2003.

CONCEPT AND INNOVATION

The project investigated the feasibility of field welding railroad rail with the Electroslag Welding (ESW) process. Two processes currently dominant the market, thermite and flash-butt welding. Thermite welding uses an exothermic reaction to produce molten steel which is cast between two rails to be joined. The molten metal is contained by single-use sand molds. Flash-butt welding passes electrical current between the two rail ends which causes heating. The rails are then forced together with enough pressure to permanently bond them to each other. In both cases excess metal is sheared immediately after weld in completed.

These two processes are at opposite extremes in almost all aspects of field rail welding. Thermite is less capital intensive, less expensive, more portable and produces welds of lower quality. Flash-butt welding is highly capital intensive and therefore expensive, requires small trains to transport and produces more consistent, high quality welds. It is intended that ESW will take the position between the two in terms of portability and will be comparable to flash-butt in quality and to thermite in cost. It is estimated that over 600,000 thermite welds are made in North America per year at an average cost of $350/weld. (1) Flash-butt welds are generally more expensive, typically $500 each.

The objective of this project was an electroslag rail weld that met or exceeded current American Railway Engineering and Maintenance-of-Way Association (AREMA) rail weld specifications. These specifications include a Slow Bend Test Modulus of Rupture of 125,000 psi, a minimum deflection of 0.75 inches, the weld metal hardness of not more than 400 BHN or 43 Rc, the weld metal hardness on the running surface within 30 BHN or 5 Rc of parent rail head hardness (except at the decarburized centerline and at the spherodized edge of the heat affect zone) and 100% pearlitic microstructure. (2)

INVESTIGATION AND RESULTS

This project consisted of three phases with the four major tasks of 1) weld metal development, 2) Heat Affected Zone (HAZ) control and characterization, 3) run-out (termination of the weld at the running surface) optimization, and 4) weld start optimization. In addition, several tasks not part of the original plan were added including weld wire evaluation, cooling shoe design and manufacturing and weld flux evaluation.

Work began with the fabrication of a rail welding fixture which positioned and held the rail to be joined and the wire drive/guide tube clamping system. A remote welder controller panel was also built.

A total of 31 complete and 4 partial rail welds were made. (Fig.1) Post-welding analyses consisted of some combination of a 4-point slow bend test, sectioning for macro and/or microscopic examination or sectioning for mechanical test or chemical composition specimens. All work was done on 136#/yard premium rail.

Five weld metal chemical compositions were investigated and tested. Several welds were instrumented with thermocouples in at least three locations and the thermal histories recorded from preheat to post-weld heating. Three flux types were used and approximately 30 references were located and studied.

Some, but not all objectives were achieved. The two objectives that were met were the hardness and microstructure. The weld metal hardness was controlled between 36 and 41 Rc with the exception of the spherodized edge of the heat affected zone which dropped to 30 Rc. The 100% pearlitic microstructure was achieved. The two objectives that were not successfully attained were the maximum rupture modulus and minimum deflection. The highest rupture modulus was 119,300 psi (target = 125,000 psi) and the maximum deflection was 0.35 inch (target = 0.75 inch). Table I lists comparative slow-bend data including electroslag weld values at the start and end of the project, the AREMA specification and the two competing welding processes. Other results, such as control of weld width, are discussed in more detail later.

TABLE 1
Comparative Slow-Bend Test Loads and Deflections

	Load (pounds, for 136#/yd rail)	Rupture Modulus (psi for 136#/yd rail)	Deflection (inches)
Electroslag, Project start	170,000	54,000	0.05
Electroslag, Project end	375,000	119,000	0..36
AREMA Specification (1)	393,000	125,000	0.75”
Thermite Weld (2)	421,500	134,000	1.27
Flash Butt Weld (3)	515,000	164,000	1.6

ADVISORY BOARD

Three advisory board meetings were held. The board members were Mr. Dan Mesford, Roadmaster, BNSF Longview, WA. and Mr. Bob Galloway, Rail Welding Supervisor, BNSF Northwest region, and the two EST&D owners. In addition to witnessing a weld, the board made suggestions on refining the welding equipment for the field, restrictions of the field environment (e.g. clearance on either side of the weld), and potential problems of electroslag rail welding such as weather or terrain limitations. The board’s comments were very helpful in directing the research toward practical solutions of field welding problems. At the suggestion of the BNSF board members, a fourth meeting and demo weld were held with Mr. John Wiederholt, BNSF’s Track Welding Manager, on October 30, 2003. Mr. Wiederholt also provided valuable suggestions and information regarding adaptation to in-track environment. It was both the Board’s and Mr. Wiederholt’s opinion that track-time for an electroslag weld would be less than that of a thermite weld, approximately 30 and 45 minutes respectively.

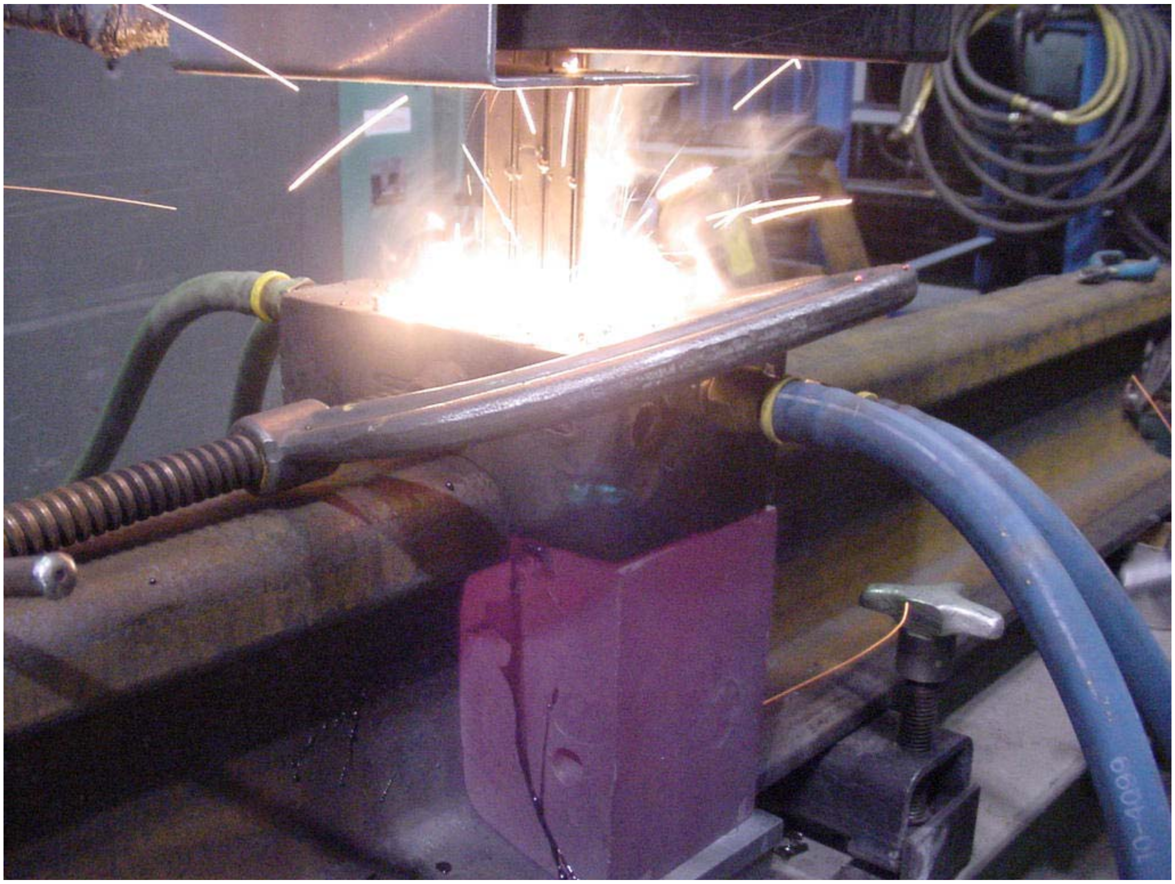

FIGURE 1. Electroslag rail weld in progress.

FUTURE WORK

Before the ESW process can be used by the railroads, the welds must meet the load and deflection requirements. To achieve those values it will be necessary to a) determine the exact mode of failure of the welds in this project and b) change the process so that the load and deflection are both increased to industry specifications. The first task, determining exact failure mode, can be accomplished by a thorough failure analysis. The results of that failure analysis will dictate what changes are needed to reach the specifications. All of the welding parameters (e.g. voltage, current, chemistry and geometry) can be altered to produce the necessary increases. The exact final combination of the dependent variables is not known.

It will also be necessary to produce more precise cost estimates for an electroslag weld. There are three categories of costs in an electroslag rail weld: capital (welder, generator, cooling shoes), labor, and consumables. Based on preliminary figures, the cost of the consumables will be approximately $100/weld. This includes welding wire, flux, insulating tape and guide tube. Labor cost is estimated to be $100/weld. The known capital costs, including a welder and controller, cooling shoes and heat exchanger, pro-rated for a reasonable number of welds, are approximately $50/weld. Existing equipment (trucks, generators, etc) and typical costs to a railroad are not known and therefore not factored into the capital figure. Without those numbers an electroslag weld will cost approximately $250.

Discussions with the Advisory Board have framed a possible scenario to get the process commercialized. First, testing by another lab would be needed to confirm this project's data. This would be followed by installation of electroslag welds in an operating rail line, one that is closely monitored like FAST in Pueblo. The next step would be putting welds into a revenue line that is also relatively well monitored. If all of these steps prove successful, a more widespread use of the process is likely.

CONCLUSIONS

Several conclusions can be made from the research. First, it is very likely that the ESW process will be successfully adapted for field rail welding. This conclusion is possible based on the following specifics. With the electroslag welding process it is possible to control the total weld width, including both heat affected zones, between 3 and 6 inches wide in 136#/yard rail. It is possible to produce weld metal running surface hardness equal to or within 5 Rockwell points of the rail running surface (premium, head hardened rail). It is possible to control the chemical composition of the weld metal over wide range depending on the combination of weld wires and consumable guide tubes used. Different fluxes perform significantly differently in terms of welding parameters and surface finish. Breaking loads were increased from first attempts of approximately 50,000 pounds to 375,000, the HAZ was manipulated by almost a factor of two and actual weld time was reduced from approximately 17 minutes to less than 10. The Advisory Board's participation directed the research toward configurations that will be much more field compatible.

IDEA PRODUCT

FIELD RAIL WELDING TECHNOLOGY

This project researched an improved method of welding railroad rail in the field with the Electroslag Welding (ESW) process. Although ESW has been used for welding rail in the past, unresolved technical issues have blocked commercialization of the process. Because the electroslag process is an inherently clean welding process, it holds promise for improvement over thermite welding. And electroslag is more portable and less capital intensive than the other common field process, flash-butt.

CONCEPT AND INNOVATION

BACKGROUND

Field welding of railroad rail is a constant issue for all railroads. The emergence of continuously welded rail (CWR) has necessitated high quality, field compatible welding processes. Although there are several different welding processes that have been used for welding rail, most field welds are made with either thermite or flash-butt.

Thermite welding is a controlled exothermic reaction of iron oxide and aluminum in a crucible placed above the gap between two rails. The reaction produces molten steel and melts a fusible plug in the bottom of the crucible. After the fusible plug melts, the molten steel pours into the gap between the rails and is contained by sand molds placed around the gap. Because of the relatively violent nature of the reaction and pouring process, thermite is prone to inclusions that can be initiation sites for sudden fractures or fatigue cracking. Between 2% and 15% of all new thermite welds contain unacceptable defects and need to be removed in the first year. The average price for a thermite weld is $350. Approximately 600,000 thermite welds are made in North America per year. (2) An average thermite weld, including set-up but not finish grinding, reportedly takes about ¾ of an hour.

The second common process is flash-butt welding. In this process two rails are clamped end-to-end and placed in close proximity. A voltage is applied across the ends and the rails are repeatedly moved closer and farther away from each other. This produces an arc that jumps the gap and produces a semi-molten region on both ends. The rails are then forced together with tons of force which extrudes the softened steel and completes the weld. Like thermite excess metal is removed, usually by shearing, after the weld has been completed. Flash-butt welds are a high quality, premium welds with better properties than thermite and are priced accordingly, approximately $500 per weld. Most flash-butt welds are made in a factory before rail is shipped. The equipment to make field flash-butt welds is a small train which consists of power generators, hydraulic rail clamping equipment, and sufficient rail handling machinery to lift the rails into the clamping/arcing mechanism.

In the early 1980's ESW research at the Oregon Graduate Center in Beaverton resulted in a rail welding patent for Southern Pacific Railroad. (4) That patent expired and was never commercialized because of unsolved technical problems. Following the rail welding work, ESW research by the original OGC team on bridge and structural steels has been supported by the Federal Highway Administration. That research has resulted in better weld metal and HAZ properties of ESW welds and incorporation of the ESW into the D1.5 Bridge Welding Code. This project combined both the previous rail welding work and the advances from the FHWA research and applied it to the rail welding.

ELECTROSLAG WELDING BASICS

The electroslag welding process is an arcless process that utilizes resistance heating of the slag pool covering the molten steel as the weld's heat source. (Fig. 2) Parts to be joined are positioned approximately an inch apart and an electrode (weld wire) guide tube is positioned between the parts. Copper cooling shoes are clamped to the sides, bottom and top of the joint and contain the molten slag and metal during the weld. After the components are assembled power is applied and the wire is fed through the guide tube. When the wire reaches the start block there is momentary arcing which melts the granulated flux, forms the slag pool and extinguishes the arc. The consumable guide tube directs the electrode (welding wire) and conducts the welding current to the molten slag pool. The electrical resistance of the slag pool generates heat which melts the wire, the guide tube and the edges of the two components to be joined. As the wire and guide tube are melted by the flux the liquid metal sinks through the slag to the metal pool below and solidifies.

Since the slag is less dense than liquid steel, it floats to the top and protects the metal from exposure to air. With continuing addition of weld wire the molten steel fills the gap, solidifies and fuses the two components. The weld is terminated when it reaches the top of the run-out cooling shoes above the rail running surface. Unnecessary weld reinforcement is removed immediately while the weld is hot.

Advantages of using electroslag for field rail welding include very clean weld metal, improved control of HAZ properties and dimensions, the ability to produce different chemistries and therefore properties in different areas of the weld, requires less operator skill and dexterity and is relatively portable and economic compared to flash-butt welding. Disadvantages are comparatively high heat input levels, vertical-up position only, and the need to access the joint with a guide tube. The high heat input, however, if properly controlled can be helpful because relatively slower cooling rates form the desired softer, pearlitic microstructure.

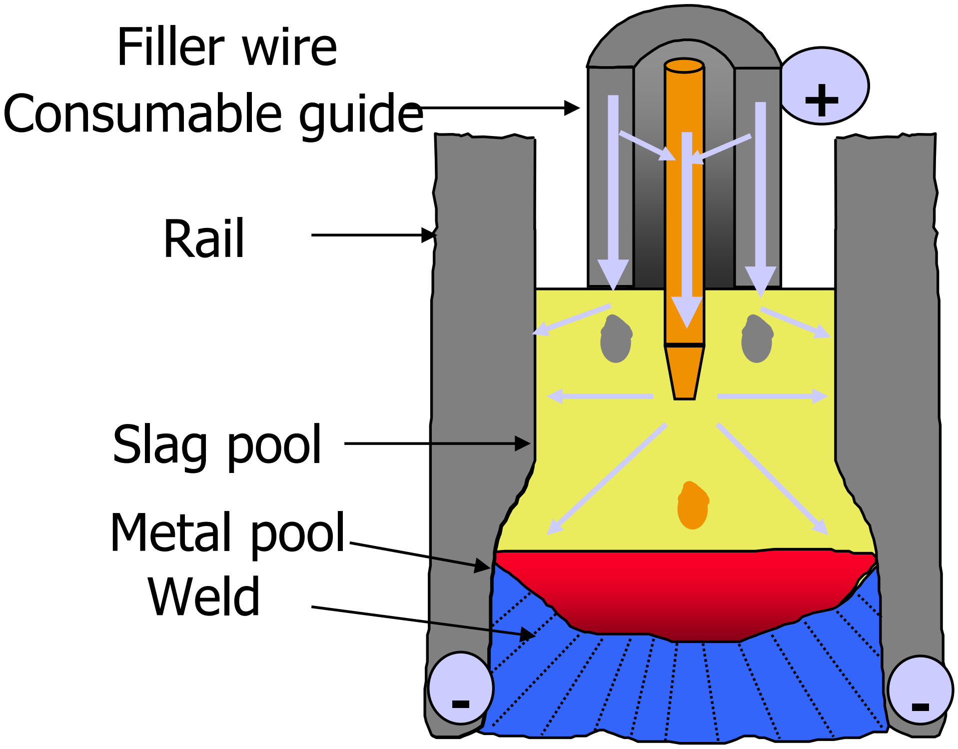

FIGURE 2. Electroslag Welding (ESW).

COST COMPARISON

Like all welding processes, ESW requires some consumables and some capital equipment. Consumables include about 10 pounds of weld wire at $1.50/pound, a guide tube which must be fabricated (estimated $85) and some insulating tape and welding flux. Consumables, then, will be approximately $100/weld. Labor, based on two man-hours, is estimated to be $100/weld. Capital costs are more difficult due to uncertainties of prices that railroads pay for equipment and length of use. An adequate welding machine and controller is less than $10,000 and should function indefinitely. Cooling shoes will cost less than $1000 per set and are assumed to be useable for 100 welds. A heat exchanger, if determined to be necessary, is about $2000 and should last for hundreds if not thousands of welds. Existing equipment (trucks, generators, etc) and typical costs to a railroad are not known. Excluding those numbers an electroslag weld will cost approximately $250.

PROJECT ORGANIZATION

The project was organized into three phases. Phase I focused on the weld metal, effect of weld reinforcement on rail stiffness, literature search and equipment fabrication. Phase II's primary tasks were the rail running surface and Heat Affected Zone (HAZ) properties. Phase III worked on the weld start configuration and combining the factors from the previous two phases. A subcontract was arranged with the Materials Engineering Group at Portland State University for laboratory support. The contract provided for access to industrial work space and analytical services including weld sectioning, mounting and polishing, microscopic examination, hardness testing and general laboratory services. The contract is part of the Oregon Metal Initiative (OMI) which is a State of Oregon sponsored metals industry incentive program that matches Oregon metal industry research dollars with state funding.

During the project several unscheduled tasks were completed. A more extensive weld wire compositional study was conducted than was originally planned. Similarly for the flux. In addition, more resources were invested in cooling shoe and guide tube configurations than anticipated.

The project was extended for four months past the original estimate of nine months.

INVESTIGATION

ADVISORY BOARD

An advisory board was formed to provide guidance for the project. The board members were Mr. Dan Mesford, Roadmaster for BNSF, Longview Washington, Mr. Bob Galloway, Welding Supervisor BNSF, and the two EST&D members. Meetings were held January 7, July 22, and October 22, 2003 at either the BNSF Longview yard or OGC.

Meeting topics included field feasibility issues (e.g. power requirements), transport vehicle considerations, available machinery (e.g. compressed air and hydraulics), preheating practices and weld time. One weld was made and witnessed by the Board and other welds were examined and discussed. The board provided valuable feedback on practical in-track issues. The last meeting spent significant time on details of possible ESW consumable configurations for field rail welding. It was also decided at the last meeting that the Rail Welding Manager of BNSF, Mr. John Wiederholt, would visit and witness an ESW rail weld. That meeting took place on Thursday, October 30 and was very helpful. Discussions regarding necessary track-time concluded that an ESW rail weld would probably require less time than a thermite weld. There were also discussions on operator skill requirements and acceptance. Since the weld set-up is the only hands on part of the process, less operator dexterity would probably be needed. The board expressed the opinion that current operators would be receptive to the new technology.

Finally, it was arranged that the EST&D members would visit an in-track flash-butt welding operation in central Oregon in November.

TASKS

Literature Search

A formal literature search was conducted at the project start and continued throughout. A total of 29 relevant articles and publications were found and reviewed. Three trade magazine subscriptions were started. Several databases, including the National Transportation Library (TRIS), the Portland State University periodical holdings, the United States Patent and Trademark Office and the ISI Web of Science were searched for literature related to rail and welding. In addition, older but still pertinent articles and publications were re-reviewed. No recent articles were found dealing specifically with ESW of rails. There were publications on improvements in thermite welding and general track maintenance strategies, including wide-gap thermite which is a potential market for ESW. The literature search results are included in the appendix.

Rail Welding Fixture

To facilitate welding of rail segments, a fixture was designed and fabricated. (Fig. 3) The fixture consists of 10" x 12" x 8' I-beam with leveling feet, fixed and adjustable rests for the rail segments, adjustable cooling shoe supports and an equipment and wire mast. The mast supports the wire drive motor-board, motor, drive units (2) and associated wiring and weld wire conduit. Four weld wire spools were mounted at the top of mast and the wire is fed down into the conduit to the wire drive motor assembly.

The welder and wire drive controller is mounted on a separate pedestal and connected to the welding power supply and wire drive units. The fixture significantly increased the precision and speed of setting up a weld.

FIGURE 3. Rail welding fixture with rail and starting block in place. Weld wire spools are supported by the mast above the wire drive board.

Weld Wire Chemical Composition

One of the critical aspects of weld properties is the chemical composition of the weld. This composition is controlled by the guide tube which is consumed and becomes part of the weld, the amount of rail metal that is melted and mixed in the weld (dilution) and the weld wire composition. The majority of the weld metal originates in the weld wire.

A total of four weld wire lots in three compositions were made for the project. These were used individually and in combination to produce five different weld compositions.

Sixteen chemical composition tests were conducted on weld or rail base metal.

Guide Tube

Guide tubes, which guide the weld wire to the slag pool between the rail ends, are consumed during the weld and incorporated into the final weld. Four guide geometries were tested. Length, width and chemical composition were the parameters varied in this task. Details of the guide tube are proprietary.

Cooling Shoes

Cooling shoes contain the liquid slag pool and molten metal prior to solidification. They are instrumental in several aspects of the weld including reinforcement volume and therefore weld time, cooling rate and therefore microstructure and HAZ dimensions. Five variations in the cooling shoes were part of this phase's test matrix. They differed in size, internal shape, heat extraction method and composition. Three sets of two versions of the side shoes were manufactured and tested, two water cooled and the other air cooled. Effects of the different versions can be seen in the weld metal properties and HAZ dimensions as described in those sections.

Preheating

Current rail welding practice requires preheating the rail ends to be joined. This is due to the high carbon levels in the rail and its subsequent susceptibility to martensite, a hard, brittle microstructure. Preheating reduces the weld's cooling rate and minimizes the potential for the martensitic phase. This project made welds both with and without preheating. The motivation for eliminating preheat is reduced equipment and track time requirements.

Extensive discussions were held with the Advisory board regarding preheating in the field. The equipment that is used by the rail gangs is much more efficient than the equipment used in the lab.

Rail Welding

Thirty-one full size and 4 partial welds were made during the project. The partial welds were made to test various starting configurations. The parameters in the test matrix were welding volts and current, guide tube configuration, starting block and cooling shoe geometry, weld wire composition, amount of preheat, rate of cooling and flux composition. Details on the various tasks are discussed in the appropriate section.

Welding Flux

Flux is melted in the initial seconds of an ESW and forms the molten slag pool on top of the liquid metal. It has several functions including protecting the liquid metal from contact with air and serving as the weld's heat source due to the electrical resistance of the welding current. The project obtained and tested three different fluxes.

The fluxes caused several changes in the welds. With similar welder settings, the voltage and current and therefore welding time, changed. In addition, the surface finish of the weld changed. Finally, the time to establish a steady-state weld pool changed. The advantages and disadvantages of each flux are important for the optimum weld properties.

TESTING AND RESULTS

Sectioning

Rail sectioning was either transverse to the rail running direction or longitudinal to it. Tensile bars were taken from longitudinal sections with the weld metal in the gauge length. Hardness traverses were also performed on the longitudinal section. Fig. 4 illustrates the sectioning schematic.

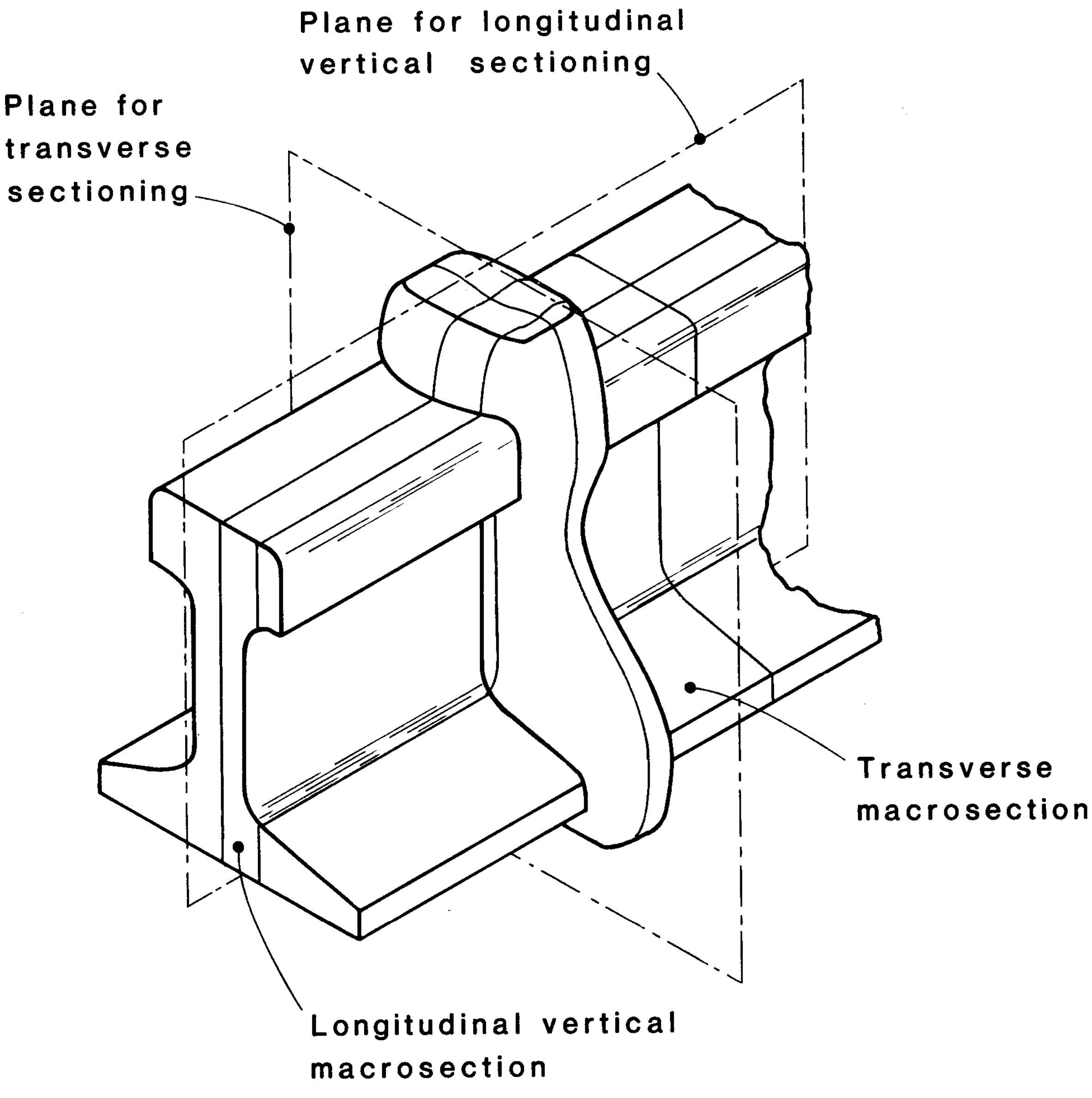

FIGURE 4. Method for sectioning rail and welds for test specimens.

Mechanical Properties

Tensile Strength

Three .505" x 2" gauge length tensile bars were machined from completed welds and tested in conformance with ASTM test standard E8. The bars were configured so the gauge length in the middle of each bar was made up entirely of weld metal.

The average yield strength was 92,600 psi and the average ultimate tensile strength was 129,900 psi. This is consistent with base rail properties. Table 2 lists the individual tensile bar results.

TABLE 2.

Tensile Testing Results

	Yield Strength (psi)	**Ultimate Tensile Strength (psi)**	**% Reduction of Area in 2 Inches**
Bar A	75,500	128,800	5.2
Bar B	77,100	120,600	2.8
Bar C	123,300	140,200	4.6

Charpy Impact Toughness

Sixteen Charpy impact bars were machined from the weld metal. Six were tested at room temperature, all resulting in 3 ft.lbs. of energy absorbed during fracture. Since all six were identical, the remaining ten were not broken and have been retained for possible future testing.

This is typical toughness for standard rail and thermite weld metal.

Weld Metal Characterization

Microstructure

Microstructure specimens were prepared by bandsawing a sample from the appropriate location, mounting and polishing with standard metallographic techniques, etching with 1% nital and examining on an optical metallograph at magnifications up to 1000x.

Most of the welds were predominately pearlitic. On some welds with higher cooling rate, isolated islands of harder phases (martensite, bainite or combination) did form. They were usually near the surfaces. No martensite or bainite were found in welds that were cooled at slower rates. The slower cooling rates produced the desired (and expected) softer pearlitic microstructure.

Macrostructure

Because ESW is a relatively high heat input process, it was essential to learn how to limit or control the heat input. Two methods of quantifying the heat input were used. The first was to calculate from voltage and amperage records the total watts consumed during the weld. The second method was to measure the weld width and HAZ dimensions.

Fifteen welds were sectioned for macro and/or microscopic examination. The cross-sections, longitudinal vertical orientation, were taken full height from the center of the rail parallel to the train rolling direction. Each macro-section was blanchard ground and polished up to 9 micron diamond. The sections were then etched with 5% nital etchant for approximately 15 seconds. The cross-sections included unaffected base metal on either end, the weld metal in the center and the HAZs on either side of the weld. Figure 5 shows a schematic of the cross section and Figs. 6 and 7 actual rail cross sections.

The dimensions and shape of the welds and HAZs can be visually determined from the etched cross sections. (Figs. 6 and 7) The weld metal is the lighter metal roughly centered in the section. The darker regions outboard of the weld is one part of the HAZ. Two thin, light HAZ lines delineate the boundary between the HAZ and the unaffected base metal. Both the weld metal width and total weld width, which includes both HAZs, were measured.

Another method of measuring the weld dimensions is with hardness testing. Each zone in the weld (weld metal and HAZs) has different hardnesses due to compositional and cooling rate variations. The dimensions measured with this method are listed in detail in the Hardness Testing Section.

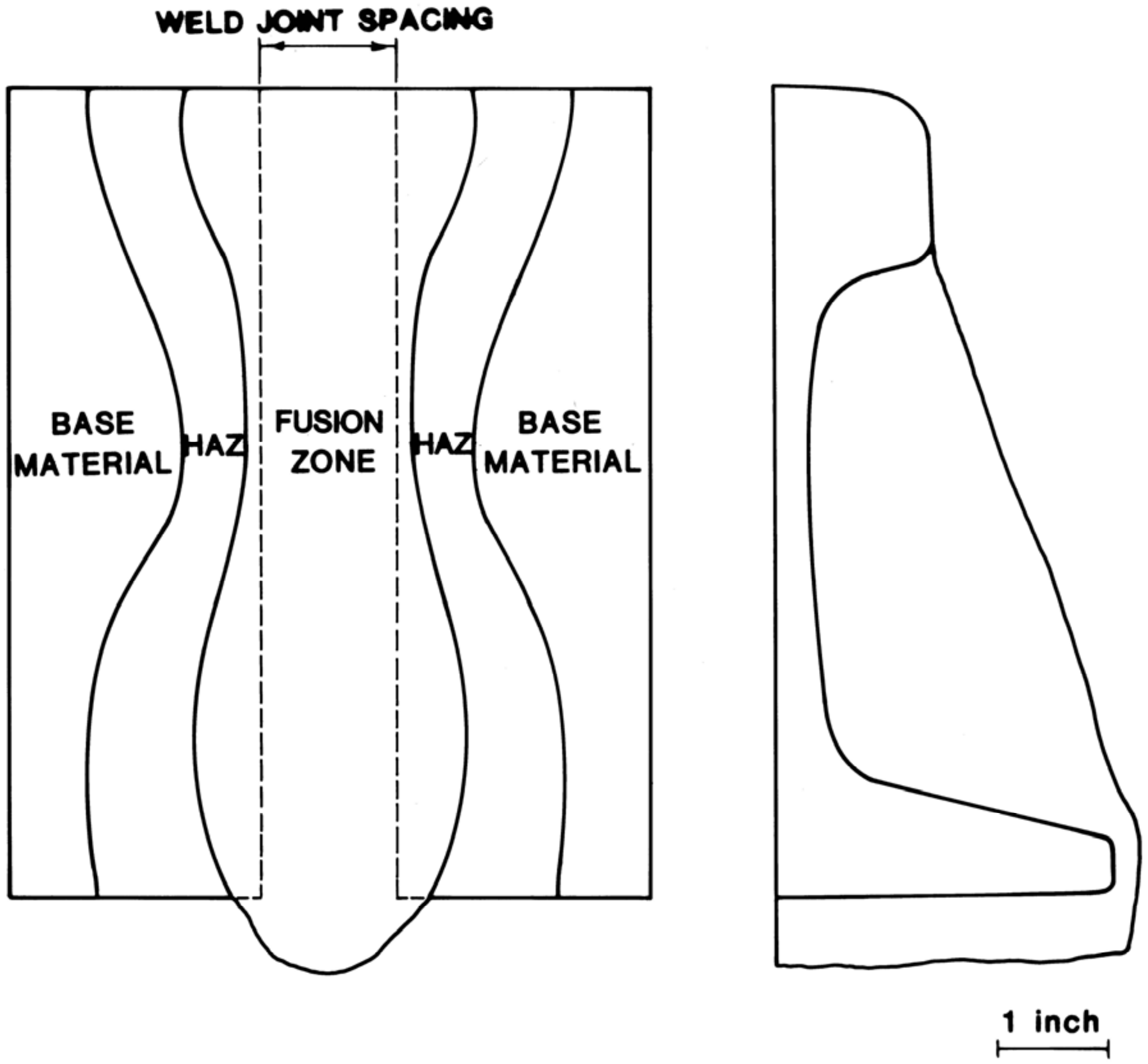

FIGURE 5. Schematic of electroslag rail weld cross section.

FIGURE 6. Etched macro cross-section of weld #30.

FIGURE 7. Etched macro cross-section of weld #27.

CHEMICAL COMPOSITION

Thirteen spark spectrograph tests were conducted on seven welds, rail base metal and in guide tube raw materials. The testing in the welds was done in the head, the web and/or the rail base areas. (Table 3)

Table 3.
Chemical Composition Results

Weld #	C	Mn	Si	Cr	Ni	Mo	Cu	S	P	Al	Zr
Rail	0.737	0.45	0.22	0.13	0.01	0.0	0.0	0.003	0.005	0.002	0.002
22 W.B.	0.61	1.19	0.32	0.1	0.04	0.0	0.08	0. 012	0.01	0.006	0.002
25 W.B.	0.665	1.08	0.46	0.12	9.63	0.0	0.11	0.013	0.012	0.015	0.005
28 W.B.	0.608	1.26	0.37	0.11	0.03	0.0	0.07	0.013	0.01	0.007	0.002
30 W.B.	0.516	1.25	0.39	0.09	0.03	0.0	0.06	0.013	0.01	0.007	0.002
33 W.H.	0.55	1.03	0.34	0.1	0.41	0.0	0.1	0.013	0.01	0.006	0.002
33 W.B.	0.702	1. 28	0.33	0.12	0.32	0.0	0.14	0.016	0.012	0.003	0.002
34 W.H.	0.495	1.21	0.45	0.1	0.85	0.0	0.11	0.012	0.011	0.008	0.002
34 W.B.	0.621	1.36	0.39	0.12	0.69	0.0	0.14	0.016	0.012	0.004	0.002
34 R.O.	0.472	1.28	0.47	0.07	0.54	0.0	0.04	0.012	0.009	0.008	0.002
36 R.O	0.486	1.29	0.45	0.07	1.02	0.0	0.06	0.11	0.009	0.003	0.002
37 R.O.	0.763	0.99	0.21	0.08	0.03	0.0	0.39	0.009	0.007	0.007	0.002
38 R.O.	0.798	1.01	0.24	0.09	0.87	0.0	0.05	0.01	0.009	0.004	0.009

Notes:
W.H.: Weld metal, head of rail.
W.B.: Weld metal, base of rail.
R.O.: Weld metal, run-out at top of weld.

HARDNESS TESTING

Hardness testing was conducted with a Leco Model LCR-500, Rockwell C scale. Complete hardness profiles were performed on the following welds: 22, 24, 26, 27, 28, 29, 30, 31, 37, 38, 40, 42 and 43. Each weld required approximately 100 individual hardness tests.

Hardness profiles were used to characterize both the weld hardness and width, including HAZ width. The surfaces were surface ground and etched with 5% Nital prior to hardness testing. Rockwell C hardness tests were conducted at 1/8" intervals parallel to the running surface in three locations: 1/4" below the running surface (called Running Surface), 3.5" above the base in the web (called Web) and 1/4" above the rail base (called Base).

The hardness profiles have three distinct regions. (Fig. 8) In the center is the weld metal. Early welds typically had weld metal hardnesses 5 to 10 Rc points less than the original rail hardnesses, later welds within 5 Rc of the running surface. Moving outward from the weld center into the HAZ a harder region is reached, followed by a narrow band with reduced hardness, and finally a return to original base metal hardness. Weld metal hardness is controlled by the chemical composition of the weld. The addition of proper elements via the weld wire and guide tube determines the weld metal composition and therefore properties including hardness. The HAZ properties are controlled by the maximum temperature and time at temperature. The HAZ consists of two zones, higher hardness directly adjacent to the weld metal and a lower hardness zone just before exiting the HAZ and entering unaffected base metal. All these regions can be seen in the head, web and base hardness traverses in Fig. 9.

Of particular interest are the hardnesses of the running surface weld and HAZs. The weld running surface should be as close to the rail running surface hardness and the HAZ should be as small as possible to minimize its disruption of rail running surface. Three weld running surface hardness traverses are compared in Figure 10. Early welds were in excess of 5 inches wide (including both HAZs) and decreased 15 Rockwell hardness points below rail hardness. Later welds reduced the weld width to less than 4 inches and the HAZ hardness to within 7 or 8 Rc of the unaffected base metal. Table 4 summarizes the weld and HAZ widths with the hardness data.

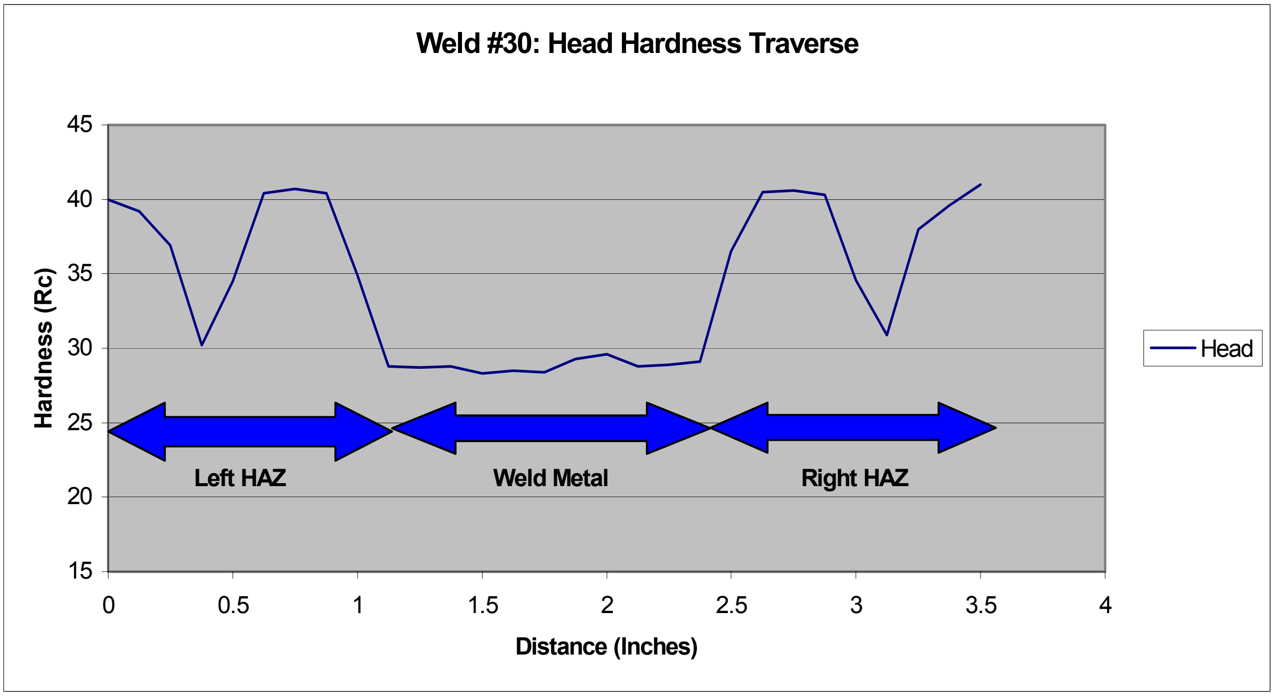

FIGURE 8. Hardness of weld # 30 in the Head. The weld metal is the softer center region, the HAZs (right and left) consist of the regions of hardness increase, then decrease, then return to base metal hardness at either end of the weld.

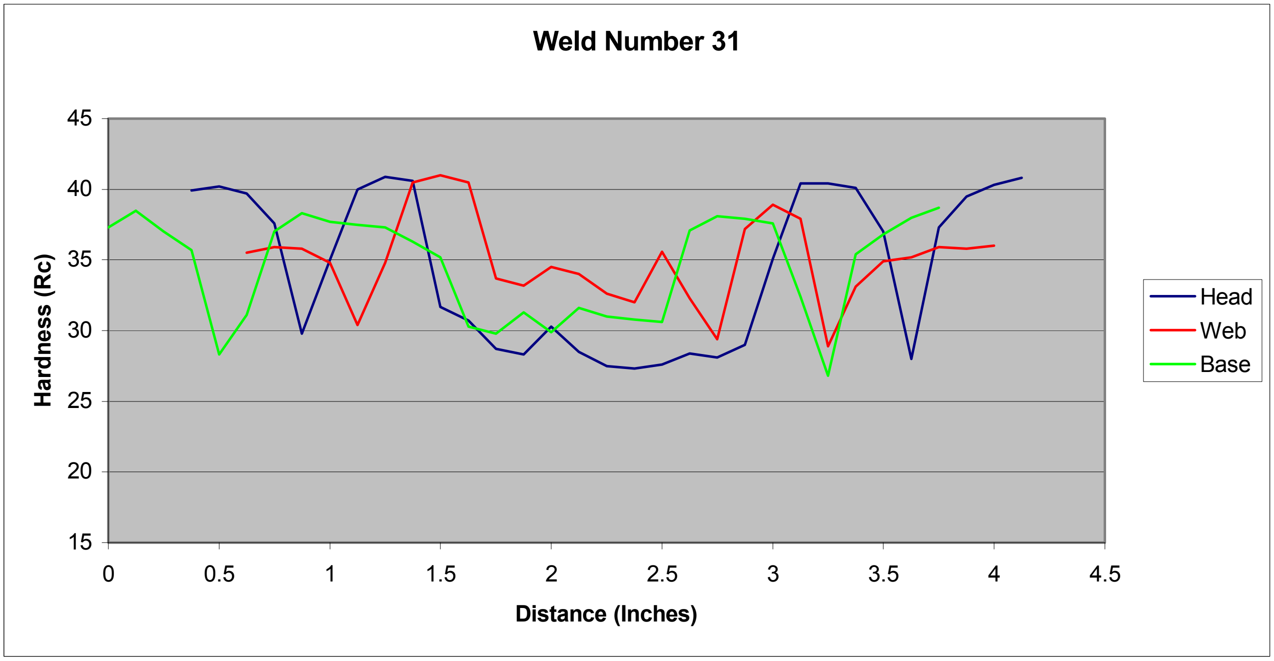

FIGURE 9. Web, head and base hardness traverses in Weld #31.

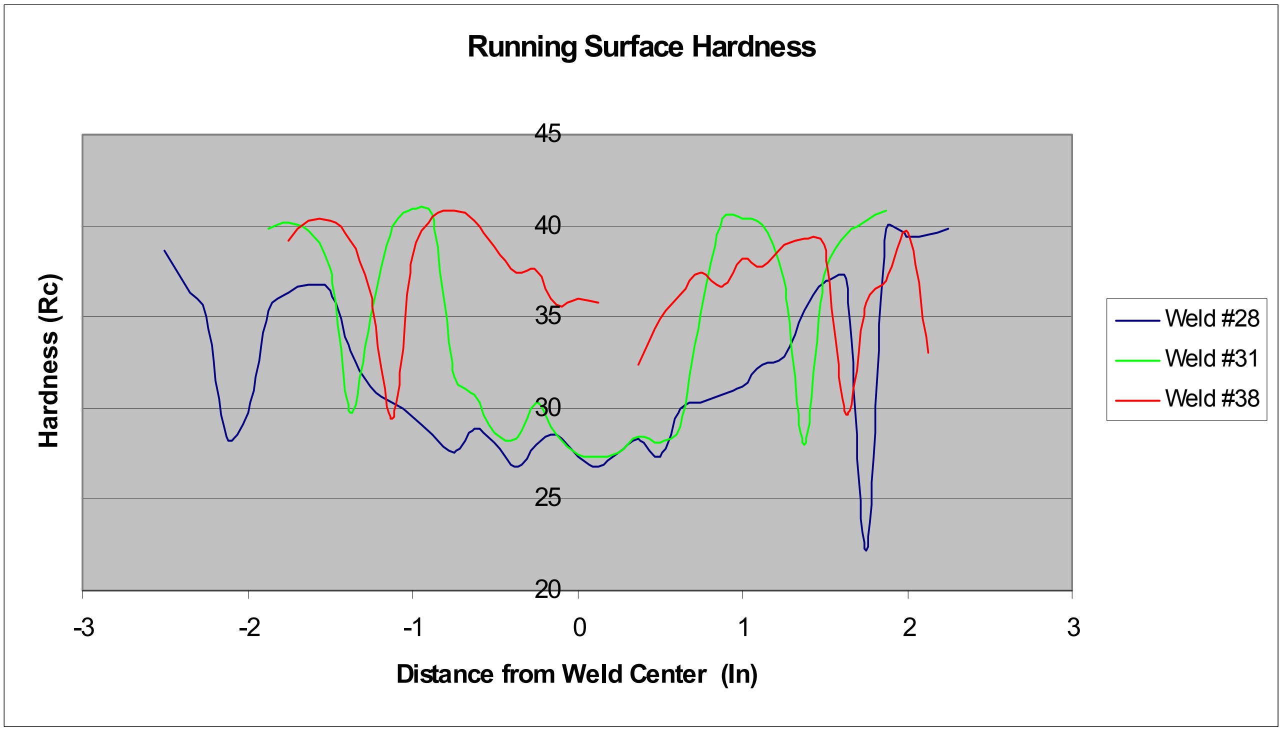

Figure 10. Comparison of weld metal and HAZ hardness and width in the Head of welds #28, #31 and #38. Gaps in hardness data indicate the location of the fracture of the slow-bend test.

Table 4.
Weld and HAZ Dimensions Determined by Hardness Testing
Width in 1/8" Increments

Weld and Location	Left HAZ	Right HAZ	Weld	Weld + HAZs
RW - 22				
Head	6	8	16	30
Web	5	(5)	15	25
Base	8	(8)	8	24
RW - 24				
Head	9	7	19	35
Web	5	7	19	31
Base	12	13	7	32
RW - 26				
Head	8	(8)	11	27
Web	5	(5)	16	26
Base	11	(11)	11	33
RW - 27				
Head	7	5	22	34
Web	9	5	20	34
Base	8	9	15	32
RW - 28				
Head	7	5	20	32
Web	6	6	19	31
Base	14	11	11	36
RW - 29				
Head	3	(3)	9	15
Web	3	(3)	11	18
Base	9	8	8	25
RW - 30				
Head	5	5	13	26
Web	6	5	7	18
Base	8	7	7	22
RW - 31				
Head	5	6	12	23
Web	3	4	11	18
Base	10	7	6	23
RW - 33				
Head	5	4	11	20
Web	4	5	7	16
Base	8	9	10	27
RW - 34				
Head	6	7	12	25
Web	3	3	12	18
Base	6	7	15	28
RW - 37				
Head	5	6	8	19
Web	NA	NA	6	NA
Base	8	5	11	24
RW - 38				
Head	5	9	9	23
Web	7	5	4	16
Base	8	8	10	26

Note: Some weld areas were not measureable due to slow-bend fracture locations. Numbers in parenthesis are the width of the HAZ in the opposing side of the same weld.

SLOW BEND TESTING

Current rail weld technology uses a four-point bend to test weld strength. The standard is detailed in the AREMA volume number Vol. 2, pp. 4-2-60, 1999. The test geometry in that standard is shown in Fig 11. The slow-bend testing was conducted in the Civil Engineering facility of Portland State University. (Fig. 12)

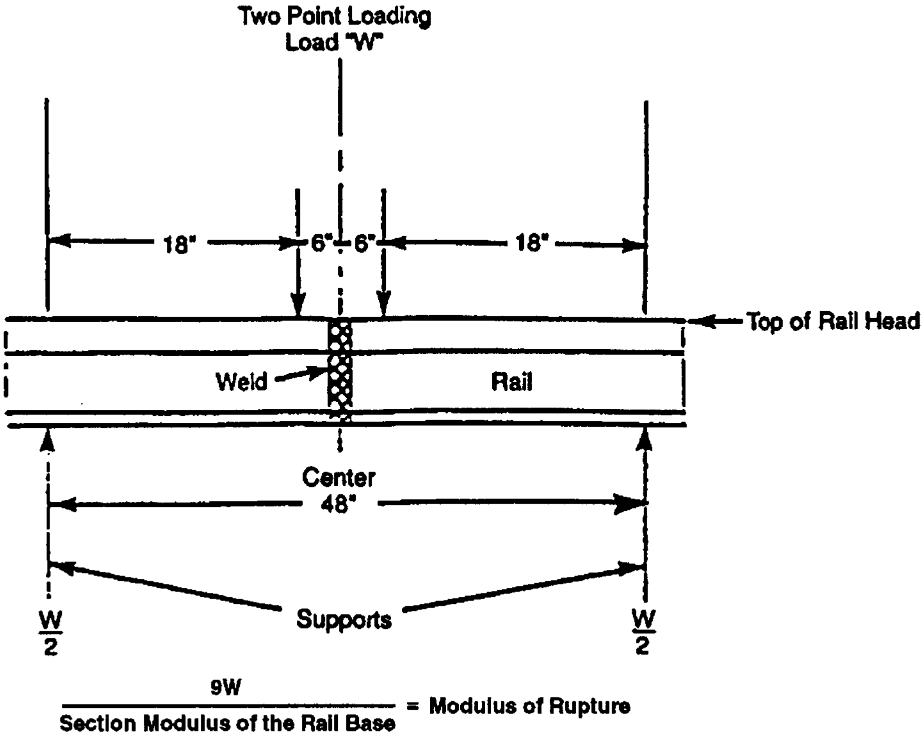

FIGURE 11. Slow-bend test configuration. Ref. AREMA, Vol. 2, pp. 4-2-60, 1999.

FIGURE 12. Rail weld breaking in four-point bend fixture at Portland State University.

One of the purposes of the slow-bend test was to compare the stiffness of welds with full reinforcement and no reinforcement. Although the optimum weld reinforcement geometry has not been determined, the possibility that an electroslag weld reinforcement affected the joint stiffness needed to be quantified. Joint stiffness and therefore reinforcement geometry is a concern if the reinforcement transfers excessive strain and stress to the adjacent rail, especially the weld HAZ. To test the effect of reinforcement on stiffness, four welds were broken with all of the weld reinforcement removed. (Fig. 13) One of the bend-test files was lost by the test lab so the data set consists of three rails with the reinforcement removed and four with standard reinforcement. The results are listed in Table 5. The stiffness is characterized by the slope of the load/deflection curve. (Fig. 14) The slope was calculated by standard regression analysis of the load/deflection curves.

The results of standard reinforced welds and welds without any reinforcement are compared in Table 5. There was no significant stiffness difference between the two reinforcement patterns.

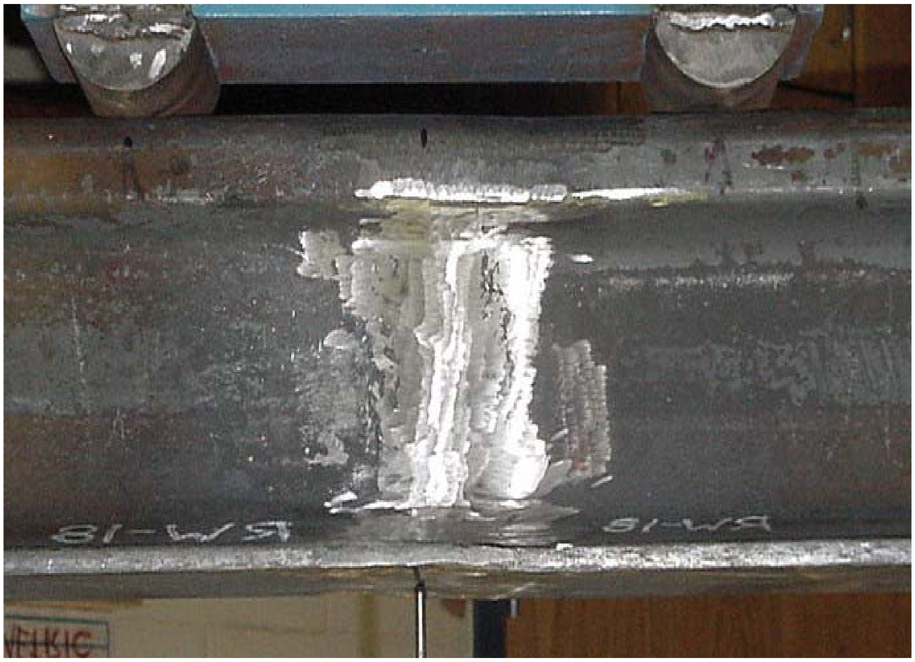

FIGURE 13. ESW with all weld reinforcement removed.

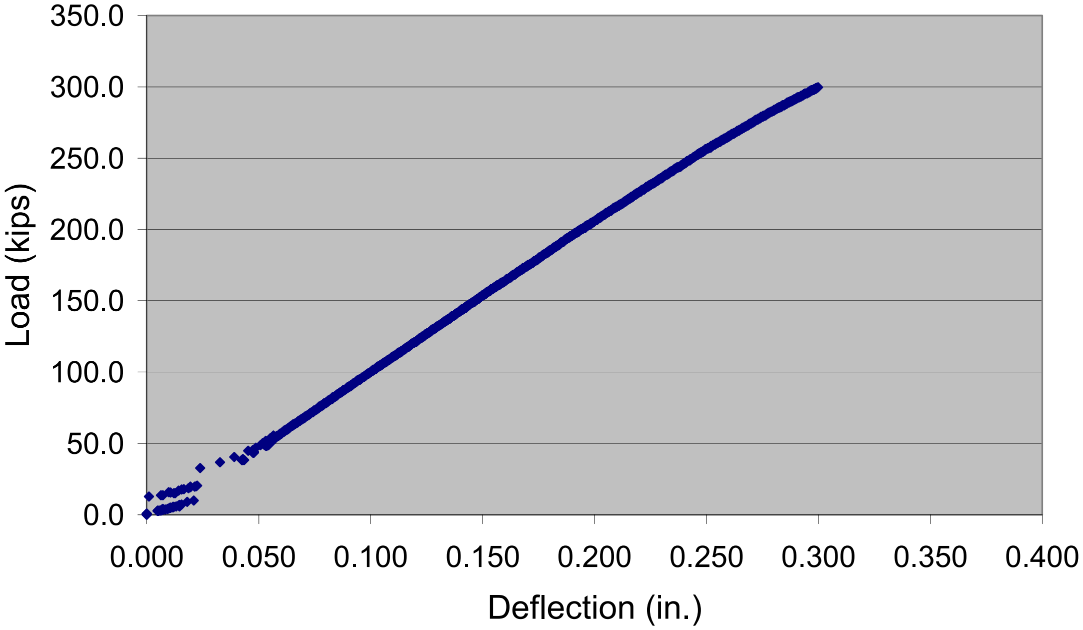

FIGURE 14. Load/Deflection curve for weld stiffness calculations.

Table 5.
Joint Stiffness Comparison, Reinforced and
Un-reinforced Welds

Weld Number	Slope (kip/in)	Y - Intercept (kips)	R^2
Reinforced			
10	974	-21	0.9995
13	956	-17	0.9985
15	1067	-20	0.9993
16	970	2	0.9844
Average and Std. Dev.	992; 51		
Unreinforced			
18	1062	-7	0.9998
20	1161	-8	0.9998
21	1130	-16	0.9993
Average and Std. Dev.	1118; 51		
Unwelded Rail	1093	37	0.9999

Slow bend tests were performed on 20 of the 31 welds. Table 6 lists the breaking strength and deflection of each weld. Since different phases of the project investigated different parameters, strength values are not listed chronologically but by breaking strength. Rupture modulus (R) is calculated from the breaking load by the equation:

$$R = 9(W)/M$$

where:

W = maximum load in pounds
M = Rail Section Modulus (28.3 in.sq. for 136#/yard rail)

Current weld standards require a minimum of approximately 393,000 pounds (equivalent to 125,000 psi rupture modulus for 136#/yard rail) and 0.75” deflection. The maximum achieved was 375,000 pounds and .35" deflection.

TABLE 6

Slow Bend Test Results

Weld Number	*Breaking Load (pounds)*	*Rupture Modulus (psi)*	*Deflection (inches)*
40	375,000	119300	0.36
29	370,000	117700	NA
27	360,000	114500	0.35
28	350,000	111300	0.325
31	350,000	111300	0.34
30	340,000	108100	0.34
41	337,000	107100	0.30
32	315,000	100200	0.24
38	310,000	98600	0.28
18	300,000	95400	0.3
36	300,000	95400	NA
43	292,000	92900	0.22
42	290,000	92200	0.31
22	280,000	89000	NA
21	277,000	88100	NA
20	276,000	87780	0.2
37	255,000	81100	0.24
35	238,000	75700	0.22
26	165,000	52500	NA

Note: NA indicates malfunction of data collection during testing.

DISCUSSION

RUNNING SURFACE HARDNESS

A critical aspect of a rail weld is the hardness of the running surface. Ideally, there should be no difference in hardness between the weld, the HAZ and the unaffected rail surface. However, since welding processes involve heat, some alteration is unavoidable. The goal then, is to minimize the variation in hardness across the weld.

This project spent considerable resources addressing two aspects of running surface properties. The first was producing weld metal that was as close to running surface hardness as possible. Early weld hardnesses were 10 to 15 Rc less than unaffected rail. With proper cooling rates and weld composition, the weld metal was brought to within 5 Rc of rail surface. This is within the AREMA specification.

The second aspect is HAZ hardness and width. Since the HAZ is not melted, its hardness is controlled by controlling the maximum temperature and the time of exposure to the elevated temperature. The amount of heat put into the rail and the rate it is removed will determine the temperature/time exposure of the HAZ. In ESW, these two parameters are controlled by a variety of items including volts, amperage, weld time, cooling shoe geometry and cooling media. Using these items it was possible to purposely manipulate the HAZ width by almost a factor of two, from the 5 to 6 inch wide range down to the 3 to 4 inch range. This is a very significant feature and represents a very important improvement with regard to the running surface hardness variation.

WELDING TIME

A critical time issue for the railroads is track-time: the amount of time the track cannot be used while a weld is being made. At the end of Phase I the ESW rail weld time was between 15 and 20 minutes. The most recent welds have been taking less than ten minutes. Advisory Board and other industry personnel who have watched an electroslag rail weld have concluded that an electroslag weld will probably take less track time than a thermite weld, approximately 1/2 hour to 3/4 hour respectively. Even small improvements in this area are valuable to railroads because of the high costs associated with dead track time.

PLANS FOR IMPLEMENTATION

This process is not ready for commercialization. Several aspects need to be optimized before it is ready for widespread implementation. The first, of course, is that the rupture modulus and deflection need to be closer to current AREMA standards. Although tremendous improvements were made in this project, another 10% increase would position the process much more favorably with the railroads.

To help reach the AREMA standards additional work is recommended. The first is to obtain the specification values. This will be done by conducting a thorough failure analysis on several of the test welds and determining what changes are needed to produce acceptable strength and ductility. Other factors that would be beneficial include adopting the efficient preheating methods used by the railroads to this process; a more thorough characterization of the effects of flux; rail and guide tube positioners; a standardized welding procedure; and a consumable package compatible with the field rail environment.

Commercialization could follow several paths. Probably the most expedient would involve an alliance with an organization that has a track presence. This could either be through a commercial railroad company, preferably Class I, or a contract rail maintenance organization. Another route would be a second level of research funding that combined weld property improvements with testing by a third party. Specific activities for each of these options would include testing welds in second or third party labs, getting test rails into controlled lines (e.g. FAST in Pueblo), installing a limited number of welds in high traffic revenue lines that can be monitored consistently, and finally wide scale implementation of the welds.

SUMMARY AND CONCLUSIONS

The project successfully improved the ESW rail welding process to within 5% of the strength goals. In addition, hardness targets, both running surface weld metal and HAZ, were met. The required microstructure was also obtained. The ability to control total weld width by almost a factor of two was also developed. It has been estimated by Class I railroad personnel that an electroslag rail weld would take less time than a thermite weld. Preliminary cost estimates are competitive with thermite welding. Based on these improvements, it is very likely that the ESW process can be adapted for widespread commercial field welding of rail.

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INVESTIGATOR PROFILES

BOB TURPIN

Bob Turpin served in the United States Navy as an aviation structural mechanic and was qualified as an air crewman and certified aircraft welder. After military service he earned an Associate of Applied Sciences Degree in Welding Processes Technology from Oregon Technical Institute in Klamath Falls, Oregon. He completed a Bachelor of Science in Education at Northern Arizona University in Flagstaff, Arizona. His graduate studies were completed at Oregon Graduate Center where he earned a Master of Science Degree in Materials Science and Engineering (Adaptation of the Electroslag Welding Process to Joining of Railroad Rail). After completing graduate studies his career at Oregon Graduate Center progressed serving as research associate, senior research engineer, Technology Transfer Manager for the Materials Science and Engineering Department, and Associate Director of the Center of Advanced Materials Science and Engineering Concepts. He has been principal investigator on a variety of research projects including development of narrow gap improved electroslag welding for bridge steels, electroslag strip surfacing for corrosion resistant thick cladding of Navy propulsion shafting, and electroslag welding for double hull ship construction. He is currently an owner in Electroslag Systems, Technology and Development (EST&D LLC) fulfilling a technology transfer role from research to commercialization of specialized welding technologies.

DAN DANKS

Dan served time in the United States Navy nuclear submarine forces as an operator and mechanic of a nuclear power plant and ship's lead welder. After an honorable discharge, he earned his B.S. in Metallurgical Engineering at California Polytechnic State University in San Luis Obispo. His graduate studies were performed at the Oregon Graduate Center where he received his M.S. (A Parametric Study of the Capacitor Discharge Welding Process) and Ph.D. (Microstructure and Wear of Railroad Rail) and the University of Portland (MBA). Dan worked at Esco Corporation in Portland, Oregon as the corporate tribologist where his duties included project management, wear research, commercialization of new technology, and tribological training for in-house engineering and marketing and Esco customers. After Esco he started Danks Tribological Services, a wear and engineering materials consulting service. His client list includes Esco Corporation (domestic and international), the Bonneville Power Administration, Pratt and Whitney Corporation, Veteran's Administration Hospitals, Schwabe Williamson and Wyatt, and other various manufacturing firms. In 1999 Bob and Dan formed Electroslag Systems, Technology and Development (EST&D LLC) with the goal of conducting research and technology transfer of electroslag welding to industrial partners.

APPENDIX

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