TECHNOLOGY DIGEST

TD-08-043

©OCTOBER 2008

TIMELY TECHNOLOGY TRANSFER

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Electroslag Welding: A Potential Alternative to Conventional Rail Welding Processes

Daniel Gutscher, Dan Danks* and Bob Turpin*

Summary

Electroslag welding (ESW) is a wire welding process that uses electrical resistive heating of a molten slag pool to melt both electrode and adjacent base metal surfaces to produce a weld. The Transportation Technology Center, Inc. identified ESW as a viable potential alternative to conventional rail welding processes and has established a cooperative agreement with Electroslag Systems Technology and Development LLC of Portland, Oregon, to continue development of ESW for rail welding under the Association of American Railroads' Strategic Research Initiatives Program for improved rail welding. Research conducted under this agreement has identified process improvements that need to be made in order for ESW of rail to achieve slow bend performance criteria necessary for implementation.

Some of the advantages of ESW include:

- Does not consume rail
- Produces welds with high degree of cleanliness
- Improves safety; e.g., no exposed weld metal or slag
- Production rate is competitive with thermite welding
- Chemistry and weld properties can be modified throughout the weld
- Per-weld cost is estimated to be lower than for thermite welding

This project was divided into several phases. Phase I analyzed the results obtained under the Transportation Research Board (TRB) Innovations Deserving Exploratory Analysis (IDEA) Program to determine what needed to be done to improve the mechanical performance of the welds. Examination of the TRB IDEA welds revealed lack of fusion at the weld base combined with martensite formation at critical locations. Altering the weld thermal cycle will correct both conditions and enable the process to achieve the necessary slow bend performance criteria. Recommendations for weld improvement from Phase I included implementing an effective preheat at the rail base and modifying the weld mold materials to control the rate of heat removal.

Phase II is active now with the implementation of recommendations from Phase I. Phase III will continue to refine the process and will produce welds for testing at the Federal Railroad Administration's Facility for Accelerated Service Testing in Pueblo, Colorado. Phase IV will continue the work of Phase III and will institute testing of welds in revenue service.

*Electroslag Systems, Technology & Development

Please contact **Daniel Gutscher (719) 584-0500** with questions or concerns regarding this *Technology Digest.* E-mail: Daniel_Gutscher@ttci.aar.com.

INTRODUCTION

ESW is a wire welding process that uses electrical resistive heating of a molten slag pool to melt both electrode and adjacent base metal surfaces to produce a weld. Figure 1 illustrates the cross-section of a typical electroslag weld. The ESW process was initially developed as a metal refining method and was adapted for joining thick section components. Invented in the USA and refined and improved in the former USSR, it has been used to join many types of large structures like buildings, bridges, missile silos, ship's hulls, nuclear pumps and vessels, and heavy section metal process equipment like forges and presses.

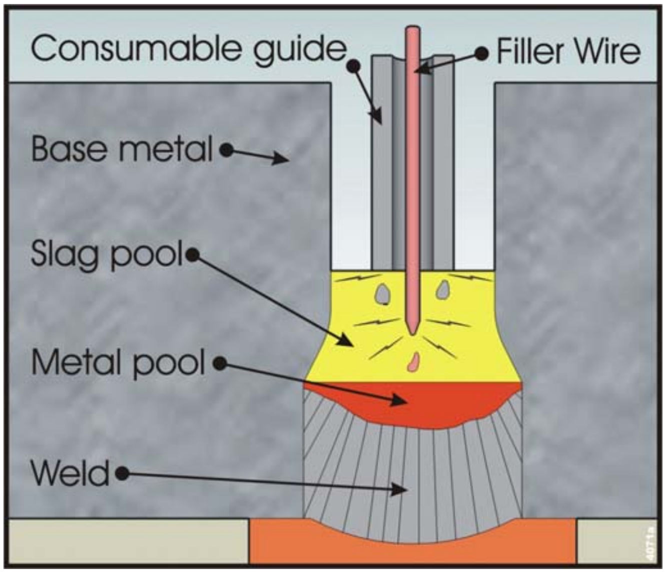

Figure 1: Electroslag Weld Cross-Section Diagram

A typical ESW system consists of several components, a power supply, a wire drive system, and mold shoes. The power supply provides the current at a constant voltage necessary to generate heat for the weld. A wire drive system feeds wire electrodes into the weld through a consumable guide tube, which is secured by a guide clamp. The guide clamp also serves to couple the power from the power supply to both the guide tube and the electrodes. Mold shoes, sometimes referred to as cooling shoes depending on the application, serve to contain the molten weld and slag pools, to establish proper weld contour, and to aid weld solidification through heat removal. The cooling shoe at the bottom of a weld is called a starting block, whereas the shoes at the top are called run out blocks.

In preparation for making a weld, a starting block is set in place and the guide tube and electrodes are secured in the gap between the surfaces to be welded. The cooling shoes are then set in place. An initial charge of powdered flux is then placed in the weld cavity. Figure 2 illustrates a typical ESW setup for welding rail and shows a conceptual view of a completed weld.

The weld is started by initiating an electric arc between the electrode and starting block. This arc serves to melt the initial charge of flux forming a molten slag pool that, in turn, extinguishes the arc. As the welding electrode is fed into the slag pool, electrical contact is made, allowing current to flow from the electrode into the slag pool. Heat is generated in the slag pool as a result of electrical resistive heating. This heat serves to melt the welding electrode, the consumable guide tube if used, and the adjacent surfaces of the base metals being welded. The molten metal, being denser than the slag, sinks to the bottom of the slag pool and accumulates to form a pool of weld metal, which quickly solidifies as heat is lost to the surrounding parent material and cooling shoes. After the initial period of arcing, the process continues, essentially in equilibrium, as the weld progresses vertically. The resulting bond has a cast microstructure that contains relatively few defects, such as inclusions and gross porosity that are typical of castings.

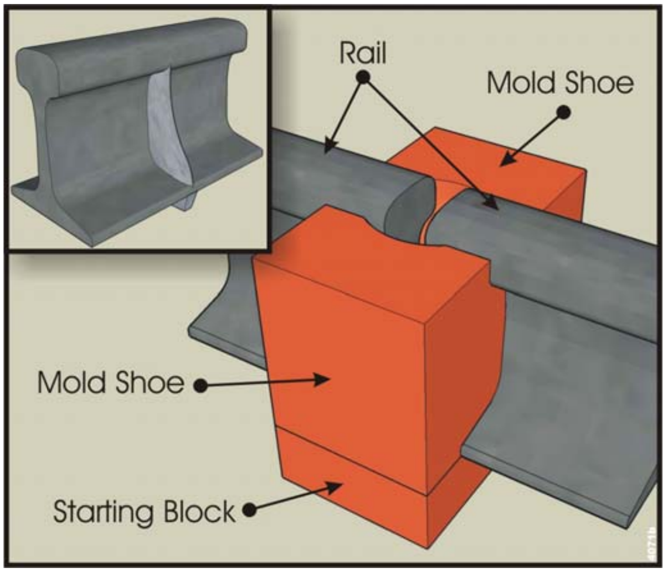

Figure 2: ESW Setup for Rail Welding. Inset shows Conceptual View of a Completed ESW Weld

One particular benefit of electroslag welding over other wire welding processes is that melting of the electrodes occurs in a slag pool, as opposed to in an electric arc. The slag serves both to protect the weld metal from atmospheric contamination and to remove nonmetallic elements, thereby refining the weld metal.

Like wire arc-welding processes, important ESW variables include voltage, current, wire feed speed, and electrode composition. Standard commercial welding power supplies and controllers are connected to ESW specific wire drives and consumable guide positioners. The process can be considered semi-automated, in that once the individual components are positioned and assembled, the weld is initiated and continues with minimal operator interaction until completion.

APPLICATION TO RAIL WELDING

ESW has a number of potential advantages that may benefit rail welding.

Potential advantages (strengths) for rail welding include:

- Produces high quality (clean) weld metal. Cleaner welds are less likely to experience fatigue failures that initiate at porosity or inclusions.
- Does not consume rail. This facilitates making closure welds and reduces required labor.
- Ability to intentionally modify chemistry (and therefore properties) throughout the weld metal.
- High production rate (competitive with thermite weld times).
- Improves safety. ESW welds are fully contained, thereby minimizing operator exposure to superheated metal and slag.
- Can be electronically documented. An electronic record of the welding parameters (voltage, amperage, wire speed, weld time, cooling conditions) can be made and archived for training and quality assurance purposes

PAST DEVELOPMENT WORK

The concept of using ESW to weld rails in North America was first explored in the mid-1980s at the Oregon Graduate Institute in Portland, Oregon, in a program sponsored by the Union Pacific (UP). Two theses were published on the work, and a patent was filed and granted.[1,2] Test welds were put into revenue service track, but they were removed after an indeterminate length of time, with no recorded performance data. The UP patent has since expired.

Also in the 1980s, the Federal Highway Administration (FHWA) sponsored research on ESW aimed at the bridge welding industry. That research resulted in significant improvements. Electroslag Systems Technology and Development LLC (EST&D) started applying the lessons learned in the FHWA research to improving the rail welding process beginning in 2000.

In 2002, EST&D received a grant from the TRB IDEA Program, designated as HSR-37, to develop and advance ESW for rail welding. That project supported the systematic investigation of the various welding parameters relating to portable rail welding. A team of rail industry representatives including Class I welding managers, district welding supervisors, and roadmasters in addition to the IDEA committee oversaw the project.[3] Figure 3 shows the ESW equipment used for welding rail.

Although the TRB IDEA project results did not meet current AREMA thermite welding standards, improvements included an approximately five-fold increase in weld strength and a three-fold increase in deflection. Specifically, a slow bend modulus of rupture of 110,000 psi and deflection of 1/3 inch was obtained.[3] Table 1 compares the performance of ESW under the IDEA program to the AREMA requirements for thermite welds.

The project also included a preliminary cost comparison with thermite welding. That comparison indicated that after an initial equipment investment, portable ESW welding would be cost competitive with thermite welding on a per weld basis.[3]

In 2006, based on the potential benefits of ESW for rail welding and on the progress that EST&D had made under the IDEA Program, Transportation Technology Center, Inc. (TTCI) identified ESW for development as a potential alternative to conventional rail welding technologies.

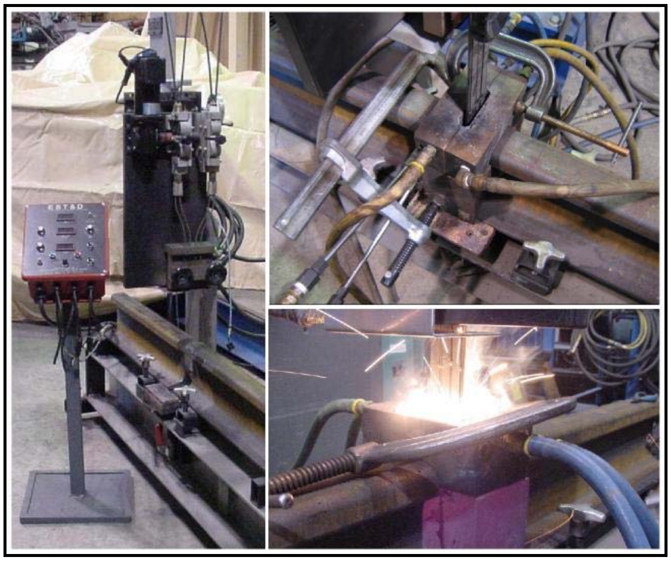

Figure 3: (Left) Welding Apparatus and Controller. (Upper Right) ESW Mold Shoes Ready for Welding. (Lower Right) ESW Rail Weld in Process Nearing Completion

Table 1: ESW Performance Under TRB IDEA Program[3]

Slow Bend Test	AREMA Thermite Requirements	ESW
Modulus of Rupture	120,000 psi minimum	119,000 psi
Deflection	0.60 inch minimum	0.36 inch

CURRENT WORK

In 2007, TTCI and EST&D entered into an agreement to continue the development of ESW with the goal of making it a viable alternative to existing field welding technologies. The research program will capitalize on advances made under the TRB IDEA project. All aspects of moving the process to revenue service including weld metal chemical composition, microstructure, heat affected zone characteristics, cooling shoe technology, weld reinforcement geometries, and portability will be investigated in the program. Heat flow modeling, alternative mold material, and adaptation of the process for existing rail maintenance technology will also be assessed. The work will take advantage of the latest in automated welding technologies to make ESW robust and reliable.

In order for ESW to be a viable field rail welding process, improvements in mechanical properties, equipment configurations, and consumable production will be required. Other potential areas of improvement could include automated weld control and documentation equipment.

A properly configured welder controller could be used to automatically vary appropriate welding variables throughout the weld. In addition, an electronic record of the weld's critical parameters could be generated and saved to provide documentation of welding parameters.

The cooperative development agreement between TTCI and EST&D established four phases of research and development. The individual phases define specific areas of research and set milestones to gauge overall progress. Table 2 briefly outlines the phases of the program. At this time, Phase I has been completed and Phase II is in progress.

Table 2: ESRW Development Summary

Phase	Description	Tentative Timeline
I	Weld analysis and preparation	June 2007 – September 2007
II	Produce ESRW welds to meet AREMA thermite weld requirements	October 2007 – December 2008
III	Refine process. Begin testing at FAST	2009
IV	Continue process refinement and FAST testing. Begin testing in revenue service	2009

Phase I focused on analyzing the welds made under the TRB IDEA Program in order to determine the weld process parameters that needed to be targeted for improvement. Phase II is directed toward implementing the findings of Phase I to produce welds using the ESW process that meet the AREMA requirements for thermite welds in regard to hardness and slow bend performance. Phase III will continue to refine the welding process and will address changes needed to successfully implement in-track installations. Welds will then be made in-track at the Facility for Accelerated Service Testing. Phase IV will continue the developments from Phase III and will implement weld testing in revenue service.

PHASE I RESULTS

In Phase I, welds that were previously made and tested in slow bend under the TRB IDEA program were examined to determine the causes that lead to weld failure below the desired values (see Table 1). Failure analysis was conducted and the fracture surfaces were examined. Welds were sectioned and metallography was performed to reveal the microstructure near the origin of each fracture. Additionally, modeling of the thermal cycle was performed to aid in understanding the overall welding process.

In general, the welds were found to have fracture origins near geometry transitions and along the fusion lines. Some areas of incomplete fusion were observed at the base of the rail. Metallography revealed a fully pearlitic microstructure with the exception of small regions of martensite in areas where insufficient melt back of the rail base had occurred. Figure 4 shows martensite at a region of incomplete fusion.

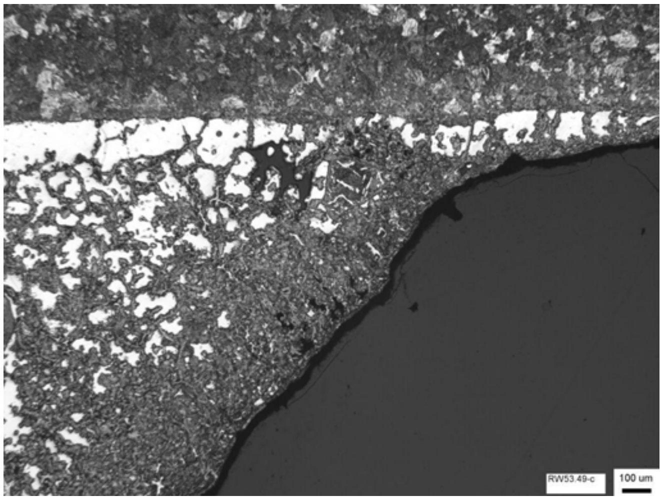

Figure 4: Microstructure of ESW Rail Weld at Rail Base. White areas are martensite.

Based on the above findings, EST&D and TTCI decided that the aim of Phase II should be to improve the overall thermal cycle of the welding process. Two specific areas were identified for research and development. First, research would involve the implementation of preheat at the rail base to improve rail end melt back and to eliminate the high cooling rates that lead to formation of martensite. Second, alternative weld mold materials would be explored. Copper molds traditionally used in ESW, while beneficial for use in low carbon structural steels, removes heat at a rate less suitable for higher carbon rail steels. Phase II research is currently implementing these changes.

Results of Phase I analysis and Phase II testing and development will be addressed more fully in a later *Technology Digest*.

SUMMARY AND FUTURE WORK

ESW has a number of advantages that may be applied to rail welding including the ability to deliberately modify weld chemistry to achieve varied mechanical properties throughout the weld. TTCI and EST&D under a cooperative development agreement have identified needed improvements to the ESW process and are working to implement the changes.

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