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Analysis of Thermite Welds Made in High Carbon Rails

Daniel Gutscher

Summary

The Transportation Technology Center, Inc. (TTCI) established a study with the Basic Metals Processing Research Institute (BAMPRI) of the University of Pittsburgh to conduct a metallurgical analysis of a series of welds made by TTCI using high carbon (i.e., near 1 percent carbon) rail steels. A summary of the findings contained in BAMPRI's report[1] is presented below:

- The microstructure in the weld heat affected zone (HAZ) would benefit from controlled-cooling process modifications. Expected benefits include narrower HAZ width and reduced austenite grain growth.
- The microstructure in the HAZ could also benefit from a post-weld heat treatment used as a separate application for existing welds. Expected benefits include improved hardness and refined austenite grain size.
- Due to their insolubility, inclusions (i.e., aluminum oxides, manganese sulfide stringers, etc.) present in the HAZ will not benefit from controlled cooling or post-weld heat treatment.
- Previous investigations established a connection between the existence of the pro-eutectoid cementite phase and the development of rolling contact fatigue in the head of the rail under heavy-axle-load traffic.[2]

The following describes the microstructures observed in the welds:

- Pro-eutectoid cementite was observed in varying degrees in each of the test welds. The pro-eutectoid cementite was located on prior-austenite grain boundaries and appeared to have coarsened in the HAZ as a result of the thermal conditions experienced.
- Correlation between the hardness measurements and the spheroidization of pearlite in the HAZ suggests that spheroidization is the dominant mechanism that controls softening in the HAZ.
- Manganese sulfides present in the rails were incorporated into welds as a result of rail end melt back. Some of these sulfides combined with aluminum oxides in the weld metal. Currently, the effect of these combinations on weld performance is not well established.

TTCI plans to use the knowledge gained in this study to explore controlling weld cooling rates as a means of limiting the width of the HAZ and to suppress the formation or coarsening of pro-eutectoid cementite. Development of a post-weld heat treatment will be researched as one means to remedy the deleterious changes that occur in the HAZ.

Future research will analyze the metallurgical changes that occur in electric flash-butt welds made using high carbon rails.

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

INTRODUCTION

Over the past several decades, rail weld manufacturers have seen the introduction of premium rail steels that have continued to increase in carbon content.[3] Rail steels have undergone numerous changes and continue to be improved at a rapid pace. The changes in rail steels include improvements in cleanliness, significant increases in hardness, and refinement of microstructure. Several manufacturers now produce premium rails with carbon content as high as 1 weight percent and with hardness values in excess of 400 Brinell.

Thermite welds have been used for rail welding for over 100 years and continue to be a major part of railroad field welding practice in North America due to their portability and relatively low cost. As with other forms of welding, thermite welds introduce a significant amount of heat into the base materials (i.e., rails) during welding. This heat affects the surrounding material and produces metallurgical changes which in turn alter properties of the surrounding material such as hardness and strength.

In thermite welded rail, both the rail and the weld form a system in which each affects the other to some extent. Welds introduce heat into the surrounding rails producing a HAZ and rail chemistry gets incorporated into the thermite weld through rail end melt back. In order to explore the effects of higher carbon content in premium rails on the rail/weld system, TTCI established a study with BAMPRI of the University of Pittsburgh to conduct a metallurgical analysis of a series of welds made by TTCI and to produce a report on the findings.[1] The following sections summarize and discuss the BAMPRI report and additional work conducted by TTCI.

EXPERIMENT SETUP

To explore the effects of rail carbon content on thermite welds, a test matrix was established defining the series of welds to be tested. Table 1 shows the test matrix.

Table 1. Test Matrix for Test Welds

Weld	Rail 1 High Carbon	Rail 2 High Carbon	Rail 3 Low Alloy
Mfgr. A	01	03	05
Mfgr. B	02	04	06

TTCI manufactured the six welds in accordance with the test matrix. The welds were sectioned into halves longitudinally. TTCI sent half of each weld to BAMPRI for metallurgical analysis and retained half of each weld for additional testing.

TTCI sent samples from each of the retained weld halves to another laboratory for chemical analyses of both the rail and weld materials. Table 2 summarizes the chemistry results for the parent rails. Rails 1 and 2 were essentially high carbon rails with carbon contents near 1.0 weight percent. Rail 3 was a low alloy rail that had a carbon content near 0.8 weight percent and a chromium content of 0.5 weight percent.

Table 2. Chemical Analysis Results of Rail and Weld Materials

Rail	C	Mn	P	S	Si	Cr	Ni	Cu
1	1.01	0.72	0.01	0.010	0.45	0.22	0.02	<0.01
2	0.97	0.84	<0.01	0.006	0.28	0.27	0.10	0.35
3	0.79	0.91	<0.01	0.007	0.64	0.50	0.02	0.02
	Note: all values are weight percent of element							

HAZ MICROSTRUCTURE EFFECTS

BAMPRI sectioned the welds and produced samples that were used for conducting Vickers hardness measurements and for metallurgical analysis. The samples were taken from the railhead at an area where the HAZ is the widest. Each sample was examined to identify microstructure changes that had occurred in the HAZ. Then those changes were compared with the Vickers hardness measurements.

Samples 01 through 04 (i.e., the high carbon rails) all exhibited similar hardness profiles and microstructure changes. Figure 3 shows the hardness results for test weld 04 and several scanning electron microscope images showing the microstructure at select locations (Points A-D) in the sample. Point A is located in the weld metal adjacent to the weld fusion line. Overall, the weld metal microstructure was fully pearlitic with some limited grain boundary pro-eutectoid cementite (Note that the research did not determine prior-austenite grain sizes or quantify the amount of grain boundary pro-eutectoid cementite. Therefore, descriptions given herein are based on visual observations only and are strictly qualitative). Pro-eutectoid cementite is cementite that forms at the prior-austenite grain boundaries upon cooling from the austenitic region prior to reaching the eutectoid temperature. Previous investigations established a connection between the existence of this phase and the development of rolling contact fatigue in the head of the rail under heavy-axle-load traffic.[2]

Point B is located in the center of the HAZ. The microstructure was pearlitic with pro-eutectoid cementite formations at the grain boundaries. The pro-eutectoid cementite in this region of the HAZ is coarser than that observed in the parent rail, indicating carbon migration to the prior-austenite grain boundaries during the weld thermal cycle. Points C and D are located at the region of lowest hardness in the HAZ. Between Points B and C the pearlitic microstructure begins to break down and transition to spheroidized cementite in a ferrite iron matrix. The degree to which this transition has occurred relates directly to the hardness. The higher the degree of microstructure transition, the lower the hardness values at a given point in the HAZ. At Point C the microstructure is fully spheroidized with no remaining pearlite or grain boundary cementite. At Point D the microstructure begins a rapid transition back to a pearlitic microstructure. Within approximately 5 millimeters, the microstructure and hardness levels are restored to those of the parent rail.

In general, the grain size was largest in the weld metal, decreased through the HAZ, and then quickly increased in size back to that found in the parent rail for all samples. This trend is common in welds made in plain carbon steels and is primarily a result of the thermal cycle experienced.

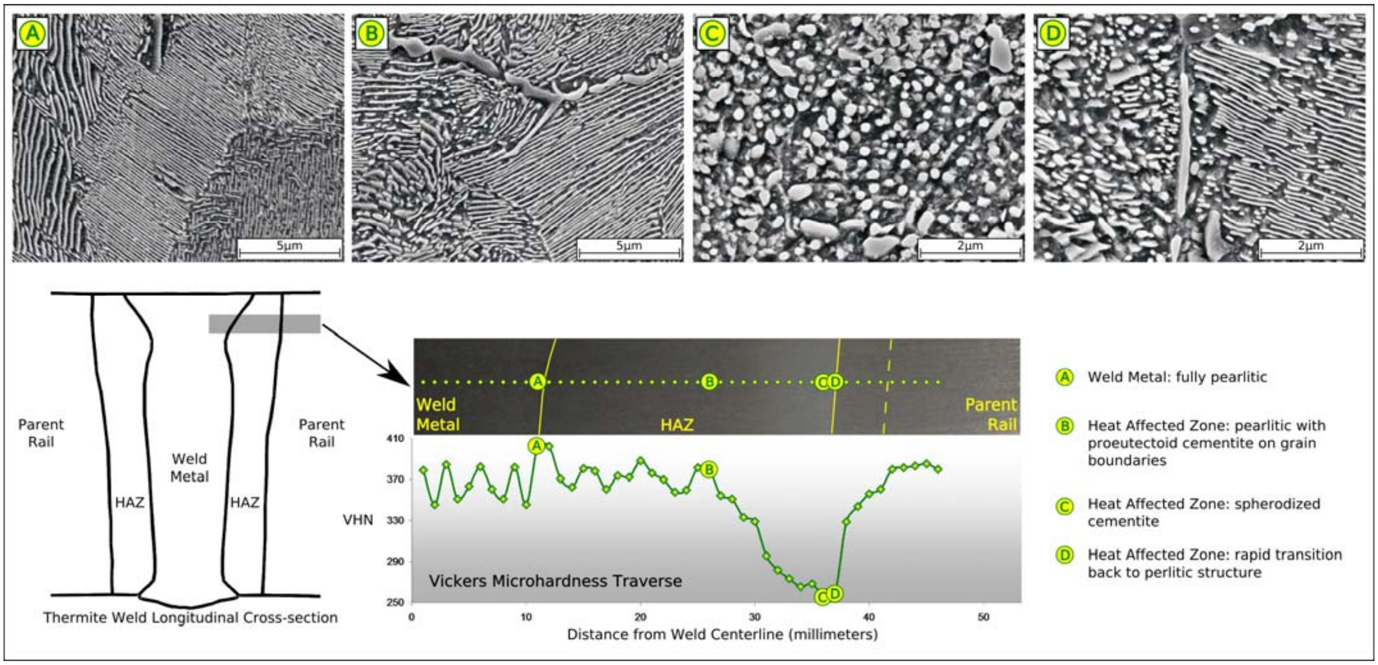

Figure 1. Microhardness Values Measured Transversely across the Weld, HAZ and Parent Rail along a Longitudinal Section near the Centerline of the Weld/rail[1]

PARENT RAIL AND WELD METAL

Manganese sulfide (MnS) stringers were observed in all the rails. MnS stringers are common in rail steels because sulfur is used in steel manufacturing as one means of controlling hydrogen and preventing hydrogen flaking.[4] MnS stringers were present throughout the HAZ and appeared relatively unaffected by the thermal cycle experienced at any point in the HAZ. Figure 2 shows the morphology typical for MnS stringers in rail steels. In the weld metal, where temperatures are significantly higher, some MnS stringers appear to melt and associate with aluminum oxides that are retained in the weld. Figure 3 shows one of the ways that MnS and aluminum oxides combine in the weld.[1,5] The effect of this combination on welds is not well established. MnS is relatively soft compared to aluminum oxide.

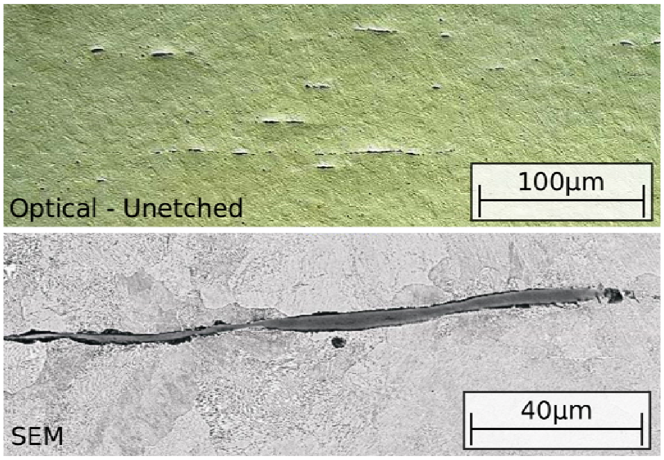

Figure 2. Manganese Sulfide Stringers in Rail[1]

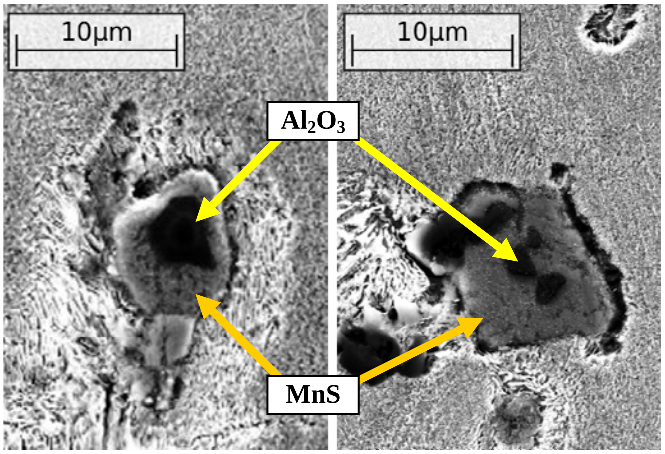

Figure 3. Secondary Electron images[1,5] of Manganese Sulfides and Aluminum Oxides associated in Weld Metal

Titanium nitrides were also observed in the low alloy rails, samples 05 and 06.

It is important to note that each of the rails used in the test contained limited amounts of pro-eutectoid cementite along prior-austenite grain boundaries. As a result, it can be inferred that a major part of the pro-eutectoid cementite found in the HAZ originated due to the thermal cycle induced by the adjacent weld.

DISCUSSION OF FINDINGS

The formation and growth of pro-eutectoid cementite in rails and rail welds is related to chemistry and cooling rates. In general, higher carbon contents coupled with relatively slow cooling rates promote the formation of pro-eutectoid cementite at the prior-austenite grain boundaries. Conversely, lower carbon contents coupled with relatively high cooling rates reduce the formation of pro-eutectoid cementite. In a rail HAZ the chemistry is defined solely by the parent rail and as such chemistry cannot be controlled in field applications. It is feasible, however, to control the cooling rate in a weld and therefore the resultant microstructure can also be controlled to some extent.

Spheroidization of cementite is a diffusion-based process in which the lamellar pearlite structure (fine layers of ferrite and cementite) begins to break down into spherical islands of cementite surrounded by a ferrite matrix. Being a temperature activated process, diffusion is dependant on the thermal cycle (i.e., time and temperature history) the rail/weld system experiences. Lower peak temperatures and higher cooling rates (i.e., less time at temperature) inhibit the breakdown of pearlite.

The implication of the preceding two paragraphs is that the development and application of a controlled-cooling process for thermite welds can potentially suppress the formation of grain boundary cementite and limit the amount of diffusion-based softening that occurs in the weld HAZs. A properly designed controlled-cooling process could also reduce the overall width of the weld HAZ. Additionally, a process that is developed to meet the needs of a higher carbon rail would generally be expected to benefit lower carbon rails as well.

A potential alternative to a controlled-cooling approach during weld production would be a post-weld heat treatment designed to recover some of the strength in the HAZ and reduce the amount of pro-eutectoid cementite.

CONCLUSIONS

- Pro-eutectoid cementite was observed in varying degrees in each of the test welds. The pro-eutectoid cementite appeared to have coarsened in the HAZ as a result of the thermal conditions experienced.
- Correlation between the hardness measurements and the spheroidization of pearlite in the HAZ suggest that spheroidization is the dominant mechanism that controls softening in the HAZ.
- Weld HAZ microstructure would benefit from controlled-cooling process modifications. Expected benefits are narrower HAZ width and reduced austenite grain growth.
- HAZ microstructure would also benefit from a post-weld heat treatment. Benefits are improved hardness and refining of the austenite grain size.
- Inclusions (i.e., aluminum oxides, MnS stringers, etc.) present in the HAZ, due to their insolubility, will not benefit from controlled-cooling or post-weld heat treatment.

FUTURE WORK

TTCI plans to use the knowledge gained in this study to explore different ways of improving weld performance. First, controlling the weld cooling rates will be researched as a means to limit HAZ width and to suppress the formation or coarsening of pro-eutectoid cementite. Second, development of post-weld heat treatment will be researched as a means to remedy the deleterious changes that take place in the HAZ.

TTCI is planning to conduct a similar investigation to determine the effects of higher carbon in premium rails on electric-flash butt welds. Electric flash-butt welds experience higher cooling rates than thermite welds. The resultant microstructures, therefore, can be significantly different from those observed for thermite welds. In particular, higher cooling rates may make the electric flash-butt welds more susceptible to the formation of martensite. Also, the higher cooling rates may tend to suppress the formation of pro-eutectoid cementite and limit coarsening of existing pro-eutectoid cementite.

In 2010, TTCI, in cooperation with rail manufacturers, started a new rail performance evaluation test at the Facility for Accelerated Service Testing. TTCI is making plans to perform a weldability study in conjunction with this evaluation.

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