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Metallurgical Analysis of Head Alloyed Welds and Standard Thermite Welds

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Summary

Transportation Technology Center, Inc. (TTCI) and Edison Welding Institute (EWI) conducted a study to better understand the metallurgical differences between head alloyed thermite and standard thermite welds. EWI completed a thorough metallurgical analysis using Atomic Emission Spectroscopy (AES) for chemistry analysis along with inclusion analysis to identify the different kinds of inclusions and their severity. TTCI performed chemistry and microstructure characterization analysis using Scanning Electron Microscopy (SEM) and Electro-Dispersive Spectroscopy (EDS). Microhardness was measured along the cross-section of the welds to better understand hardness variation due to chemistry effects. The results show how the head alloyed welds can provide higher strength at the head of the weld than standard thermite welds. The following is a summary of the findings of this analysis of the elements found in the head alloyed welds and how they provide additional hardness and strength to the weld microstructure:

- The head alloyed thermite weld was found to contain significantly higher level of vanadium and slightly higher levels of niobium and nickel than the standard thermite welds. Vanadium and niobium provide higher strength to the austenite matrix and cause secondary hardening by forming carbides, whereas nickel provides higher strength to the pearlite matrix.
- The weld metal in the head alloyed thermite weld showed chemistry segregations in the pearlite matrix at a microscopic level that were not observed in the standard thermite welds. SEM-EDS scans showed differences in carbon, niobium, and vanadium contents, although the chemistry segregations had no influence on hardness variation at the macroscopic level.
- Chemistry analysis showed that the alloying elements of the container plug of the head alloyed thermite weld diffused throughout the head region and down into the middle of the web of the rail.
- Heat affected zones (HAZ) of all welds had spheroidized cementite, which causes lower hardness in HAZ and increased wear.
- Both head alloyed and standard thermite welds showed similar low levels of inclusions and internal defects.
- Manganese sulfides and aluminum oxides were the main inclusions in all welds, but no silicates were present.

INTRODUCTION

Transportation Technology Center, Inc. (TTCI) and Edison Welding Institute (EWI) conducted a study to better understand the metallurgical differences between head alloyed thermite and standard thermite welds.

Thermite welding is commonly used to join rail. It is portable and has lower installation costs. Thermite welding is a form of casting, as it involves melting of the thermite mixture that fills up the gap between the rails. As a result, high amounts of heat are conducted into the joining rails and cause various metallurgical changes. These metallurgical changes along with entrapment of inclusions cause changes in hardness and strength of the welds. Weld manufacturers have developed head alloyed thermite welds in which a plug of alloying elements melts into the thermite mixture and adds more hardness and strength to the weld material in the railhead. Over the last few decades, rail manufacturers have made harder and stronger rails to withstand increasing traffic and higher axle loads. As rails have increased in hardness, the difference between the rails and the weld has increased, causing more batter and premature failures. Thus, the need for improved hardness welds.

TTCI had tested head alloyed thermite welds and standard thermite welds at the Facility for Accelerated Service Testing (FAST) and results of these tests were reported in TD-13-029.[1] This TD describes the metallurgical analysis performed by EWI and TTCI to identify the chemistry differences and other dissimilarities between a head alloyed thermite weld, referred to here as HAW, and two standard thermite welds made by two different manufacturers referred to here as Thermite A and Thermite B. Currently, four HAW with TTCI's HAZ overlay process have been installed in revenue service and there are plans to install more. A future TD will report performance results of the HAW welds in revenue service.

EXPERIMENTAL PROCEDURE

For this metallurgical study, three welds that had recently been removed from track at FAST were randomly selected for evaluation. These welds were marked as HAW, Thermite A, and Thermite B. Since these were maintenance welds and not test welds, their performances had not been monitored. These welds were cross-sectioned, and EWI performed chemistry analysis using Atomic Emission Spectroscopy (AES) in accordance with ASTM E415[2] for all elements except carbon, sulphur, nitrogen, and oxygen. These lighter elements were measured using Leco combustion analysis in accordance with ASTM E1019.[3]

Figure 1 shows the test locations of the HAW. The weld center on the web for the HAW was chosen to find the depth of diffusion of alloying elements of the alloy container[1] plug into the weld metal. For Thermite A and Thermite B, the weld center on the web of rail was not scanned for chemistry or inclusion analysis. An earlier TD[1] showed Brinnell Hardness (BHN) range of 310-340 at a depth of approximately 2.25 inches from the top of the rail, which is believed to be affected by the diffusion of alloying elements from the HAW alloy container plug. In this study, the sample at the web was 1-inch tall and was cut out at a depth of 3-4 inches from the top of rail. The other samples were chosen from the locations shown in Figure 1 and were 1-inch by 1-inch cross-sections.

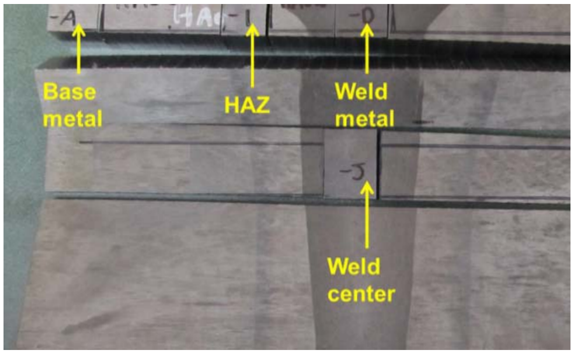

Figure 1. Locations on HAW Cross-Section Selected for Chemistry and Inclusion Analyses

TTCI performed further chemistry and microscopy analysis using Scanning Electron Microscopy (SEM) and Electro-Dispersive Spectroscopy (EDS). SEM and EDS results were compared with AES results; the inclusion types were identified. Microhardness was measured on the weld cross-sections below the running surface of the rails at 0.125-inch intervals, and the results were compared for the three welds.

CHEMISTRY AND MICROSTRUCTURE ANALYSIS

Table 1 compares the chemistry differences of the three welds for carbon (C), silicon (Si), phosphorus (P), sulphur (S), niobium (Nb), vanadium (V), chromium (Cr), manganese (Mn), and nickel (Ni). The AES method has lower values than the EDS method, because the AES method heats the entire sample and it provides a more representative estimate of the actual weight percentages of the elements. Because of the complexity and high cost of the AES process, there is only one set of data for each weld.

The EDS method is localized and scans the surface of the sample. This results in higher readings, because the scanned area is microscopically small with a depth of 2 microns. The material inhomogeneity at microscopic levels can be identified by EDS, and scans of two locations few inches apart can vary significantly, which is a disadvantage of the EDS process. Also, the accuracy of EDS scans depends on the voltage of electrons that are passing through the sample. However, multiple quick EDS scans on various locations can give multiple sets of data for each weld that can be averaged to get mean values, which is good for qualitative comparison and observing trends.

The differences in elements of interest in Table 1 are shown in red. Table 1 shows that the HAW weld has higher V and slightly higher Nb levels than Thermite A and Thermite B. Although the EDS values of the V level are higher than the values using the AES method, a comparison of AES results and EDS results of the three welds show a similar trend of higher V levels in HAW compared to Thermites A and B. The AES method found very low levels of nickel (Ni) in all three welds, whereas the EDS results found higher levels of Ni.

Table 1. Chemical Analysis Results of Thermite A, Thermite B, and HAW by both EDS and AES Methods

Type	Method	C	Si	P	S	Nb	V	Cr	Mn	Ni
EDS	A	0.63	1.44	0.32	0.24	0.50	0.27	0.28	0.91	0.20
	B	0.63	0.98	0.25	0.18	0.53	0.29	0.52	1.42	0.27
	HAW	0.63	1.35	0.31	0.25	0.58	0.55	0.35	0.98	0.34
AES	A	0.77	1.07	0.01	0.01	0.03	0.06	0.05	0.58	0.01
	B	0.65	0.76	0.02	0.01	0.03	0.05	0.27	0.93	0.07
	HAW (Head)	0.79	1.08	0.01	0.01	0.05	0.46	0.08	0.52	0.02
	HAW (Web)	0.78	1.01	0.01	0.01	0.05	0.35	0.11	0.58	0.01
Note: All values are weight percent of elements										

Figure 2 shows the higher contents of Nb, V, and Ni in the HAW compared to the standard thermite welds. The HAW shows a much higher percentage of V than in Thermites A and B, whereas the Nb and Ni percentages are comparatively higher in HAW, but to a smaller extent. It is possible that the rails welded by the HAW had higher Nb and Ni percentages than the rails welded by Thermites A and B, and the container plug of HAW might not contain any Nb or Ni.

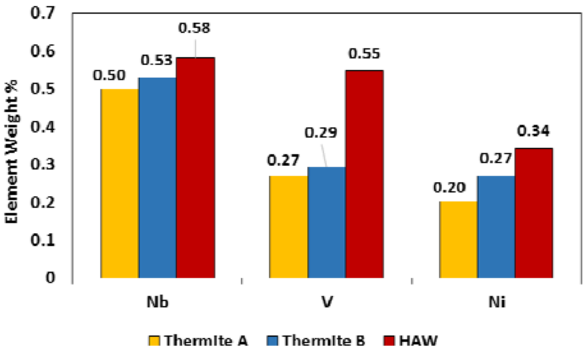

Figure 2. Different levels of Nb, V, and Ni among HAW, Thermite A, and Thermite B (weld heads) measured by EDS

Nb and V are strong carbide formers and cause secondary hardening. Ni strengthens the pearlite phase. Nb, V, and Ni are known to increase the hardenability of pearlitic-ferritic steels and may explain the increased hardness of the HAW. Table 1 shows AES data of the weld metal present in both the head and the web of the HAW joined rail. Comparison of V levels of AES data show 0.46 percent in the head and 0.35 percent in the web of the HAW, whereas the V levels in the weld metal of the head area of both standard Thermite welds A and B are 0.06 percent and 0.05 percent, respectively. A study by Moller et al. had observed a higher level of V percent at ~1.57 inches (40mm) below the top of rail.[4] These results indicate that the alloying elements melting from the container plug during the HAW process are capable of diffusing into the web of the joined rail, causing further strengthening of the web. Strengthening of the web of a weld increases the life by reducing the propagation of cracks formed at web defects.

Another observation on the weld metal of HAW was noticed using the SEM at high magnification. In addition to the pearlite phase, some grains embedded in the pearlite matrix had higher levels of V and Nb, and lower levels of C compared to the chemistry of the pearlite matrix. Figure 3 shows a 4489X magnification snapshot of the presence of chemical segregation in HAW. The level of Ni was found to be 0.33 percent in both phases. This chemical segregation was not observed in the other standard thermite welds. Overall hardness variation in the weld metal of the head alloyed thermite weld was not significant, which indicates that these segregations do not have any influence on material strength at a macroscopic level. Microstructural examination of HAZ and base metal showed no differences among the three welds. Equal proportions of spheroidized cementite was observed in HAZ areas of all three welds. This spheroidized cementite is a soft phase and causes lower hardness in HAZ, which increases wear and reduces the life of welds.

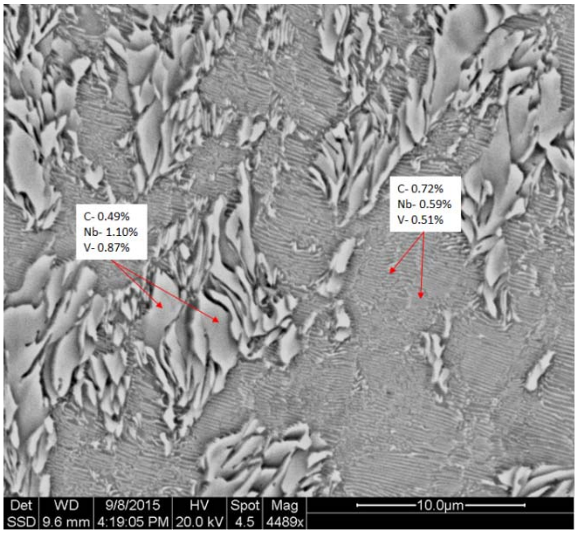

Figure 3. Chemical segregation having different levels of C, Nb, and V in HAW weld metal

MICROHARDNESS RESULTS

Microhardness values were measured using Rockwell Hardness (HRC) scale on all three welds and the results were converted to Brinell (BHN) scale. Table 2 shows mean values of 11 measurements taken across the weld cross sections. Since these maintenance welds were in service for considerable time, work hardening had caused the hardness values to increase above 410 BHN, which is the AREMA maximum specification for rail hardness. Also microhardness results are generally higher than macrohardness because of the localized penetration of the indenter. But the comparison shows the HAW had higher values of hardness at the weld center of both head and web compared to standard Thermites A and B. This is explained by the observation seen in Table 1, which shows higher levels of secondary hardening elements of Nb, V, and Ni in HAW.

Table 2. Microhardness results of three welds

Type	Head	Web
A	371 BHN	286 BHN
B	421 BHN	258 BHN
HAW	451 BHN	311 BHN

INCLUSION ANALYSIS

EWI characterized the inclusion distribution using ASTM E45[5] Method A and identified the different kinds of inclusions and their severity in the base metal, HAZ, and weld metal of all three types of welds. EWI used image analysis software to further classify the inclusions as thin and heavy. Although the severity index ranges from 0-5, none of the welds showed any thin inclusions with a severity rating higher than 1.5. Heavy inclusions were either 0.5 or 0 in severity. Figure 4 show examples of thin inclusions with 1.5 severity (left image) and heavy inclusions with 0.5 severity (right image).

Figure 4. Inclusion Classification by EWI

No silicate inclusions were observed in any of the welds. The inclusions were either sulfides or oxides. All three welds had comparable amounts of internal defects like hot shrinkage or porosity. An in-depth analysis of the quantification of internal defects of HAW revealed more than 2 percent average internal defects over the examined area in the weld metal on the head of the joined rail. The web area of the rail containing weld metal showed less than 2 percent internal defects. Thus, the weld metal in the head area had more defects and was less clean microscopically than the web area. This is characteristic of thermite welding and of any casting process because of entrapment of impurities in the liquid metal from the slag layer on top. These defects and impurities have been proven to be the reasons for fatigue defects as pointed out in an earlier TD.[6] The chemistry of the sulfides and oxides were identified using SEM-EDS and were found to be manganese sulfide (MnS) and aluminum oxide (Al_2O_3), respectively. Figure 5 shows examples of MnS and Al_2O_3 inclusions as found in the HAZ area of HAW at 2606X magnification.

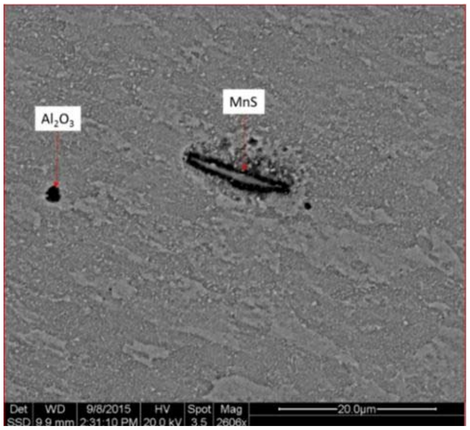

Figure 5. Al_2O_3 and MnS using SEM in HAZ of HAW

MnS inclusions are thin slivers and act as stress concentrators, whereas Al_2O_3 inclusions are globular and are less detrimental. This analysis and identification of internal defects indicate that Thermite welds A and B, and HAW have detrimental sulfide inclusions and internal defects. The thermite welding procedures are the same among all these welds, so these problems persist irrespective of the chemistry changes in the HAW weld metal.

CONCLUSIONS

- HAW had significantly higher levels of V and slightly higher levels of Nb and Ni at the weld center compared to standard thermite welds, which led to higher strength and hardness.
- Formation of different grains was observed in addition to pearlite showing C, Nb, and V segregations in HAW. This chemical segregation was not present in Thermite welds A and B, although it had no influence on macroscopic hardness variation.
- HAZ areas of all welds had spheroidized cementite phase, which cause softening of HAZ.
- Inclusion levels were comparable among all welds; the highest severity was 1.5 on a scale of 0-5, which is considered to be low.
- MnS and Al_2O_3 inclusions were predominant in all welds, but no silicates were found. Porosity amounts were similar in all welds.

REFERENCES

1. Gutscher, Daniel and LoPresti, Joseph. November 2013. “Testing of Head Alloyed Thermite Welds at Facility for Accelerated Service Testing.” *Technology Digest* TD-13-029. Association of American Railroads, Transportation Technology Center, Inc., Pueblo, Colorado.
2. ASTM E415-14, Standard Test method for Analysis of Carbon and Low-Alloy Steel by Spark Atomic Emission Spectrometry, ASTM International, West Conshohocken, PA, 2014.
3. ASTM E1019, Standard Test Methods for Determination of Carbon, Sulfur, Nitrogen, and Oxygen in Steel, Iron, Nickel, and Cobalt Alloys by Various Combustion and Fusion Techniques, ASTM International, West Conshohocken, PA, 2011.
4. Moller, R., P. Mutton, and M. Steinhorst. 2001. “Improving the Performance of Aluminothermic Rail Welding Technology, through Selective Alloying of the Rail Head.” In *Proc. 7th International Heavy Haul Conference*, Brisbane.
5. ASTM E45-13, Standard Test methods for Determining the Inclusion Content of Steel, ASTM International, West Conshohocken, PA, 2013.
6. Kristan, Joseph. July 2000. “Thermite Weld Failure Survey.” *Technology Digest* TD-00-013. Association of American Railroads, Transportation Technology Center, Inc., Pueblo, Colorado.