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**Rail Safety IDEA Program**

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## **Laser Cladding of Welds to Improve Railroad Track Safety**

Final Report for Rail Safety IDEA Project 22

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## Table of Contents

Acknowledgments	1
Table of Contents	2
Executive Summary	3
Background	4
Investigation	5
Modified Cladding Procedure	5
Induction Heating	14
Torch Heating	16
Cladding and Heat Treatment Research Summary	17
Service Testing	18
Delamination Problem	20
Findings and Conclusions	24
References	26

### Figures

Figure 1. Thermal weld process.	5
Figure 2. Microhardness values measured transversely across the weld, HAZ, and parent rail.	6
Figure 3. Examples of laser cladding on rails.	6
Figure 4. Laser cladding and thermal analysis.	7
Figure 5. Thermal analysis system including the instrumented approach.	10
Figure 6. Jominy test results of hardness for samples quenched under air and water conditions.	12
Figure 7. Thermal Analysis and simulated continuous cooling diagram.	13
Figure 8. Microstructural characterization of the rail cooled at different rates.	14
Figure 9. Microhardness test and effect of heat treatment on hardness.	15
Figure 10. Experimental setup of the inductive heater/rail.	16
Figure 11. Laser cladding practice.	17
Figure 12. Microstructure of the heat treated rails.	18
Figure 13. Dye penetrant analysis of the cladded welds rails.	20
Figure 14. Condition of the welds 4 and 6.	22
Figure 15. Rail profiles from the cladded rails before and after field test.	23
Figure 16. Photos of cladded welds after field tests.	24

### Tables

Table 1. List of Chemistries Used to Identify the Best Laser Cladding Powder for Railway Use	8
Table 2. Temperatures of Transformation Reactions During Water Quenching Conditions	9
Table 3. Brief Summary of the history of the test welds	21

## **EXECUTIVE SUMMARY**

The purpose of this project was to explore the use of a laser-based technology, laser cladding, to reduce surface and near-surface defects resulting from thermite field welds of rail. Thermite field welds are often used to splice together continuous welded rail segments or to replace damaged sections of rail. Thermite welds, however, often experience plastic deformation, or batter, along the heat affected zone (HAZ) of the weld. The objective of this project was to develop a procedure to prevent excessive plastic deformation along the HAZ by means of laser cladding coatings. Such a procedure has the potential to increase the life of thermite field welds and thereby reduce track maintenance costs and enhance rail safety.

Laser cladding is a process to apply metal coatings using a laser as a heat source. The laser melts the base metal and an additive powder to deposit a protective coating (see Figure 4). Previous attempts to use this procedure resulted in cracking of the cladding and poor toughness (resistance to fracture). This project examined the cracking problem, the toughness problem, investigated potential solutions, and explored the feasibility of using laser cladding in the field.

The main reason for the cracking previously encountered in laser cladding is the formation of martensite resulting from rapid cooling during the cladding process. Martensite is brittle and responds poorly to dynamic impacts due to its poor toughness. Accordingly, one focus of this work was the *in situ* reduction (retention) of martensite during laser cladding in order to improve the service life of the welds.

The primary project objective was the development of an improved cladding process. Initial project tasks included the evaluation of powders and the selection of a powder composition for use in the cladding process, and an investigation of alternative heat treatment protocols to solve the cracking problem. Sample sections of laser-cladded rail welds were then prepared using the revised process. These test sections were then installed and tested in the tracks at the Transportation Technology Center Inc. (TTCI) high-tonnage Facility for Accelerated Service Testing (FAST) loop at Pueblo, Colorado. The objective of these tests was to subject the test welds to 50 MGT (million gross tons) of heavy axle load train traffic and to monitor the performance of the cladded welds during the tests.

Six test welds using the new laser cladding process were prepared. Two of the six were never installed in FAST due to the presence of pores in the cladding. The remaining four test welds were installed as two sets of two welds. The two welds in each set were installed in the same location (on the opposite rail). One weld was removed after approximately 20 MGT due to delamination of the cladding. TTCI also removed the adjacent weld in that pair for safety reasons. Another test weld was removed after approximately 42 MGT, also due to delamination. TTCI again also removed the adjacent weld in that pair for safety reasons.

A preliminary assessment of the process necessary to apply laser cladding in the field was also conducted. This included *in situ* heat treatment using induction heating and a preliminary assessment of other elements of the process including the use of CNC (computer numerical control) or robot arms.

The following is a summary of the results, conclusions, and recommendations of this project:

- Based on a limited sample of six welds made using the laser cladding procedure developed in this project the new heat treatment protocol appears to have solved the cracking problem previously encountered with laser cladding.
- The appearance of pores on two of the six test welds indicates the need for further investigation to determine the cause and cure for this problem.
- The delamination of the cladding on two of the four welds installed in the test track also indicates the need for additional investigation if laser cladding is to be further considered.
- Further consideration of laser cladding would also require a more comprehensive investigation of the entire process of laser cladding of thermite welds in the field from the standpoints of practicality and costs. Elements of this process of particular concern are the need for a heat treatment process suitable for use in the field, the need for high-precision CNC or robot arms, and the logistics of getting this equipment into the field.

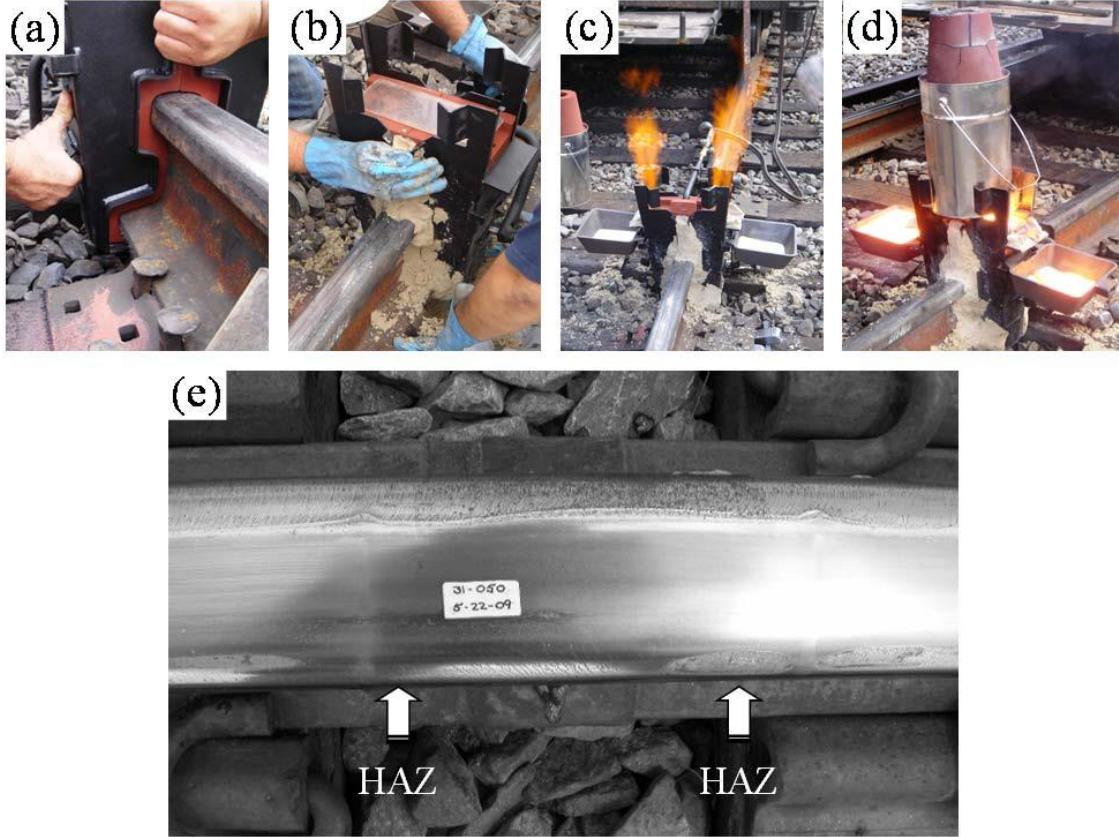
## BACKGROUND

Field welds are the characteristically weak links of a railroad track and when they fail, or when a rail defect is repaired, a section of rail is removed and a replacement rail plug is placed in track, typically using two thermite welds. This practice increases the number of field welds and compromises the integrity of the track due to excessive plastic deformation (batter) along the heat affected zone (HAZ) of the welds (Figure 1). Hardness reduction at the HAZ is the result of the welding temperature exceeding that of the austenite, thereby promoting annealing during welding. In the last 50 years rail hardness has improved from 248 HBN to >400 HBN through the development of new rail chemistries. Unfortunately, this increased hardness has not been sufficient to mitigate batter. Laser cladding coatings can potentially be used to develop a highly stiff region on the rail running surface along the welds to prevent batter.

Previous attempts have been made to use laser coating methods, including laser cladding and laser glazing, for rail life extension. However, these attempts demonstrated that laser coatings require further improvements for their full implementation into service. The main reason is the formation of martensite and excessive cracking along the laser-treated surface, subsurface, and parent rail. Untempered martensite is brittle under dynamic impacts; therefore, it reduces the fracture toughness of the material. This project examined methods to achieve martensite retention during laser cladding and the alternative of post-treatment during tempering in order to improve the service life of the welds.

The HAZ is softer compared with the parent rail and weld material (Figure 2), resulting in metallurgical changes taking place during the heat/cool cycle of the weld (1). One of the most common methods for rail life extension is top of rail lubrication; however, this does not remediate the batter along the HAZ. Laser rail weld coatings are a potential solution. Previous attempts to use laser coatings include rail glazing (2, 3). This surface treatment was unsuccessful due mainly to the poor metallurgical bond with the parent rail, which resulted in loss of cohesion from the parent rail over a short time (often less than 5 MGT). The glazing method melts the rail surface promoting a fast solidification with high hardness that is the result of the presence of a fully martensitic microstructure. The hardness in those coatings can reach

values between 850 and 920  $\mu\text{HV}_{100}$ . This can be considered a great advantage for wear; unfortunately, this practice negatively affects toughness. The glazing problem was eliminated in the present work by avoiding the melting of the rail; instead, the welds were coated using a metallic powder that becomes molten with a laser and rapidly welds to the rail surface.



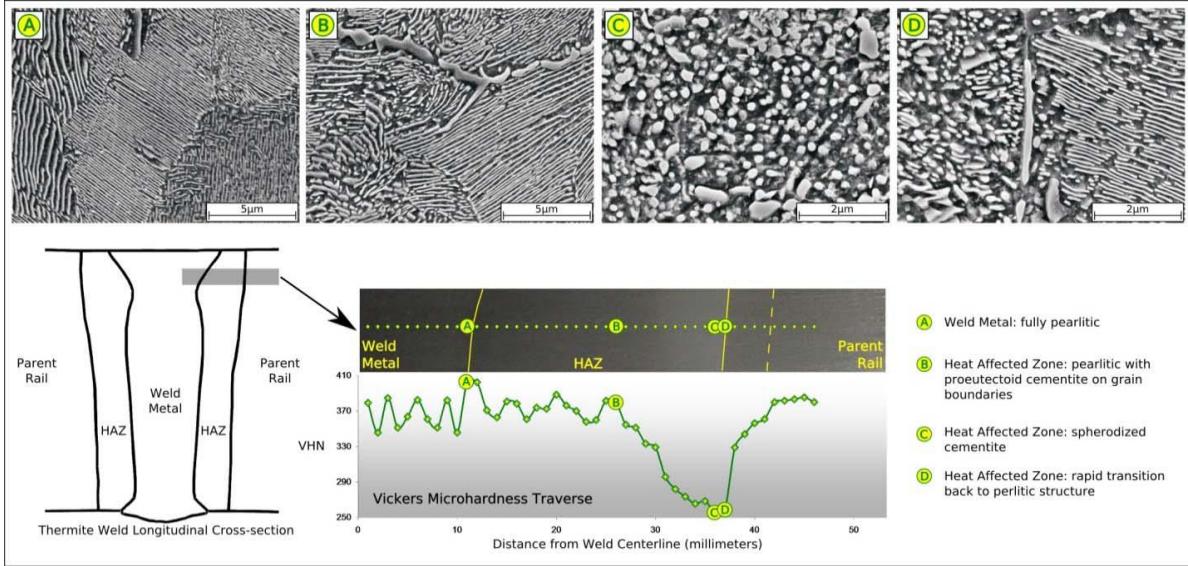
**Figure 1.** Thermite weld process: (a) mold, (b) sealing of the mold, (c) preheating of the mold and rail, (d) thermal welding process, and (e) thermal weld example of a typical plastic deformation (batter) observed on the HAZ (arrows).

## INVESTIGATION

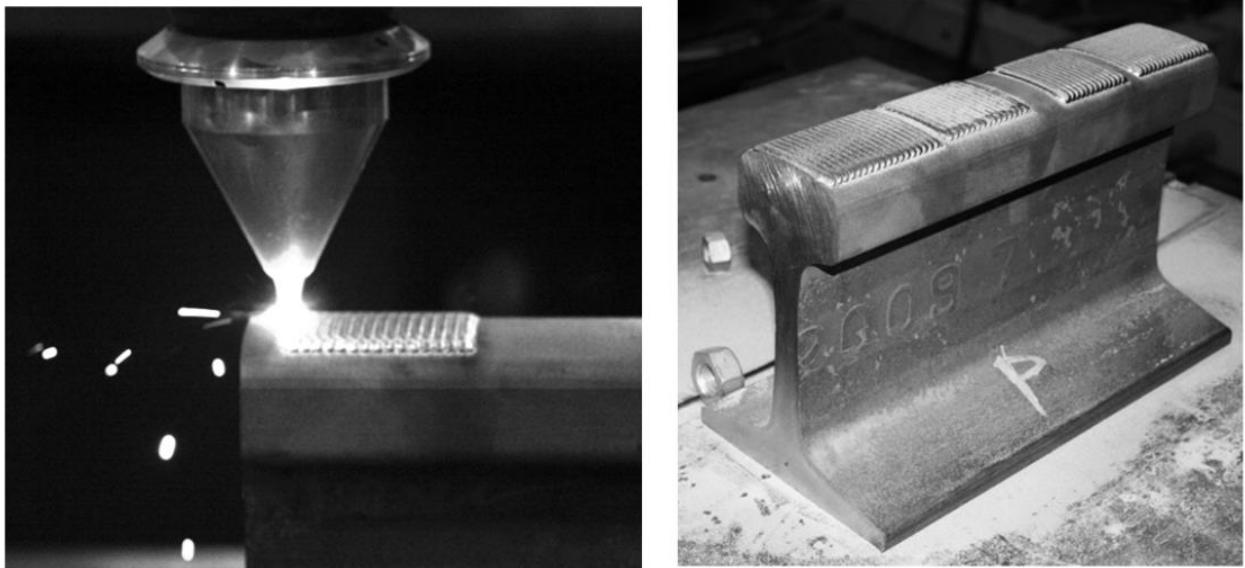
### Modified Cladding Procedure

Initial steps in this work consisted of the study of the metallurgy of rail steels and the investigation of ways to properly apply laser cladding coatings on rails. Previous attempts to use laser cladding resulted in the presence of cracking due to martensite, caused by rapid cooling after the laser coatings were applied. Instrumented laser cladding (Figure 4c), Jominy test samples (to test hardenability), metallography, thermal analysis, and numerical simulations were used to develop a new heating and cooling protocol. This protocol focused on the pre-heating conditions to help minimize the cooling severity. This protocol was incorporated into a modified laser cladding procedure designed to prevent martensite formation and cracking. As a part of this investigation we developed a new induction heating procedure and, to hinder martensite formation, new cooling protocols. Thus, we demonstrated that it is possible to retain martensite by proper cooling or, in the event that martensite forms, it can be tempered to reach allowable hardness and toughness conditions.

Test specimens of laser cladded rail using the new procedure were then installed in the track of the high-tonnage test loop at the TTCI, located in Pueblo, Colorado, where they were subjected to trains carrying cars with heavy (39-ton) axle loadings.



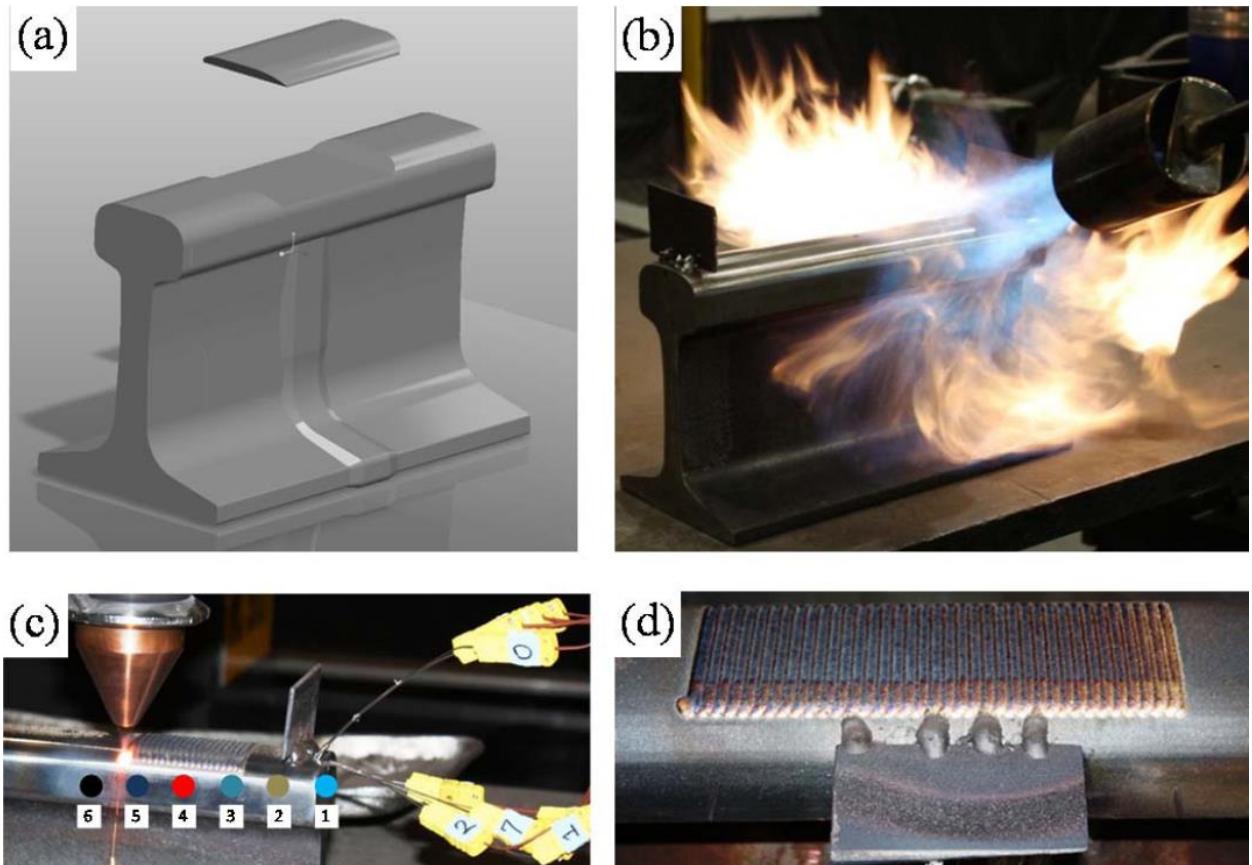
**Figure 2. Microhardness values measured transversely across the weld, HAZ, and parent rail.**



**Figure 3. Examples of laser cladding on rails.**

Figure 4a is a sketch of the machining of the rail head prior to laser cladding. The machining was designed based on the amount of material added during coating to allow a smooth transition from the rail to the cladding back to the rail, thereby minimizing impacts. Figure 4 (b-d) shows other steps in the procedure to assess the effects of laser cladding on the microstructure. The cooling curves in Figure 7 are the cooling history of the samples. These results were analyzed to determine the exact temperatures reached in the samples during the laser cladding process. Originally, we tested two

types of rails, commercial head hardened and premium quality. We found that the commercial grade had a higher tendency to form martensite; therefore, we decided to use premium rail steel rather than commercial grade steel for this preliminary work. In Table 1, the commercial chemical compositions of the powders used for laser cladding are given. The first composition (FAP F-R 0042 J 01) was selected as the ideal candidate for railway applications. This approach helped to reduce the cracking, but this problem was more effectively mitigated by the heating/cooling protocol developed in this project. The cracking was attributed to fast cooling occurring after the sudden heating of the material and coating surface. This effect behaves as a thermal shock that promotes cracking along the coatings. In this project, the cracking was prevented by in situ heat treatments using induction and torch heating.



**Figure 4. Sketch of a weld and an overview of the laser cladding procedure:**  
**(a)** sketch of the thermite welds as proposed for the laser cladding, **(b)** preheating of the rails samples before laser cladding, **(c)** laser cladding and in situ thermal analysis, and  
**(d)** sample after laser cladding. The dots in (c) indicate the approximate location of each thermocouple.

The preliminary test was conducted by installing a battery of six thermocouples under the surface of the rail to be cladded (Figure 4c). Those thermocouples monitored the heating and cooling history of the entire process. In the heating curve (Figure 7) it is clear that every time the laser passed close to a thermocouple the temperature increased. The determination of the maximum temperatures is key because they are used to determine if the steel is transforming into austenite that will result in further phase transformations (e.g., into martensite) during cooling. The increase in temperature due to the laser passes is cumulative and results in continuous temperature increases. The data collected during the laser cladding (Figure 7a) show that the thermocouples reached temperatures of up to 680°C. Based on our

heat transfer calculations and considering that the thermocouples are located 6–7 mm below the surface, the actual temperature in the surface easily exceeds 800°C. This steel has approximately 1 wt% C, and based on the Fe-C diagram (4), 800°C is the minimum transformation temperature to form austenite. Therefore, under the cladding conditions, this steel is definitely within the austenitic range that, upon cooling, will transform into other phases depending on the cooling environment. Due to the nature of laser cladding, it is usually expected that some martensite will be formed. As mentioned before, martensite is unwelcome in rails used in revenue service. Therefore, martensite retention was a major goal in this project. For this reason, numerical simulations were run to calculate the Continuous Cooling Transformation (CCT) diagram for this steel. The composition of the steel is proprietary; therefore, it cannot be disclosed in this report. Still, we used the exact composition to produce a CCT diagram (Figure 7b).

**Table 1**

**List of Chemistries Used to Identify the Best Laser Cladding Powder for Railway Use**

ID	C wt%	Mo wt%	Ni wt%	Fe wt%	Mn wt%	Cr wt%	Si wt%	O wt%	Co wt%	V wt%	B wt%
<b>FAP F-R <u>0042 J 01</u></b>	<b><u>1.3</u></b>	<b>=</b>	<b><u>35.0</u></b>	<b>=</b>	<b>=</b>	<b><u>9.5</u></b>	<b><u>2.0</u></b>	<b>=</b>	<b>=</b>	<b>=</b>	<b><u>0.9</u></b>
3533-10	2.2	5.5	11.8	Bal	1.1	27.9	1.34	0.2	—	—	—
Stellite 21	0.3	5.5	10.0	1.0	0.5	27.0	0.6	—	Bal	—	—
SP46M	0.74	—	Bal	3.9	—	15.0	4.22	—	—	—	3.1

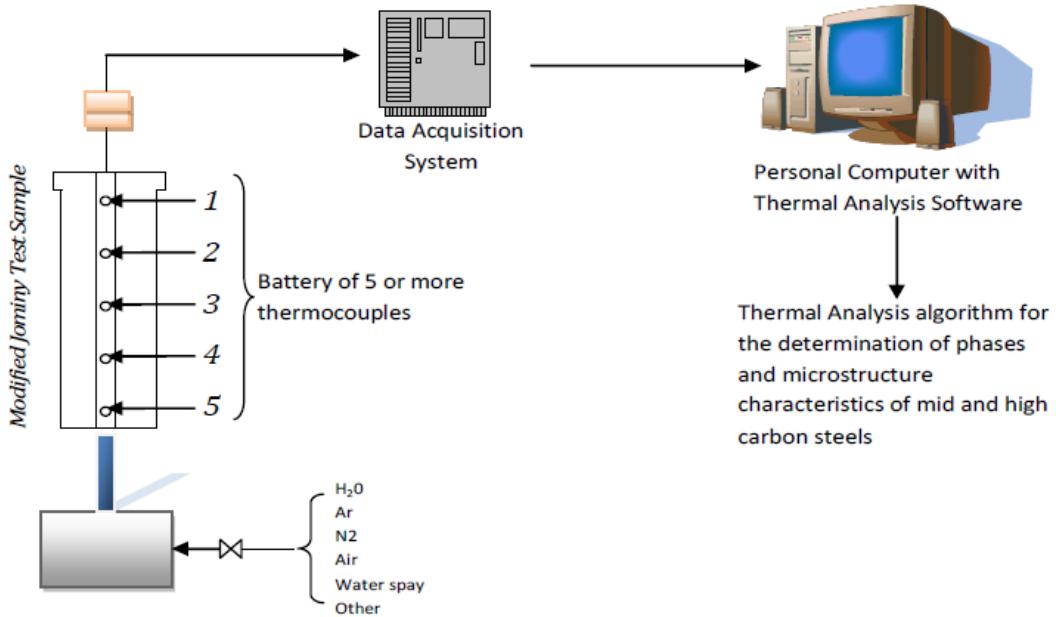
Following the previously described set of experiments, laboratory testing was undertaken to determine the exact times and temperatures where the transformation to martensite occurs. These tests were conducted using a procedure similar to that used for the Jominy samples. The Jominy test is also known as the hardenability test for carbon steels, and its procedure is described in the ASTM A255 standard. In this test a 1-inch-diameter sample of 4 inches in length is heated to austenitic conditions followed by water quenching from one end of the sample. Once the sample reaches room temperature the hardness is measured along the side of the sample. Austenitic conditions are needed for the steel to transform into other phases as a function of the cooling rate severity, resulting in differences in hardness. The expected phases include ferrite, pearlite, bainite, and martensite, listed in the order of softest to hardest. The instrumented Jominy test used herein is more complex and complete in this case and uses a battery of thermocouples to record the temperature–time history of the samples during cooling. The cooling histories are used for thermal analysis, which is a combination of automated and numerical methods to calculate the exact temperature, time, and fraction transforming for each phase. Ferrite and particularly pearlite are recommended phases in rail steels. In the case of laser cladding, the rail behaves as a heat sink, so the cooling environment is severe. For this reason, the cooling rate was controlled to ensure a pearlitic microstructure, which was then confirmed by metallography.

This procedure was developed at the University of Houston along with the algorithms for thermal analysis. This characterization process is called “Instrumented Jominy test with in situ thermal analysis characterization.” The sketch of the thermal analysis apparatus is given in Figure 5. Hardness measurements using the Rockwell C scale on the Jominy samples were conducted as recommended in ASTM A255. Figure 6 shows the Jominy test sample results along with the respective microstructures, cooling curves, and the Rockwell C hardness results. The cooling history (Figure 7) allows one to determine the temperatures and times when a phase transformation occurs during heating or cooling. However, the most important information for our applications was the first derivative that allows the identification of the exact temperatures, times, and fraction transforming during this analysis (5–11). Following the thermal analysis the samples were sectioned and analyzed metallographically to determine their constituents. This work was conducted to correlate the phase transformations to precipitation temperatures and times to be able to hinder the undesirable presence of martensite after cladding.

To properly design the heat treatments, the welds were heat treated in the laboratory. In this heat treatment we identified that the cooling rate of the samples should be up to 2°C per second to achieve a steel microstructure of pearlite, which is the desirable phase. Faster cooling rates result in martensite formation. This cooling rate was taken directly from the CCT diagram given in Figure 7 and was accurate for the lab conditions. The other option is to hold the samples at temperatures above the bainitic transformation temperature (about 400°C). The phase transformations were identified with thermal analysis and are presented in Table 2, where the thermocouples were numbered by the locations indicated in Figure 4c. Each thermocouple cooled at a different rate resulting in different transformation temperatures.

**Table 2**  
**Temperatures of Transformation Reactions on the Investigated Rail**  
**During Water Quenching Conditions**

Rail and Cooling Condition		Pearlite	Bainite	Martensite
Air	Thermocouple 1	N/A	N/A	350.3
	Thermocouple 2	N/A	533.04	291.07
	Thermocouple 3	696.13	617.55	243.71
	Thermocouple 4	690.53	624.63	N/A
	Thermocouple 5	594.13	N/A	N/A
Water	Thermocouple 1	556	395.54	N/A
	Thermocouple 2	710.46	610.31	N/A
	Thermocouple 3	756.21	685.17	N/A
	Thermocouple 4	724.09	665.95	N/A
	Thermocouple 5	630.1	614.62	N/A



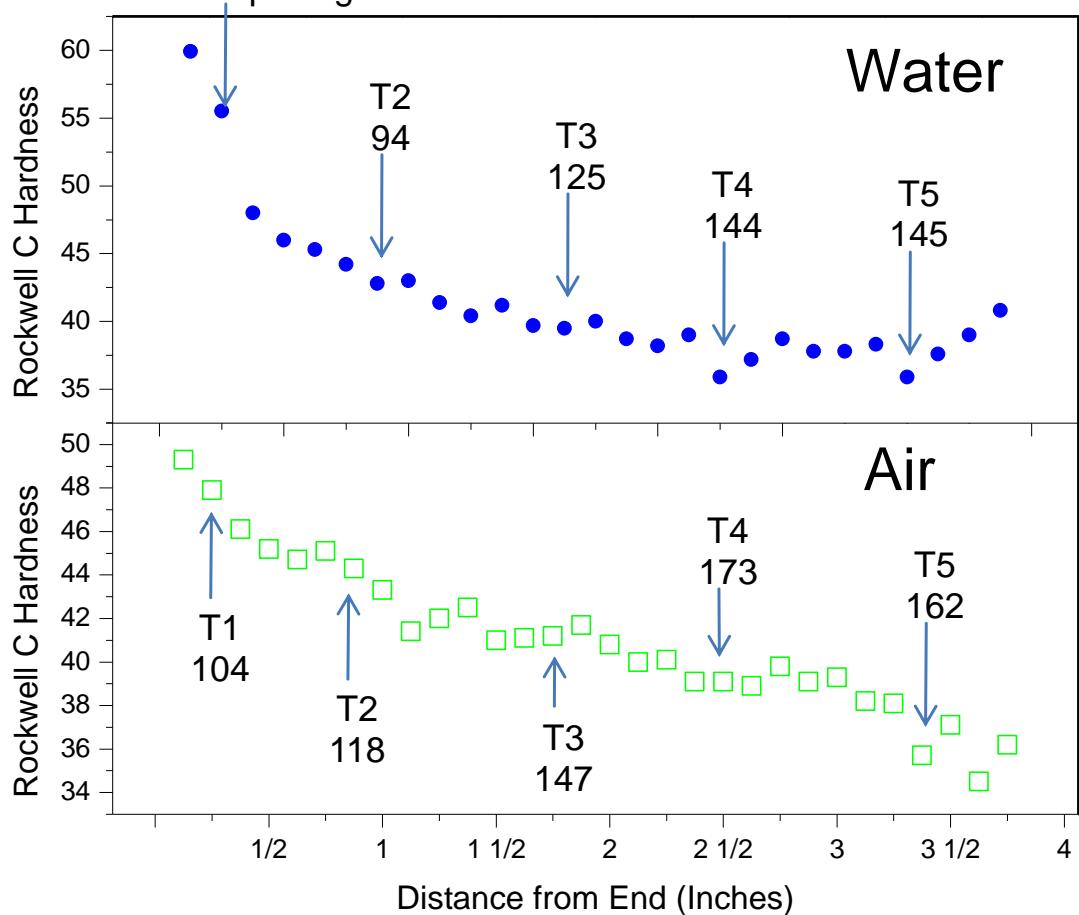
**Figure 5. Sketch of the thermal analysis system including the instrumented Jominy test.**

In addition to hardness, the samples were analyzed for their microstructure and the respective micrographs are presented in Figure 6 for air- and water-quenched samples. The interlamellar spacing was measured in the samples to provide a better understanding of the mechanical properties. It is well known that as the interlamellar spacing decreases, the hardness and strength increases, which is in direct agreement with the results presented in Figure 6. However, this also has detrimental effects; as hardness and strength improve, ductility and toughness may be affected negatively. In the present work the interest was in hardness improvements and the resulting wear benefits, but the primary interest and focus was martensite retention and proper laser cladding cohesion to preserve toughness.

Figure 8 shows the microstructure analysis using optical and scanning electron microscopy for the investigated material. In these figures, microstructures typical of the steel investigated when cooled at different rates can be identified. Images of the interlamellar spacing measurements and pearlite colony size are also presented. As per the AREMA recommended practices, the steel must have a fully pearlitic microstructure that is obtained in the investigated steels with slow cooling or after heat treatment. The narrower the interlamellar spacing the better, and this occurs by properly controlling the cooling rate. Again, however, the limit is to avoid the presence of bainite or martensite. The interlamellar spacing in pearlite can be tuned by cooling the samples at different conditions after the laser cladding process is completed, but before the sample has cooled. This cooling can be controlled by means of induction heating or torch heating. Both processes were used herein and both were successful. Torch heating could likely be unacceptable for use in the field, unless the flame is contained similar to the pre-heating operation in thermite welding (see Figure 1). Therefore, any future work should include the optimization of the induction heating process for field application.

The heat-treated samples were used to identify the post-processing conditions. The hardness after cladding is significantly higher than that of the raw and tempered rails, which is expected due to martensite. The post-processing conditions may not eliminate the martensite, but can anneal it or temper it. Tempered martensite partially recovers its ductility, resulting in proper improvements in toughness. Therefore, tempering the martensite may result in generating microstructure characteristics similar to those specified in the AREMA recommended practices for rails. This is recommended for rails and welds that have already been installed in the field; new welds can be treated in situ before they cool. Figure 9 shows the hardness results along the subsurface of the laser cladded sections from actual head hardened rails after cladding. The heat treatments showed that tempering temperatures as low as 200°C were effective to treat martensite. The tempering temperature protocol was designed for 10 minutes. Any temperature between 200°C and 500°C is effective to temper martensite. Still, the higher the temperature the softer the steel becomes. This requires a balance or trade-off between time and temperature to comply with the needs of specific rail tracks. In the test conducted in the present work temperatures between 200°C and 300°C were selected for 10 minutes. The 10 minute time was selected because the railways require rapid in-track processing to minimize the time tracks are out of service. If necessary, this time could be reduced further by using higher temperatures; however, this can compromise rail hardness. Accordingly, if further reductions in time are determined to be desirable, this would require additional investigation to further determine the relationships among temperature, time, and hardness.

Thermocouple: T1  
Interlamellar Spacing: 57



**Figure 6.** Jominy test sample results of hardness for air-quenched and water-quenched conditions. The micrographs were taken at the approximate locations corresponding to the given scale and represent the microstructure in the water-quenched samples. T1–T5 are used to identify the respective thermocouple and the number below is the interlamellar spacing in nm for the identified pearlite in the respective microstructures.

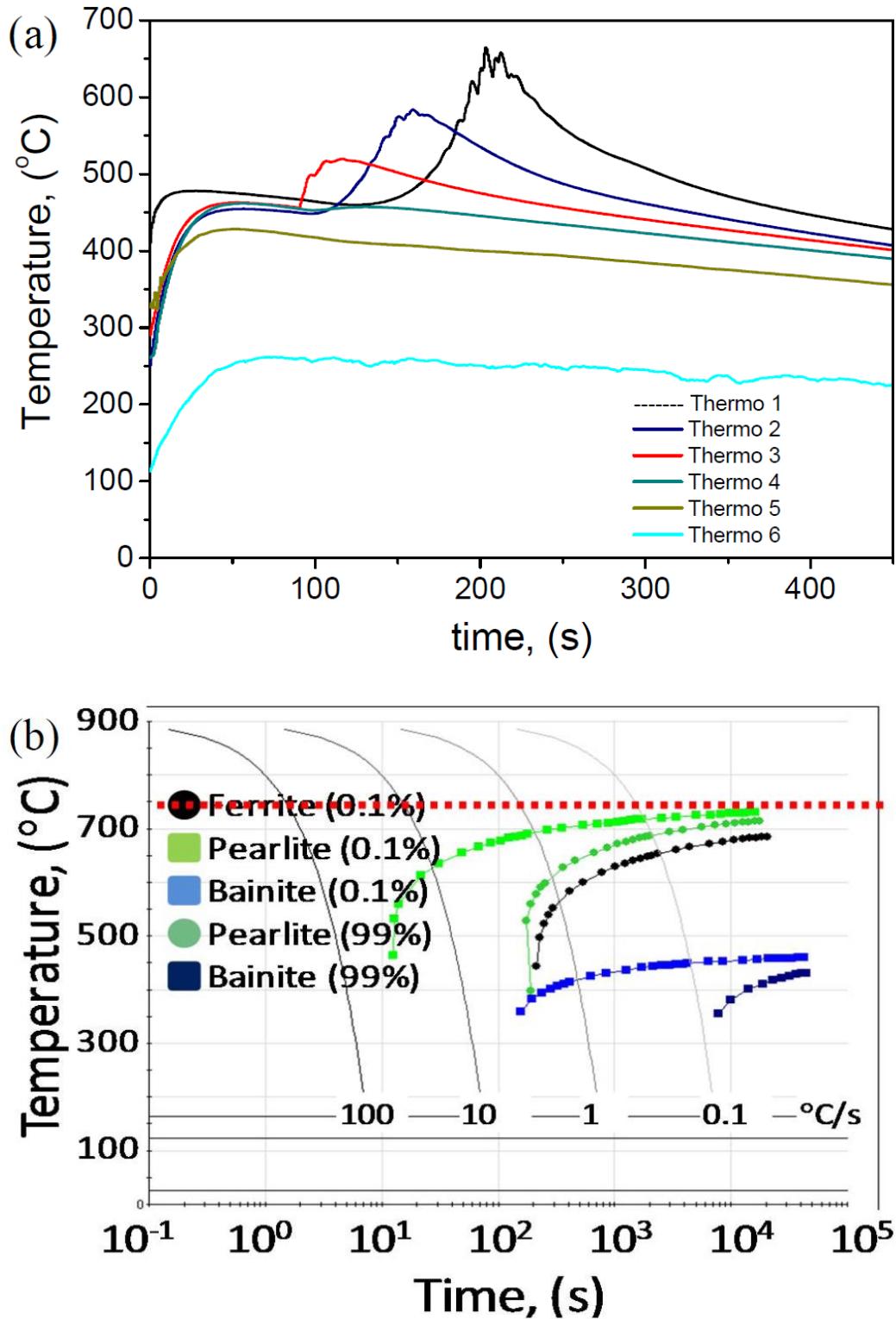
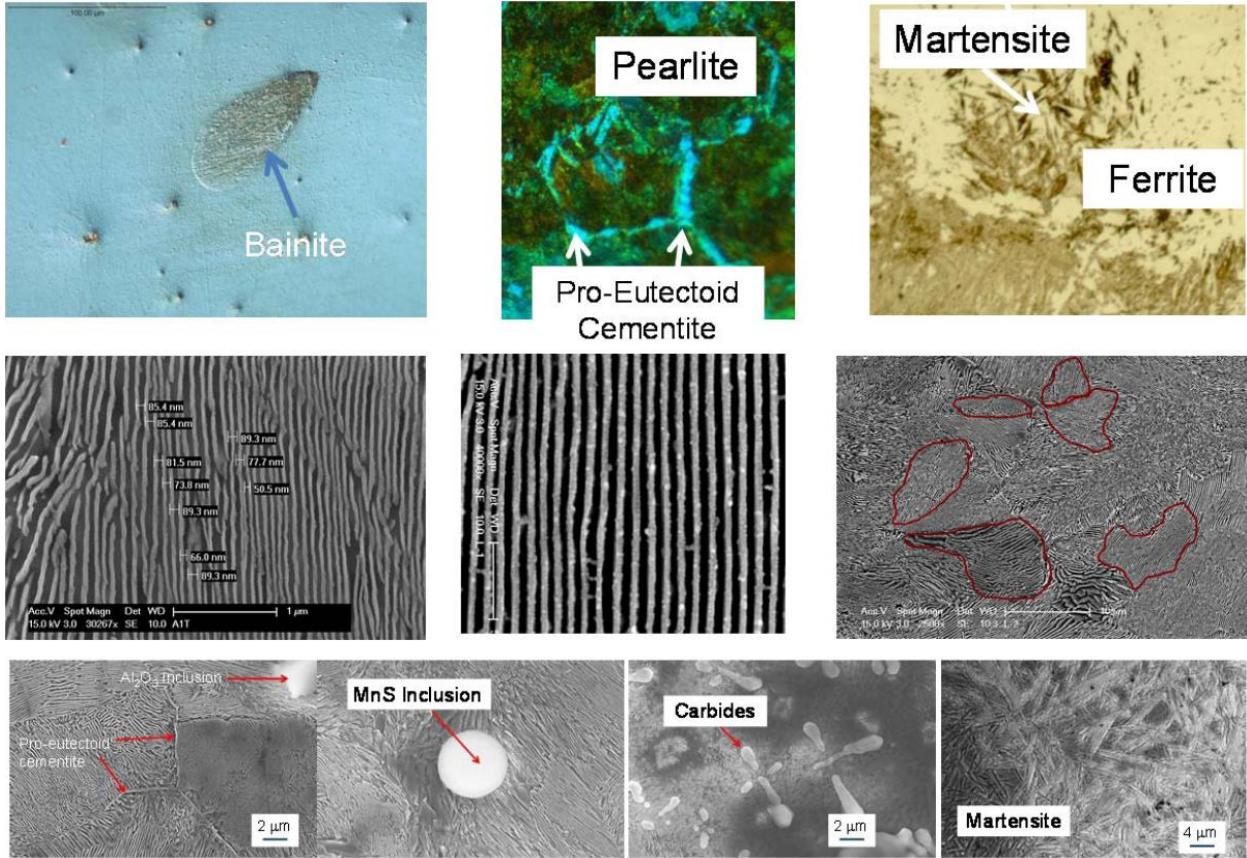


Figure 7. Thermal analysis and simulated continuous cooling diagram: (a) heating/cooling curve collected from the thermocouples connected in Figure 4c. The colors and numbers correspond to both images and (b) simulated CCT diagram for the investigated steel.



**Figure 8.** Microstructural characterization of the rail cooled at different rates. The scanning electron microscope images show further analysis including the interlamellar spacing measurements and pearlite colony size that are useful to determine empirically the mechanical properties.

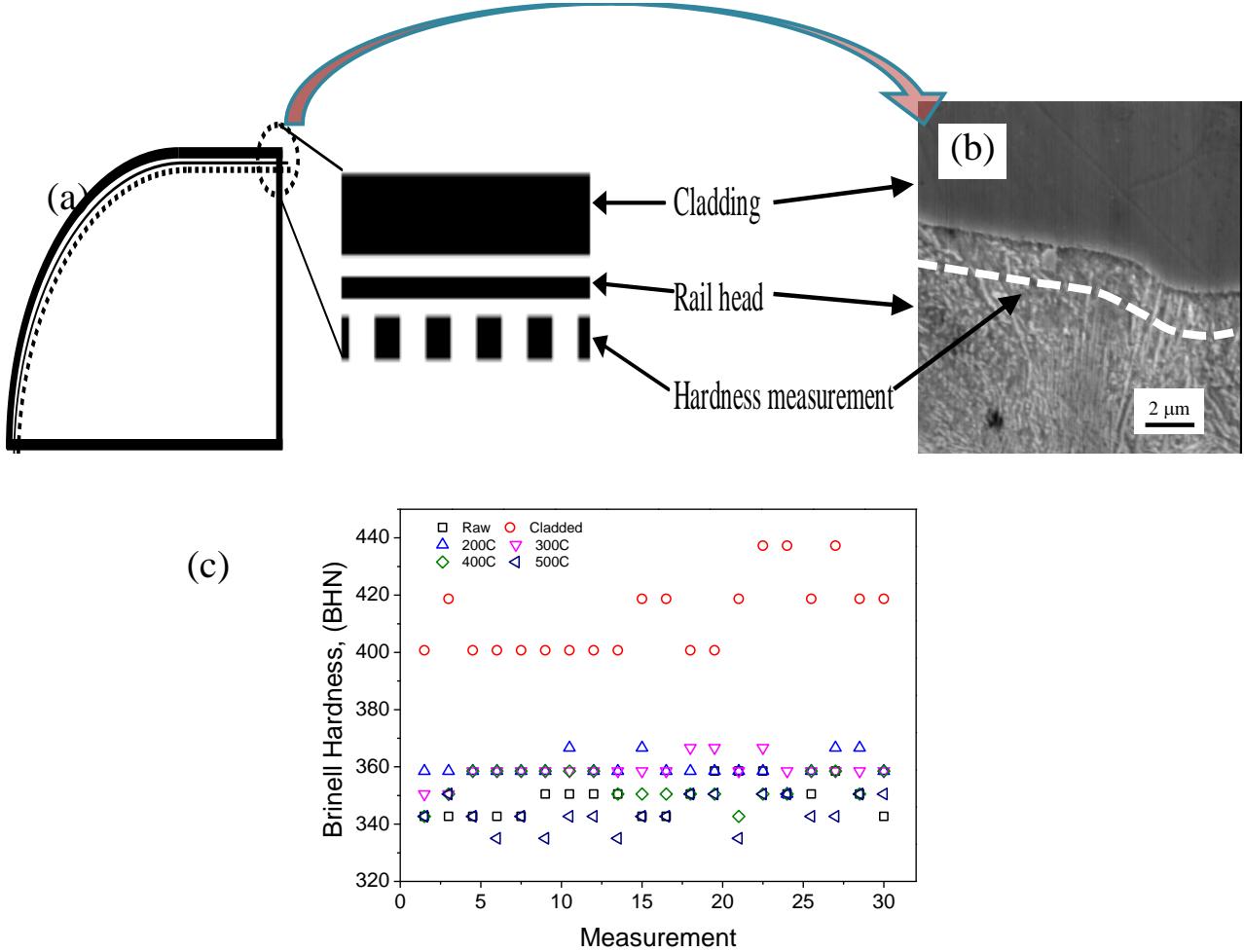
### Induction Heating

One of the techniques developed under the scope of this work was martensite prevention using post-heat treatments. In this case, we developed a rapid-tempering process to reduce the residual stresses in martensite. Ideally, this would provide the ability to control the final hardness and toughness. The post-treatment was conducted using two methods: induction and propane torch heating. The induction heating is a better alternative since it can be easily controlled; in addition, it avoids the use of open flames in the field, which is a concern for the railways.

This section reports on the preliminary design, setup, and test of an electromagnetic inductive heater on the rail/coating in support of a laser cladding post-processing treatment to prevent martensite formation. The device uses induction heating by which electrically conducting materials are heated by a non-contact method in an alternating magnetic field. Such a field induces an “Eddy current” inside the component being heated. This technique is becoming attractive for today’s manufacturing post processes. To evaluate this concept, the following components were required:

- High current transformer
- Variac

- Copper coil
- Electrical cables
- Water cooling lines
- Thermocouple sensor and meter.

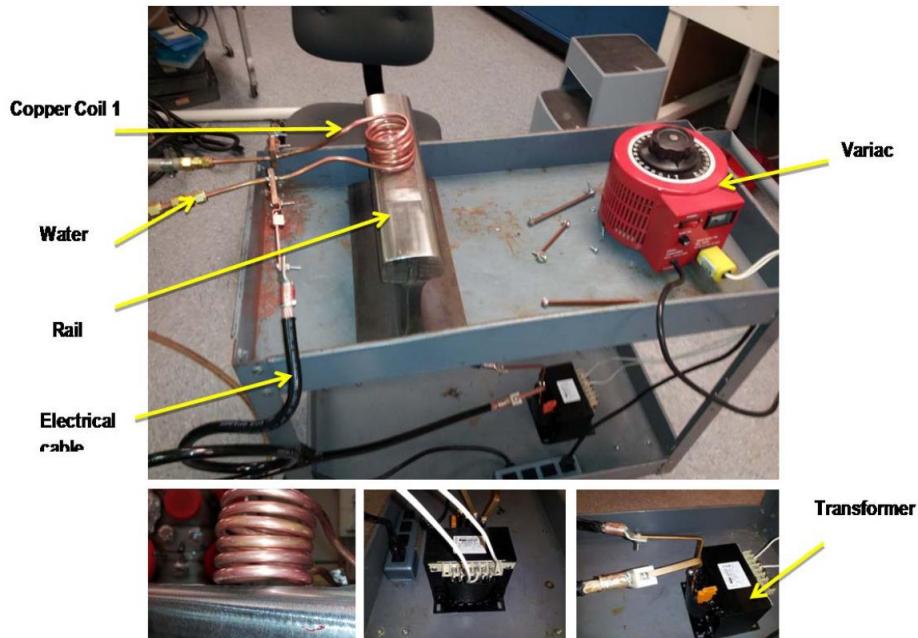


**Figure 9. Microhardness test and effect of heat treatment on hardness. (a) Sketch of the hardness testing for the laser cladded rails, (b) microstructure of the laser cladding surface showing the cladding microstructure and pearlite and (c) Experimental hardness results before and after post-treatment (martensite tempering). “Raw” identifies the commercial head hardened steel before cladding. “Cladded” is the rail after the cladding process without tempering treatment.**

The high current transformer and Variac were used as the induction power source, which provided a power output of about 1 kW to the coil assembly. A coil made of ¼ inch copper tubing was used for the electromagnetic induction generation to accommodate the large currents flowing through it. Tap water was pumped through the tube to keep the copper coil inductor cool. The high current transformer was a Sigma Transformer Co. MPI-900-10 and provided up to 90A@10V and 180A@ 5V, depending how its two secondary coils were connected. The transformer was power fed by a high-power Variac (20 A@110V, 60 Hz). Serial and parallel configurations of the MPI-900-10 secondary outputs were accomplished through jumpers made of machined and fastened copper plates.

The Variac fed the primary of the MPI-900-10 transformer at a controlled voltage up to 110 volts. The secondary of the transformer (MPI-900-10) was attached to the copper coil through silver soldered copper connectors attached to electrical cables. The copper coil was water cooled during the induction heating experiments. The experimental setup of the inductive heater is depicted in Figure 10. A current clamp meter around the coil lead measured a current of 75A at about 7 volts. Temperature of the metal bar rose rapidly to 135°C in less than 3 minutes. Increasing the voltage of the Variac to 90 volts brought the temperature to 320°C in less than 2 minutes. As seen in Figure 9, increasing the temperature to 200°C was enough to temper the martensite. From the earlier description it is clear that it is possible to temper the rails using induction heating. The disadvantage at this point is the attractive forces between the rail and coil. In future work, this could be prevented by using high temperature insulation in the coil.

The proof of this concept was demonstrated using a low frequency (60 Hz) electromagnetic signal at the inductive heater. The higher the operating frequency of the inductive heater, the closer to the surface the induced currents will concentrate and will produce relatively high-energy heat. Any further development of the laser cladding process should include an optimized induction system for in-track use. It is anticipated that induced currents in the rail/coating produce heat and when the temperature rises, the electric conductivity of the rail/coating changes. There may be a need to use a high induction power source that can provide a power output of about 3 kW to the coil assembly.

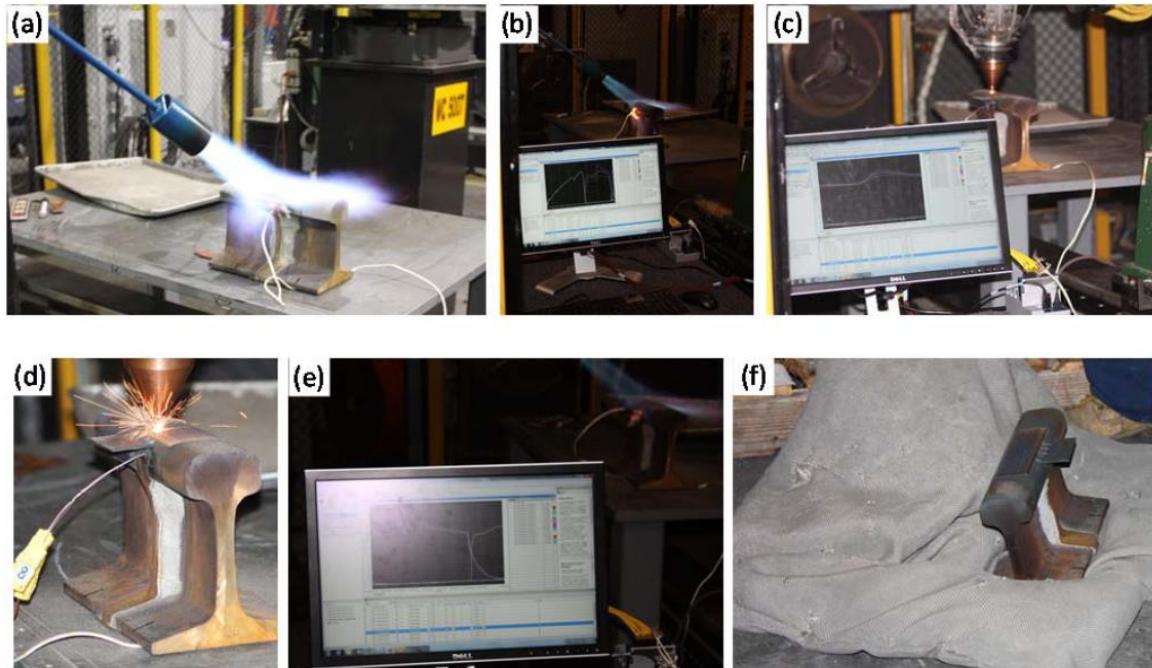


**Figure 10. Experimental setup of the inductive heater/rail.**

### Torch Heating

Torch heating is a common practice in laser cladding. The technique is shown in Figure 11a through use of a propane torch. In our experiments, we were able to preheat the rail to 600°C in approximately 10–15 minutes depending on the intensity of the flame. This was done in a laboratory environment where open flames are allowed. In other words, the

induction heating is the best method at this point, but it still needs optimization. The torch heating is presented in Figure 11, which also shows the entire laser cladding process with in situ thermal analysis to monitor the process in real time. Before the laser cladding process is conducted, the rails need to be pre-conditioned to have a clean surface free of organics (e.g., grease) and other potential contaminants that may prevent proper coating. The preconditioning can be conducted by shot blasting and, when necessary, grinding the surface.

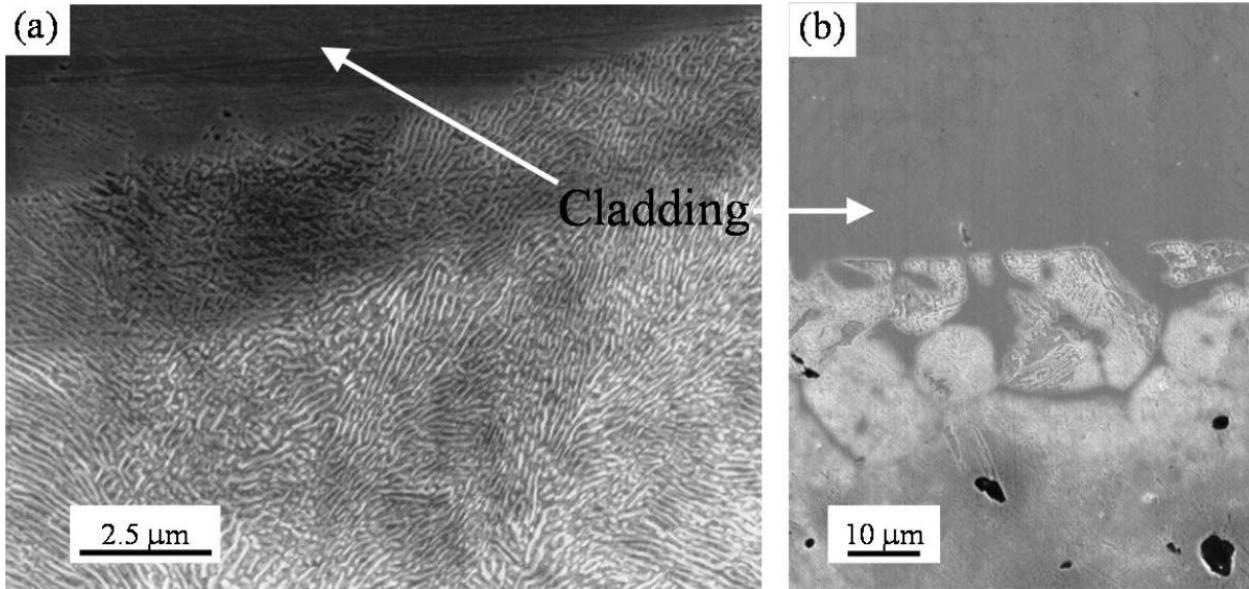


**Figure 11.** Laser cladding process: (a) propane torch preheating, (b and c) thermal analysis monitoring the preheating process, (d) the laser cladding process, (e) torch heating during cooling to prevent martensite formation, and (f) blanket for slow cooling.

### Cladding and Heat Treatment Research Summary

The heating/cooling procedure developed herein is capable of producing coatings with hardness levels in the desirable range and preventing cracking, which was one of the main problems faced in previous cladding attempts. In Figure 12a, the scanning electron micrographs of the laser cladding surface, as well as the parent material, are presented. Figure 12a shows a fully pearlitic microstructure; therefore, the heating/cooling protocol was successful. This protocol can enable the tuning of the hardness and toughness necessary to meet the recommendations specified by AREMA. In Figure 12b, the well-integrated cohesion between the coating and the parent rail is shown. The successful prevention of martensite formation was made possible by simulating the CCT diagram for the investigated steel, based on its chemical composition. The AREMA recommended practices suggest that rails should be fully pearlitic with rail head hardnesses above 430 HB. Therefore, laser cladding can be challenging because those two conditions are not easy to accomplish together. In the present work a series of laboratory, numerical, and field tests were conducted with the objective of an optimum laser cladding operation that could produce coatings with characteristics similar to those observed in premium rails. A heating/cooling protocol was developed for the coatings and welds. The main objective of this protocol was to

eliminate martensite by varying: (1) time and/or (2) temperature. The heating/cooling protocol was optimized by numerical simulations and Jominy testing to tune the hardenability of the laser cladding coatings and rail steel.



**Figure 12. Microstructures of the in situ heat-treated welds. The micrographs show**  
**(a) a fully pearlitic microstructure and (b) the near surface region showing full cohesion**  
**(b) among the cladding and steel microstructure.**

## SERVICE TESTING

Following laboratory test trials at the University of Houston, using 1 ft rails as seen in Figure 4, and once the heat treatment was optimized, service testing of samples of rail welds was conducted that were cladded using the newly developed procedure. The TTCI in Pueblo, Colorado, produced a set of six thermite-welded rails, each 6 ft in length, and each cladded using the new procedure. The rail used in this test was a recycled rail with minor damage. The welds were machined before laser cladding as seen in Figure 4a. For welds 1 and 2, this machining was not sufficient to remove the prior damage, resulting in the formation of the pores. Recycled rail is, nevertheless, representative of the rail conditions encountered in the field where laser cladding would be used.

TTCI then characterized the integrity of the cladded weld specimens by means of dye penetrants. The six welds are identified as 1 through 6 and three of them are shown in Figure 13. Each of these images is representative of a pair of welds. Figure 13a shows weld 6, which was defect-free, as was weld 4. Another set had small cracks as seen in Figure 13b (welds 3 and 5) and the last pair shows pores (welds 1 and 2). Table 3 summarizes the six cladded welds produced along with their testing history.

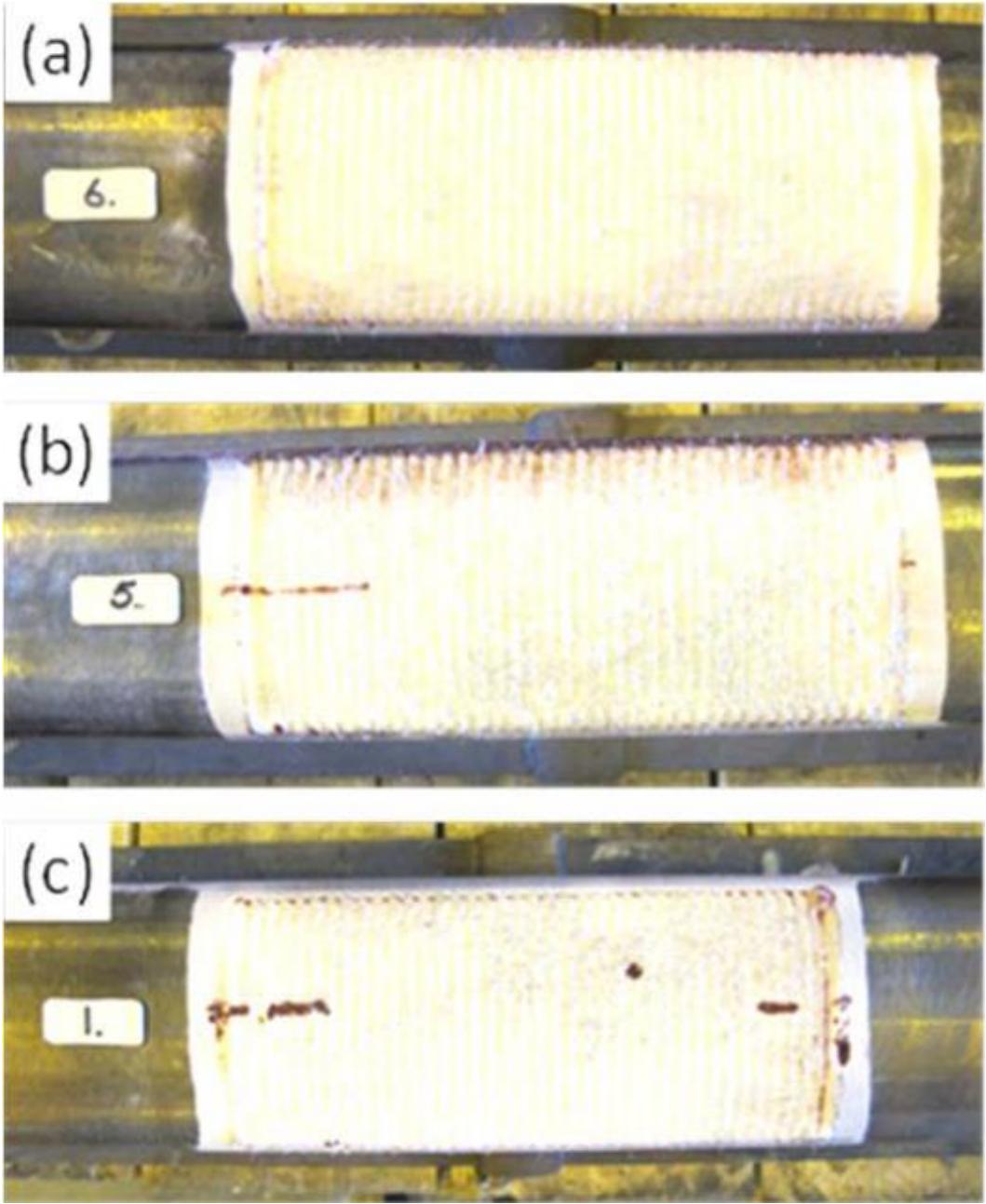
Since test welds 1 and 2 exhibited pores, they were judged to be unsuitable/unsafe for service testing. The remaining four test welds were installed in the track of TTCI's test loop, at its FAST. The train operated on the FAST track is made up of 39-ton axle load cars and achieves an average load accumulation of approximately 1.7 million gross tons per day (MGT/day) of operation. This severe operating environment accelerates the wear and dynamic impact conditions of the

rail and allows for a rapid assessment of rail life under full-service load conditions comparable to, or exceeding, heavy-haul revenue service.

The test plan called for an accumulation of 50 MGT on the four test welds. The two welds with no defects (4 and 6) were installed as a set in FAST on March 3, 2014. The other two welds were put on hold while welds 4 and 6 were monitored for performance. These two test welds were monitored daily with dye penetrants to assess their integrity. The dye penetrants clearly revealed cracks after a day of testing with an accumulated traffic of approximately 1.5 MGT. Pictures of the in-track welds are presented in Figure 14 where a network of cracks is revealed. The cracks were identified at the surface of the rails and judged to be safe, so the test continued. The welds were monitored constantly, and on April 15, 2014, the dye penetrant inspection showed that after 23.5 MGT the cracks had not expanded/or grown. Accordingly, it was decided to install the other set of two welds (3 and 5) on April 15, 2014.

On May 14, 2014, welds 3 and 4 exhibited delamination (spalling) and were removed from the track. Based on safety concerns, TTCI also removed the companion welds for each of these two welds; that is, weld 5 was removed together with weld 3, and weld 6 was removed together with weld 4. Both welds 5 and 6 were in good condition when removed. Weld 4 had accumulated 41.76 MGT before removal due to delamination, and weld 3 had accumulated 19.85 MGT before removal, also due to delamination (see Table 3).

The profile measurements of the welds after the field testing are presented in Figure 15. Weld 1, which was not installed, was used as a reference profile. The profiles were taken at TTCI with Miniprof®. The profiles for the in-track tested rails are in Figure 15a and b. Of the four welds tested at FAST, two (3 and 4) showed delamination. The first one accumulated 41.76 MGT (installed in March 3, 2014) and the second at 19.85 MGT (installed in April 15, 2014). The other two welds did not fail; however, TTCI decided to remove them due to safety concerns. The profiles of welds 5 and 6 show minor differences when compared with the reference sample weld 1 (Figure 15a). The surface of welds 5 and 6 is presented in Figure 16a, b, d, and e, where minor damage is observed with the exception of a few cracks revealed by dye penetrants. The profiles in Figure 16c and 16f are from welds 3 and 4, which were removed due to spalling or delamination, wherein the cladding detached from the rail. The actual nature of this delamination is not yet known, but we believe that it may be related to the use of recycled rail.



**Figure 13.** Dye penetrant analysis of the 6 foot welded rails. The pictures show (a) ideal condition (welds 4 and 6), (b) with a crack (welds 3 and 5), and (c) a coating with pores (welds 1 and 2).

#### Delamination Problem

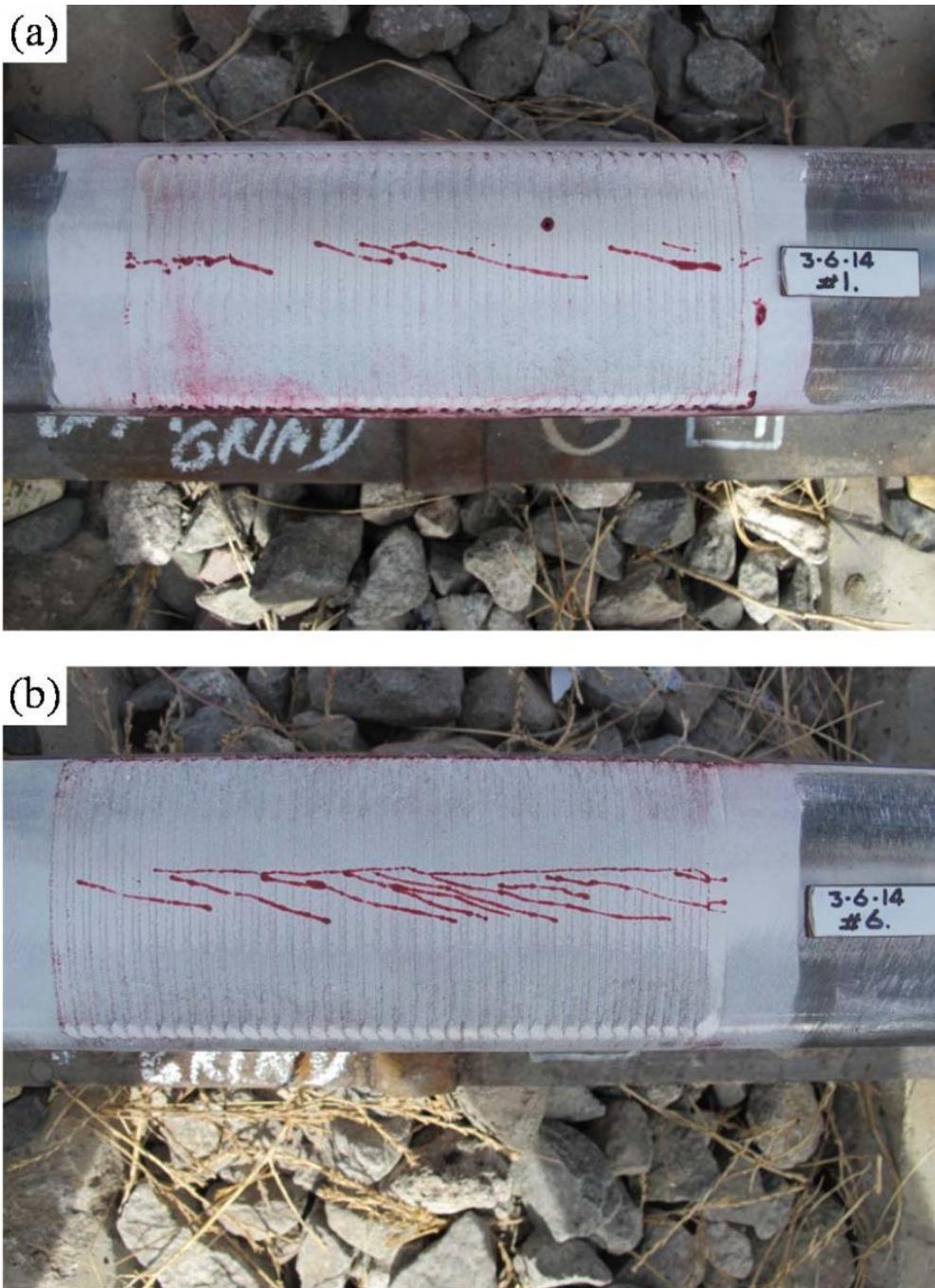
The two welds that failed during the field test (3 and 4) presented a delamination problem. This delamination is shown in Figure 16c and f. Such delamination can be the result of several factors; however, the two most common are typically untempered martensite and deep porosity or cracks. As previously mentioned, the pores, cracks, and delamination could have been the result of using recycled rail for the cladding test specimens. Any future efforts to develop a laser cladding system should, therefore, examine the effects of using used or recycled rail. Test specimens, for example, should include

cladding on new commercial grade rail, new premium rail, and used rail. As mentioned, field applications of cladding would typically be on used rail.

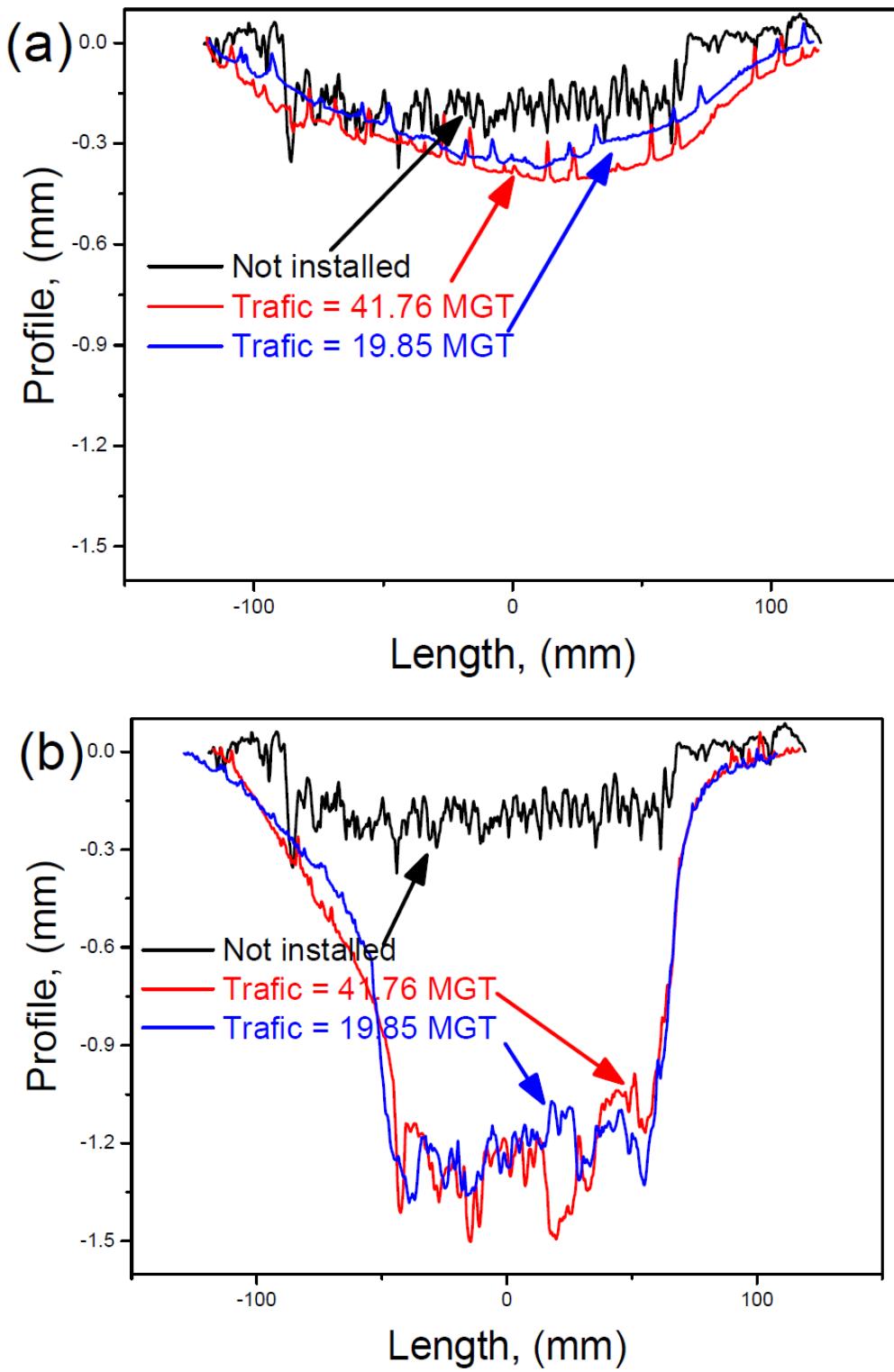
**Table 3**

**Brief Summary of the Test Welds Produced for the Testing at FAST. Welds 1 and 2 were never installed due to pores (Figure 13c), welds 4 and 6 appeared in good condition prior to testing (Figure 13a), and welds 3 and 5 showed minor cracking prior to testing (Figure 13b)**

Weld ID	Installed	Removed	Total MGT	Comments
1	N/A	N/A	N/A	Never installed due to pores in cladding
2	N/A	N/A	N/A	Never installed due to pores in cladding
3	4/15/14	5/14/14	19.85 MGT	Removed due to delamination
4	3/3/14	5/14/14	41.76 MGT	Removed due to delamination
5	4/15/14	5/14/14	19.85 MGT	Removed in good condition along with weld 3 for safety
6	3/3/14	5/14/14	41.76 MGT	Removed in good condition along with weld 4 for safety



**Figure 14.** Condition of the welds 4 and 6 installed at FAST. The dye penetrants were taken after approximately 1.5 MGT of traffic. Both welds were produced free of defects after laser cladding. Analysis conducted March 4, 2014.

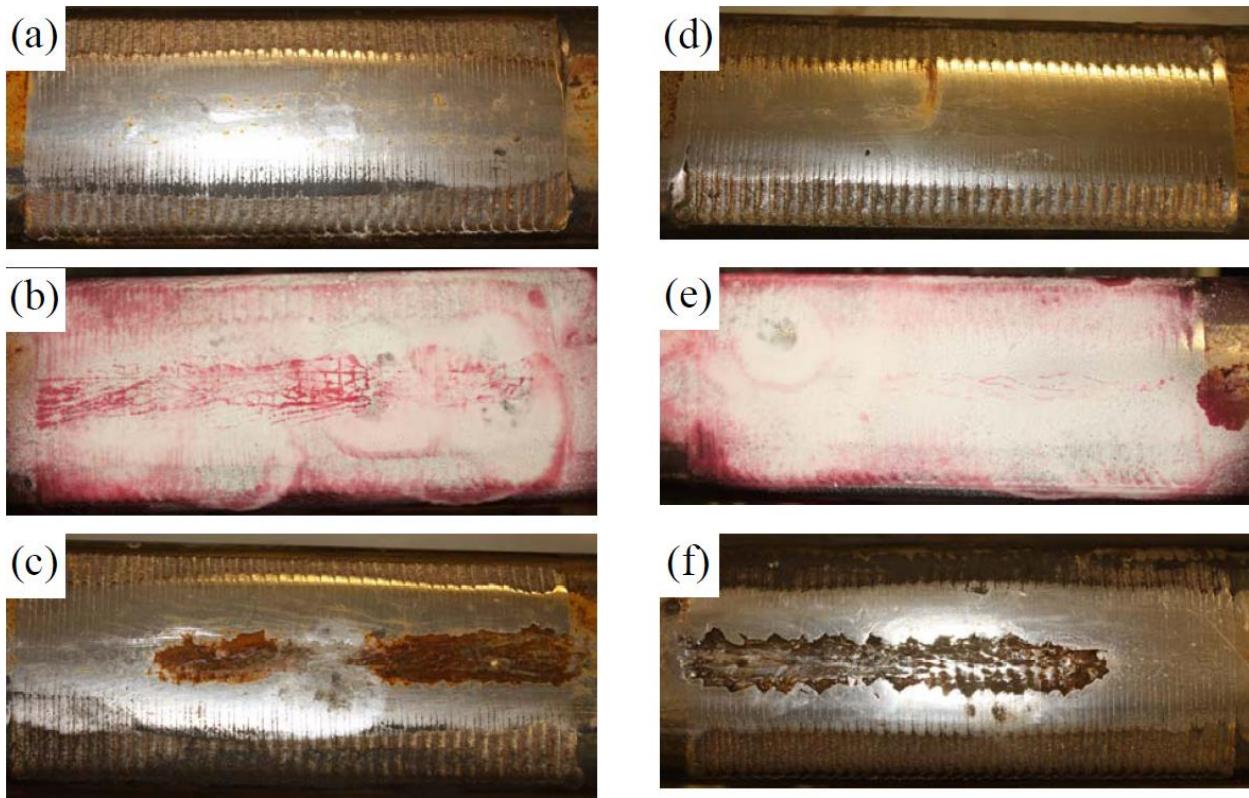


**Figure 15.** Miniprof® profiles from the cladded rails before and after the field test.

The first set of cladded welds (a) were removed but did not fail (welds 5 and 6);

the cladded welds in (b) were removed due to delamination (welds 3 and 4).

The “not installed” correspond to welds 1 and 2 and were used as a reference for profile analysis.



**Figure 16. Pictures of field-tested cladded welds at FAST after their removal.**

The welds in a, b, and c were tested for 41.75 MGT and the welds in d, e, and f were tested for 19.85 MGT. Welds a, b, d, and e were removed from test without apparent damage other than small cracking and safety concerns. Welds c and f were removed due to delamination.

## FINDINGS AND CONCLUSIONS

Laser cladding is a technique that has the potential to prevent the plastic deformation or batter that can occur along the heat affected zone on rail welds (particularly thermite welds) in service. This would result in a reduction of weld failures and lower the need for weld removal due to plastic deformation or cracking. Past attempts to extend the life of thermite welds using laser-based coatings or glazing were unsuccessful as a result, in part, to cracking of the cladding and poor toughness (resistance to fracture) because of the presence of martensite. In this project, this cracking problem was solved through the development of a new heating/cooling protocol incorporated into the laser cladding procedure. A major accomplishment of this project was to determine the exact heat treatment conditions needed to prevent martensite, or to avoid this phase altogether during cooling.

Although the cracking problem was solved, the field testing revealed other problems. Two of the four laser cladded test welds experienced delamination when subjected to heavy axle loadings in FAST after only 20 and 42 MGT. Thermite welds at FAST have an average life expectancy of 120 to 130 MGT. In revenue service, thermite weld life can range from 200 to 500 MGT. Accordingly, substantial improvements in laser cladding technology will be necessary

before it can be considered for revenue service. Such improvements include an automated induction heating system to control the temperature of the rail within specified ranges.

The welds tested in this study were laser cladded in a shop environment. To be practical, however, cladding will need to be applied to thermite welds in the field. Field cladding could likely be applied immediately after a field weld is cast, when it is still relatively hot, allowing for a slow cooling and taking advantage of the rail preheating applied prior to the pouring of the thermite weld. This will require additional research to develop a portable cladding process; for example, truck or Hi-Rail-mounted, suitable for in-track service. Components of this portable system would include a robotic control system, CNC lathe, and laser(s).

Another potential application of laser cladding is temporary rail repairs in cold weather. Welds have a propensity to break during cold weather (e.g., winter in the northern United States and Canada); unfortunately, their replacement in cold weather builds up residual stresses in the track, compromising its integrity. As a result, welds with major damage (e.g., batter) are often removed and replaced with a joint bar that has to be replaced when the temperature increases (spring or summer), incurring further cost and compromising the integrity of the track. Instead, assuming the problems identified in this project are resolved, laser cladding could be applied to temporarily extend the weld's life until it can be replaced in warmer weather.

Further development of the laser cladding process will need to address the delamination problem revealed in this project. This problem is likely caused by several factors, primarily inadequate rail surface cleanliness, pre-existing cracks, inadequate pre-heating of the rail prior to laser cladding, and precipitation of unwelcome phases (e.g., martensite) due to improper cooling. Accordingly, further research on laser cladding should include the development of procedures to reduce or eliminate the effects of these factors.

Rail surface cleanliness: A procedure should be developed to clean the rail surface prior to laser cladding. The surface of the rail must be cleaned to remove any grease and oil to prevent potential defects along the cladding coating.

Pre-existing crack removal: A grinding procedure to remove all cracks in the rail should be identified or developed. This procedure could be based on general rail-grinding practices (e.g., AREMA). If those general practices are determined to be inadequate, then a new practice would need to be developed based on laboratory work where the rail surface is monitored by non-destructive (ultrasonic) and destructive testing (e.g., metallography).

Preheating of the rail: For the preheating of the rail prior to cladding, it will be necessary to develop a procedure similar to that conducted for thermite welds. This preheating should result in a temperature such that the energy from the laser is sufficient to achieve a proper melting of the surface of the rail. The mechanical characteristics of the rail interface, including the heat affected zone, must comply with rail characteristics already existing in the recommended practices (e.g., AREMA). This procedure should be based on laboratory work, such as mechanical testing (e.g. micro-hardness, and toughness) and metallography.

Precipitation of unwelcome phases: Both preheating and cooling procedures should be developed that prevent the formation of unwelcome phases, such as martensite. One approach could be the simulation of alternative cooling procedures using metallurgical software to understand the cooling path necessary to avoid martensite and, potentially, bainite. Ideally, the microstructure should meet AREMA specifications (fully pearlitic). In addition, to make sure that no untempered martensite is present in the area of the rail to be cladded, a post-treatment (tempering) procedure could be developed. Preliminary laboratory work demonstrated that temperatures as low as 300°C for 10 min are enough to temper martensite.

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