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Research Results

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Fracture and Fatigue Evaluation of Slot-Welded Railhead Repairs

SUMMARY

Slot welding is a new method that can be used to repair defects that may be present in the head of the rail. In this method, instead of using a plug rail as is done in all other defect removal techniques, the defect is removed from the railhead via machining a perpendicular slot containing the defect. The slot is then heated to a specified temperature. Once the rail reaches the desired temperature, the slot is filled using gas metal arc welding (GMAW). Any excess weld material is then ground to conform to the contour of the railhead. Based on encouraging results of this project's preliminary work, the goal of the current effort is to perfect this welding process.

Pearlitic rail sections, approximately 1 foot long, were provided by Transportation Technology Center, Inc. (TTCI) were used. Two slots were milled in the railhead, each 1 inch wide by 0.75 inch deep, and 2.5 inches from either sides of the rail. GMAW was performed to fill the slots. Electrical discharge machining (EDM) was then used to slice samples parallel to the railhead that was 6 inches long, 0.75 inch wide and 0.08 inch thick. Hardness tests were then performed on these samples. Preliminary mechanical and fatigue tests were performed to study the weld's integrity. Fatigue experiments were performed on unnotched samples to identify the failure behavior of the welded joints. Optical microstructures of different sections of the welded railhead were captured.

Finite element analysis was performed on the rail before and during the welding process as shown in Figure 1. From this analysis, it was deduced that the size of the heat affected zone (HAZ) and fusion zone would be approximately 15 mm and 5 mm respectively. There was a strength and hardness mismatch between the rail and the weld metal. The yield strength of the rail and weld were 850 and 620MPa, while the Brinell hardness was 325 and 264 respectively. The low hardness of the weld is explained by its optical microstructure that consists of mainly ferrite which is known for being soft. In an attempt to increase the hardness of the weld, heat treatment was applied to the rail, which increased the weld's Brinell hardness from 264 to 280.

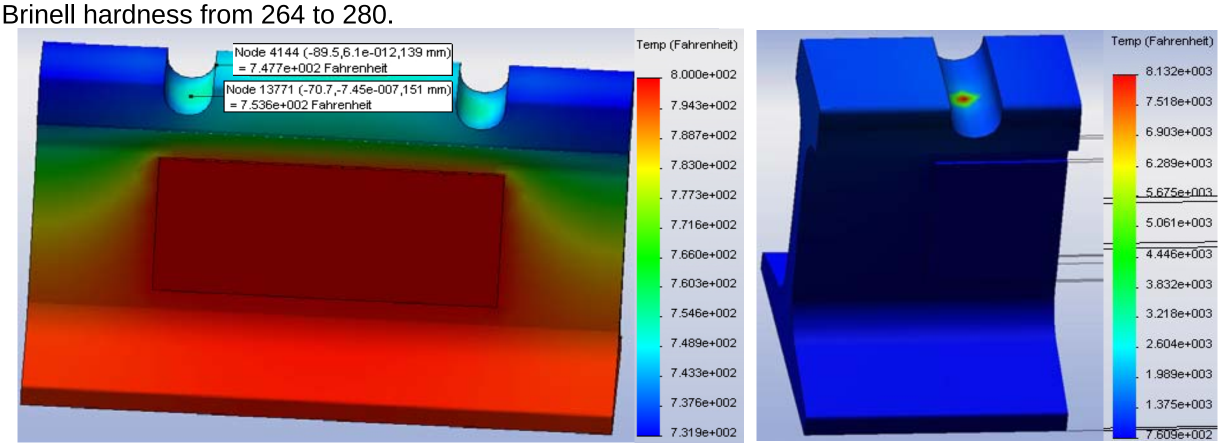


Figure 1: Diagram of heat distribution before welding (left-1a) and during welding (right-1b)

BACKGROUND

The main techniques used in welding of rails include thermite, flash-butt, and gas pressure arc welding. All three methods, when used to remove defects, involve cutting out the defect in a 20-foot piece of rail and welding a new plug rail. This method introduces two new welds that may be potential for new defects.

In the current work, the slot welding process is proposed as an alternative to removing defects found in the railhead. In this method, early detection of the defect is imperative, as the defect needs to be removed before it propagates to the rail web [1]. The defect is detected by a non-destructive testing method and once found it is removed from the railhead by grinding. This method allows the web and base of the rail to remain untouched and intact [2]. The slot is then filled using the GMAW process and any excess material is grinded from the rail. When compared to the other types of welds, slot welding allows for the least amount of defects due to the size of the welded area; it should also possess higher mechanical properties as the web and base of the rail remain unmodified.

Finite element analysis (FEA) was performed on the rail to determine the width of the HAZ and fusion zone. Preliminary mechanical and fatigue testing were also performed on rail samples sliced from the rail using EDM.

REPRESENTIVE RESULTS

Rail Geometry and Boundary Condition

The length of the rail provided by the Transportation Technology Center, Inc. (TTCI) was approximately 12 inches long. Two slots, each 1 inch wide and 0.75 inch deep, were removed. Two heat strips having dimensions of 7 inches long by 1.5 inches wide were placed on both sides of the rail web in the center of the longitudinal direction.

Finite Element Analysis (FEA) Calculations

FEA was used to study the heat transfer of the rail steel before and during the slot welding process. A temperature of 800° F was applied to the web of the rail and the heat flux of the heaters was calculated from the following equation:

$$\text{Heat flux} = \frac{Q}{A}$$

Where Q is the amount of heat transferred and A is the area of the heating surface. The heat flux of each electrical strip heater was found to be 36.93 KW/m^2.

The boundary conditions that were used in the thermal analysis of the rail steel includes: that the web and base of the rail were considered as adiabatic because an insulation of ceramic fiber was used to help prevent loss of heat, and that the head of the rail was considered as undergoing convection as it will be open to the surrounding. The ambient temperature used for this analysis was 80° F and the value for convection was calculated using the equation below.

$$h = \frac{NuK}{L}$$

Where h is the convective heat transfer coefficient, Nu is the Nusselt number, K is the thermal conductivity and L is the average characteristic length of the railhead top surface represented as a square. From the calculation, it was found that the convective heat transfer coefficient of the rail is 10.26 W/m^2 K.

Pre-Welding

All the boundary conditions mentioned above were used in the pre-welding analysis of the rail. The finite element analysis obtained from these conditions is shown in Figure 1a. From this plot, it can be seen that there is an insignificant difference in the temperature distribution in the rail, as the highest temperature is 800° F and the lowest is 731.9° F. This demonstrates that the heaters are very efficient in heating the slots to the desired temperature.

During Welding

In this simulation, during welding, all the boundary conditions that were applied previously were applied again with the inclusion of the welding arc applying a heat of 8130° F. This heat was applied to a small circular location at the bottom of the slot, which was indicative of a weld bead. The temperature profile at the welding arc to the center of the electrical strip heater was studied to understand the temperature distribution of the arc on the rail and is shown in Figure 2, with the temperature taken every 5 mm beginning from the bottom of the slot.

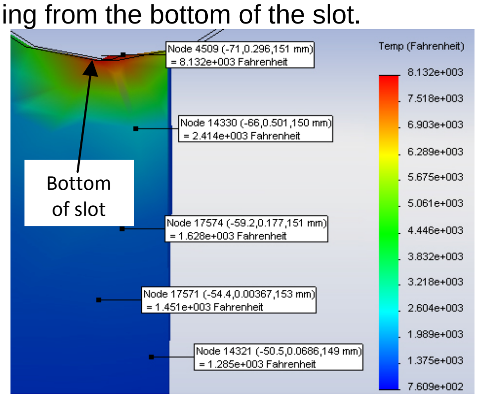


Figure 2: Heat distribution during welding

The phase diagram of iron-carbon system is shown in Figure 3 and the line labeled RA shows the carbon content of the rail that is being studied. From the diagram, the temperature of 1333° F indicates where the HAZ would start, as this is the temperature that the microstructure of the material changes. From Figure 2, it is shown that the width of the HAZ would be approximately 15 mm. It can also be seen from the phase diagram that once the temperature reaches 2630° F, all of the metal becomes liquid. This also illustrates where the fusion would start, and the corresponding temperature is approximately at 5 mm, which shows that the rail should be properly fused with the weld metal.

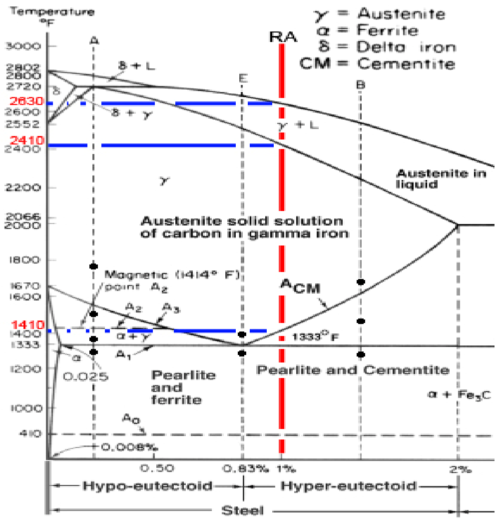


Figure 3: Iron-Carbon phase diagram

Welding Process

When performing the actual experiment, the rail was placed in a box, which contained ceramic fiber as insulation and was then heated to 800° F. The slot was then filled using the GMAW process. When selecting the welding wire, the strength of the filler metal and rail were matched. The yield strength of the rail is approximately 850 MPa and the most comparable wire that matched these strengths was the Super Arc LA-100, which is manufactured by Lincoln Electric and has as-welded yield strength of 807 MPa.

Mechanical Properties Relationships

The stress-strain relationship of the welded and unwelded rail steel is shown in Figure 4. It can be seen that both the yield and ultimate tensile strength of the unwelded rail steel is higher than that of the welded steel. With the yield strength of the unwelded and welded rail being 850 and 620 MPa, respectively, and the ultimate tensile strength of the unwelded and welded rail being 950 and 730 MPa, respectively. All welded samples tested failed at the fusion line, which indicates that there wasn't proper fusion between the weld and the parent rail.

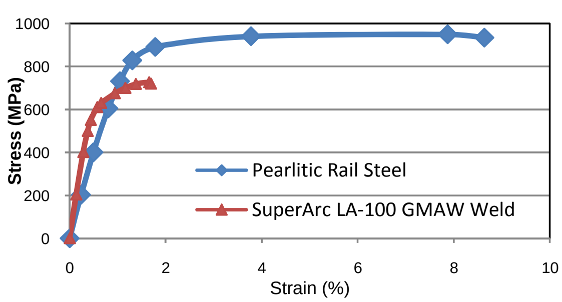


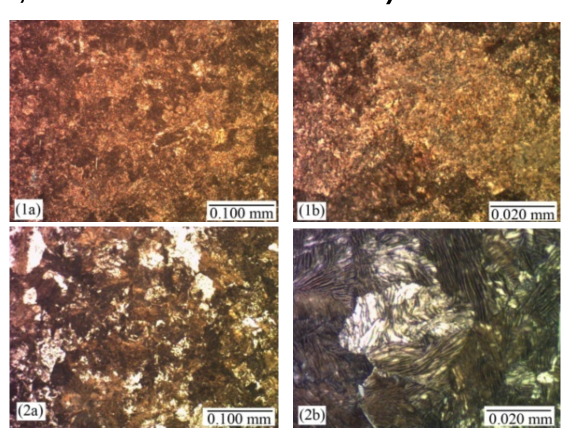
Figure 4: Stress- Strain relationship of welded and un-welded rail steel

The Brinell hardness of the middle of the rail and the welded area were measured and found to be 325 and 264 HB, respectively. The rail was heat treated in an attempt to harden the welded area. It was observed that after heat treatment the hardness of the rail did not change but there was a slight increase of 6 percent in the hardness of the weld.

Optical Microstructure

The optical microstructure of the parent rail was studied. The section of the sample where the microstructure was taken is shown in Figure 5. The micrographs labeled (1a) and (1b) in Figure 6 are the parent rail at 20X and 100X, respectively. From these micrographs, it is shown that the parent material consists of very fine pearlite. The micrographs labeled (2a) and (2b), show that the microstructure of the HAZ has been altered during welding as its' appearance is different from that of the parent rail. The HAZ contains a structure of coarse pearlite. Pearlite is a mixture of alternate strips of ferrite and cementite in a single grain. The fusion zone of the weld shown in the micrographs (3a) and (3b) of Figure 6 consists of the welded area to the top and the HAZ at the bottom of the image. The change in the microstructure from the HAZ to the weld can be clearly seen and it is observed that the grain size of the weld is much smaller than that of the HAZ. The optical micrographs of (4a) and (4b) reveal that the metallurgy of the weld is different from the parent material. The weld material consists of a lower acicular ferrite plate structure containing small amounts of cementite. The dark regions between the ferrite consist of mainly martensite. This micrograph containing mostly ferrite and small amounts of cementite and martensite explains the hardness of the weld, as ferrite is soft while martensite and cementite are hard.

Figure 5: Test specimen indicating the locations of the microstructural analysis. Each number corresponds to the section of the rail that optical micrographs were taken and is used to label the micrographs in Figure 6. (1 – Parent material, 2 – HAZ, 3 – fusion zone and 4 - weld)



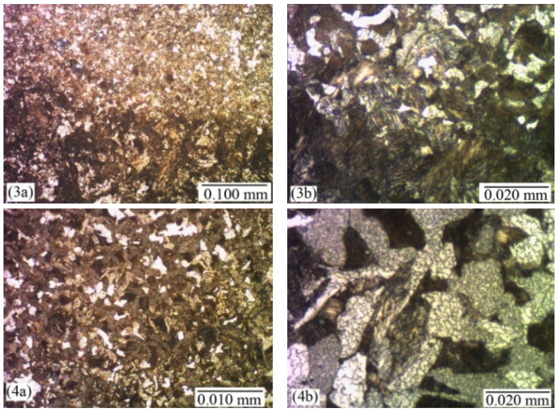


Figure 6: Micrograph at (a) 20X and (b) 100X with the numbers representing the section of the rail steel sample being studied as seen in Figure 5.

Fatigue Testing

Fatigue study of the slot-welded samples will provide a better understanding of how the welded rail will withstand cyclic loading during service. During preliminary fatigue tests of the unnotched slot-welded rail steels, it was observed that the samples failed at the fusion line. This was similar to the tensile tests, which indicate that the fusion between the rail and weld metal is the weak point. This problem, as stated before, may be a cause of inappropriate heat input. The hysteresis loop of the unnotched welded pearlitic steel is shown in Figure 7. The first loop to the left represents the early stage of fatigue, where the damage to the material is small. As the specimen undergoes more cyclic loading, the area of the loops evolved and the intensity of the damage increased. This is clear from the loop to the right which has the highest number of cycles. Thus, the fatigue failure of the slot-welded rail steel samples occurs due to damage accumulation and evolution.

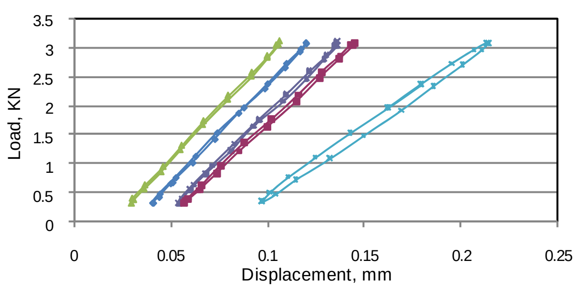


Figure 7: Hysteresis loop of slot-welded rail steel sample, showing their evolution as the number of cyclic loading increases.

Slot-Weld Challenges

Testing and evaluation of slot welds revealed the apparent challenges which include: 1) lack of fusion, 2) porosity, 3) hardness mismatch and 4) mechanical properties mismatch. To minimize some of these challenges, a higher heat input will be used to allow for better fusion between the weld metal and the rail. The cooling rate of the heaters will be lowered to allow sufficient time for hydrogen and other gases to diffuse from the weld. Heat treatment of the weld will also be applied. These parameters need to be optimized and are currently being addressed.

CONCLUSIONS

FEA performed on pearlitic rail steels concluded that the size of the HAZ and fusion zone should be approximately 15 mm and 5 mm, respectively.

Tensile and fatigue tests showed that the welded samples failed at the fusion line which indicates that fusion between the parent metal and the filler metal was not sufficient. Therefore, the heat input and cooling rate need to be adjusted in order to have a proper fusion between the weld and the rail. The strength and hardness of the rail was slightly higher than that of the weld. The low hardness of weld is manifested in its microstructure, which mainly consists of ferrite. It was also concluded that heat treatment may be performed to increase the hardness of the weld.

REFERENCES

1. Judge, T., *Rail welding market heating up*, Railway Track and Structures, July 2005
2. Kristan, J., *Railhead repair by gas metal arc robotic slot welding: an evaluation of newly-developed technology,* Railway Track and Structures, February 2005.

ACKNOWLEDGEMENTS

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