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Ultrasonic Impact Treatment of Thermite Rail Welds

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The research described was performed by Transportation Technology Center, Inc., a wholly owned subsidiary of the Association of American Railroads.

Key Findings:

- By some estimates, 90 percent of thermite rail weld failures in revenue service are caused by fatigue cracks that form in the lower web and base region of the weldment.
- In full-scale laboratory tests, UIT applied to the surface of the rail at the edge of the weld collar of thermite rail welds showed a substantial improvement in the fatigue life of the welds in the lower web and base region of the rail.
- In tests under heavy axle load train operations at FAST, 100 new and existing thermite welds treated with UIT have accumulated an average of 190 MGT to date. No fatigue failures in the treated zones have been observed.
- Revenue service tests of thermite rail welds with UIT began April 2021.

As part of the Strategic Research Initiatives (SRI) program funded by the Association of American Railroads (AAR), TTCI has been investigating methods to enhance the performance and integrity of rail welds. This report describes the results from the use of Ultrasonic Impact Treatment (UIT) technology on thermite rail welds.

FATIGUE BEHAVIOR OF THERMITE WELDED RAIL

Figure 1 shows a thermite rail weld specimen that failed after it was subjected to fatigue loading in a laboratory.

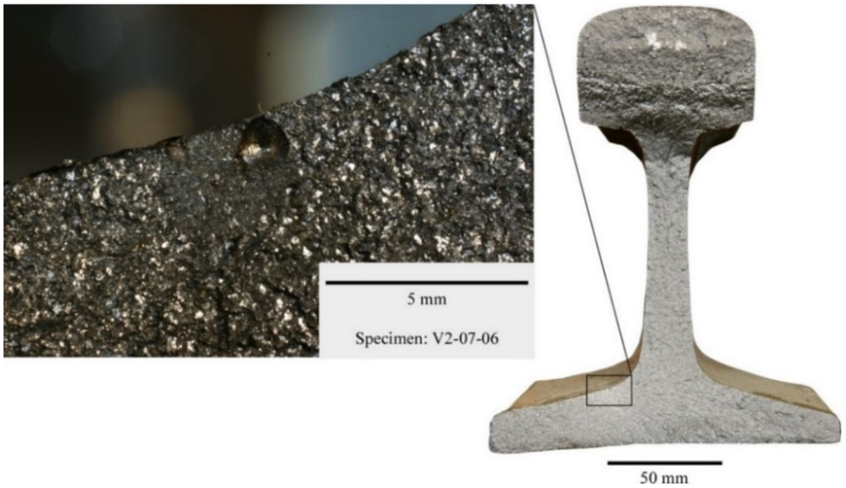

Figure 1. Photograph of a thermite rail weld fatigue specimen.

The inset macrograph in Figure 1 exposes an imperfection that was present at the base toe of the web to base fillet. The imperfection was located in the fusion zone of the weld immediately adjacent to the edge of the collar of the thermite weld. As seen in Figure 1, a fatigue defect originated at and grew around this imperfection and then propagated as a thumbnail crack until the defect reached an unstable size, triggering the failure of the weldment.

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This mode of failure, often observed in revenue service, was common to other specimens in the fatigue testing program described below. By some estimates, 90 percent of thermite rail weld failures in revenue service are caused by fatigue cracks that form in the lower web and base region of the weldment.[1]

FATIGUE DEMAND IN THE RAIL BASE

There are two important features often associated with thermite weld failures. First, the location of the fracture origin is often localized at the edge of the weld collar near the web-to-base fillet. Second, the final fast fracture is the result of the unstable growth of a fatigue crack that has initiated and has begun propagating.

The initial fatigue crack and the edge of the weld collar are linked from a stress analysis point of view. The fatigue crack results from accumulated cycles of applied stress range in the rail base, and the edge of the weld collar is a geometric stress riser. Figure 2 shows a rendering of a three-dimensional, nonlinear model of a thermite rail weld under a rolling wheel.

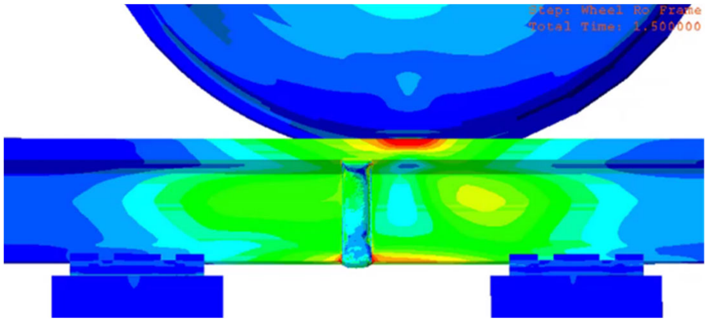

Figure 2. Rendering of a 3D, nonlinear computational model of a thermite rail weld under a rolling wheel.

In the rail base, the stresses are roughly uniaxial, and the stress range is the arithmetic difference between the maximum applied stress, which can be tensile directly beneath a wheel, and the minimum applied stress, which can be compressive between the axle and truck centers. Figure 3 shows a plot of the computed stress history in the rail base at the edge of a thermite weld collar. Under 36 kip wheel loads, the maximum applied stress is roughly 12 ksi and the minimum applied stress is roughly –4 ksi, yielding an applied stress range of 16 ksi.

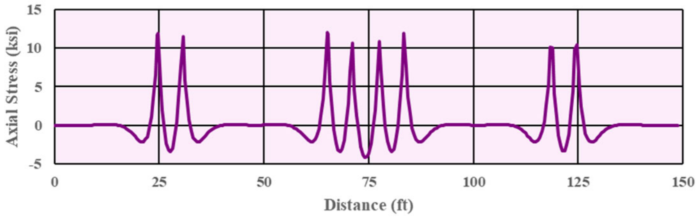

Figure 3. Plot of applied axial stress in the rail base at the edge of a thermite weld collar—results from a 3D, nonlinear computational model. Each wheel passage causes a full stress-range cycle.

ULTRASONIC IMPACT TREATMENT OF WELDS

Empirically, it is often observed that the number of stress cycles needed to initiate a fatigue crack in steel correlates exponentially with the magnitude of the applied stress range—roughly to the power of three for many structural alloys. In such a case, if the stress range at a critical location in a steel component can be halved, the expected fatigue life will increase by a factor of 8. This fact has motivated several developments aimed at changing the post-manufacture stress state of steel components to a more favorable disposition in terms of fatigue resistance.

Various techniques, including peening and autofrettage, used for mechanically upsetting steel components to induce favorable compressive residual stresses have been used successfully for decades. With these techniques, a loading that plastically deforms the steel locally within a surrounding elastic region is introduced. Using this method, the elastic region "pushes back" against the plastically deformed region, creating compressive residual stresses in the plastic zone and tensile residual stresses in the neighboring elastic region. The objective is the creation of a lens of compressive residual stresses within a local area that would otherwise be prone to fatigue damage accelerated by geometric stress risers or locked-in tensile residual stresses from manufacturing.

The last two decades have witnessed the improvement and widespread deployment of ultrasonic impulse drivers to actuate small, hard steel pins as a means of peening local, fatigue-sensitive zones of structural welds.[2–4] The technique is referred to as Ultrasonic Impact Treatment, or UIT. The fatigue localization associated with thermite rail welds presents as a strong candidate application method for UIT.

LABORATORY FATIGUE TESTS OF RAIL WELDS AND UNWELDED RAIL

Figure 4 shows a schematic drawing and a photograph of a "four-point" bending fixture and a rail configuration used in a fatigue testing program aimed at investigating the effectiveness of UIT on thermite rail welds. The rail was 136RE cut to a 4-foot length. The base of each specimen was supported on roller bearings spaced 39 inches apart. A pulsating load, i.e., zero to maximum, was applied to the head of the rail through two roller bearings spaced 6 inches apart. In this manner, the rail was subjected to a bending moment that generated tensile stresses in the base. This was done to simulate the major features of the loading cycle experienced by a rail under a rolling load from passing train wheels (Figure 3).

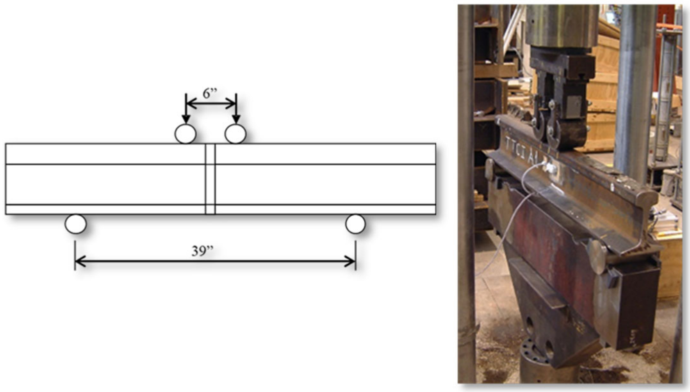

Figure 4. Schematic drawing of rail fatigue test configuration and photograph of specimen during testing.

The maximum controllable frequency of the applied load during the test was 2.5 Hz applied as a sine wave. Applied load magnitudes were selected to remain well below the proportional limit of the rail steel. The load magnitudes were high enough, however, to generate test results in both a scientifically correct and an efficient manner in terms of time and cost. A range of peak load values was selected to establish trend lines that would illustrate the relative fatigue behavior among the various rail specimens. The purpose of the tests was to generate controlled data that would facilitate a comparison among weld types as well as establish the limiting maximum expected performance associated with an unwelded rail.

Figure 5 shows a plot of the results from 26 tests: 8 thermite welds (yellow), 8 electric flash butt welds (blue), 5 UIT thermite welds (red), and 5 unwelded rails (black). As is customary for the presentation of fatigue data, the axes of the plot are drawn to a log-log scale. The horizontal axis represents the number of cycles to failure for each specimen. The vertical axis represents the magnitude of the total load applied to each specimen. For each specimen group, a mean trend line is indicated as well as an envelope around the mean trend line. The envelopes are computed assuming normal distributions, and they indicate an estimated 90 percent probability that an envelope will contain the mean trend line for its associated group .

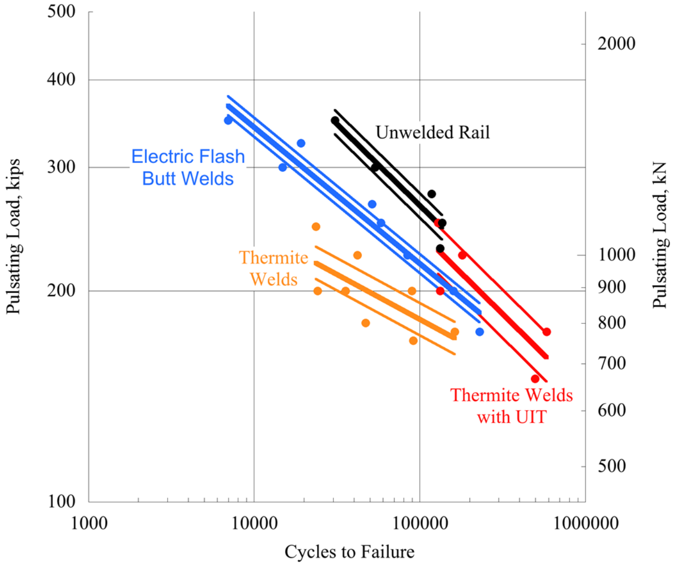

Figure 5. Fatigue test data from laboratory tests of full-scale specimens of unwelded rail and rail welds.

Considering the trends and envelopes associated with the thermite welds, the electric flash butt welds, and the unwelded rail, the results are as expected. There is clear separation among three groups with the unwelded rail performing the best, followed by the electric flash butt welds, and ending with the thermite welds representing the lowest performing group among the three. In terms of variability, the results are also consistent with expectations—the thermite welds exhibit the highest variability among the three groups.

The UIT thermite weld group is ranked second among the four, fitting into the space between the unwelded rail and the electric flash butt welds. This is a marked improvement in the mean-trend behavior over the standard thermite welds. The variability of the UIT thermite welds, however, was nearly identical to that of the standard thermite welds.

It is worth emphasizing, once again, that these tests were meant to exercise the rail base, as this is a predominant failure mode observed with thermite rail welds.[1] These tests were not relevant to the fatigue behavior of the rail head that exhibits surficial rolling contact damage, as well as subsurface shelling, transverse defects, detail fractures, etc.

TESTS OF THERMITE WELDS AT FAST

Given the encouraging results from the laboratory tests, the UIT process has been applied to more than 100 welds at the Facility for Accelerated Service Testing (FAST)—70 percent as new weld installations and 30 percent as existing welds with preexisting accumulated heavy axle load tonnage. Figure 6 shows the UIT process used at FAST. Most thermite welds failures happen in the fillet region of the base, and given the difficulty with using the UIT tool to access the bottom of the rail with sufficient precision, 48 percent of the UIT thermite welds at FAST do not include treating the bottom of the rail as a test of efficacy.

Figure 6. Photograph of the manual UIT process at FAST.

To date, the UIT thermite welds at FAST have accumulated an average of 190 million gross tons. Among the 100 treated welds, 27 have been removed: 22 as part of overall rail maintenance activities, 2 because of shells under the running surface, 2 because of vertical web failures, and 1 due to base failure. Among the five failed treated welds, none of the failures initiated in the treated zones.

As part of the treatment effort at FAST, TTCI has been working with a vendor to develop UIT equipment and procedures specific to the railroad environment and for treating thermite rail welds. This work has led to hardening a portable UIT equipment package and to the geometric and mechanical improvement of a handheld tool to work around rail welds.

TESTS OF UIT THERMITE WELDS IN REVENUE SERVICE

Following the same protocols as in the FAST UIT weld installations, testing of UIT thermite welds began in revenue service in April 2021. There is no data to report at the time of this writing.

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