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Increasing Thermite Weld Fatigue Life Through Improvements in Weld Profile

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Summary

The Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign in cooperation with Transportation Technology Center, Inc. investigated the effect of the external geometry of thermite welds on resistance to fatigue induced cracking and failure, and the extent that modifications could improve weld durability. The investigation found:

- The web-base fillet weld toe (collar edge) is a frequent location of thermite rail weld service failures.
- Cold laps, principally due to flashing from mold leakage, are a frequent fatigue-crack initiation site at the web-base weld toe of thermite rail welds.
- Theoretical studies indicate that the improvement of the weld toe profile and the elimination of cold laps can lengthen the fatigue life of thermite welds failing in the web-base area.
- Fatigue tests confirmed the theoretical predictions and showed that when the weld toe profiles were improved and large cold laps were eliminated, 3.5-fold increases in the average thermite weld fatigue life could be achieved.

Modifications suggested for field-weld performance improvement:

- Modifying the weld molds to smooth the contours of the weld's external shape in the fatigue-critical locations increased the fatigue life of thermite rail welds in laboratory tests.
- Modifying the shape of the molds using a refractory molding compound reduced the weld-toe flank angle (stress concentration site).
- Sealing the gap between the mold and the fillet with refractory paste to prevent weld metal from running between the mold and the rail eliminates the formation of large cold laps or "fins."
- Increasing the initial rail gap width from 1 inch to some larger dimension can reduce problems with insufficient melt-back.

Tests will be performed at the Facility for Accelerated Service Testing and in revenue service using the suggested modifications to evaluate their effectiveness and practicality in a railroad environment.

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- ❑ Safety
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INTRODUCTION AND CONCLUSIONS

AAR member railroads spend about $140 million annually on weld defect repair. Thermite welds are among the leading causes of rail service failures. Analysis of data from one Class I railroad showed that they accounted for 35 percent of the total rail service failures,[1] which is typical for other railroads as well. Detailed analysis of the causes of broken welds by another major railroad showed that service failures due to broken welds were frequently the result of cracks that originated in the web-base fillet weld toe area (this analysis showed imperfections in the surface geometry of the welds in this region). Consequently, jointly funded research was begun to develop fundamental changes and improvements to enhance the performance of thermite welds.

Researchers in the Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign (UIUC) and at Transportation Technology Center, Inc. (TTCI) investigated the effect of the external geometry of thermite welds on resistance to fatigue induced cracking and failure and to what extent modifications could improve weld durability. Results of the investigations showed:

- The web-base fillet weld toe (collar edge) is a frequent location of thermite rail weld service failures,
- Cold laps, principally due to flashing from mold leakage, are a frequent fatigue-crack initiation site at the web-base weld toe of thermite rail welds,
- Theoretical studies indicate that the improvement of the weld toe profile (collar edge angle) and the elimination of cold laps can lengthen the fatigue life of thermite welds failing in the web-base area.
- Fatigue tests confirmed the theoretical predictions and showed that when the weld toe profiles were improved and large cold laps were eliminated, 3.5-fold increases in the average thermite weld fatigue life could be achieved.
- At load levels corresponding to a 110-kip load (489 kN), welds having reduced flank angle and free of large cold laps had a mean fatigue life approximately 3.5 times greater than that of welds with the standard flank angle.

EXPERIMENTAL PROCEDURES

Materials and Welding Procedures for Standard Welds

The Canadian National/Illinois Central (CN/IC) Railroad provided new 136-pound rail. Thermite welding materials, equipment, and procedures of the three most common North American thermite weld suppliers were used. The welds were created in the welding shop in the Newmark Structural Engineering Lab (NSEL) at UIUC. Welding personnel from CN/IC, CSX, and thermite weld manufacturers assisted in preparation of a number of welds and in developing procedures that were consistent with railroad industry field-welding practice.

Fabrication of Modified Welds

Examination of standard thermite welds revealed two possible ways that their resistance to fatigue cracking could be improved. Experimental modifications were developed to address each. These modifications were all intended to reduce the concentration of stress that occurs in a rail weld under load from a rail vehicle, stress concentration points can lead to the formation of minute fatigue cracks that can grow under repeated loading until the weld breaks.

1. A sharp angle (collar angle 80° is typical) between the solidified weld metal and the parent metal at the collar edge (the weld-toe flank angle) causes stress to be concentrated at this point. The shape of the molds was modified to reduce the angle to about 0-15 degrees (Figure 1).
2. The gap between the mold and the rail web-to-base fillet often does not seal completely, causing molten weld metal to flow over the surface of the parent metal beyond the point of fusion between the weld and parent metal. When this weld metal cools, it results in a "cold lap" where stress is again concentrated during loading. This gap was sealed using refractory pastes to reduce the incidence of cold laps (Figure 2).

The standard weld is drawn with a large weld-toe flank angle (≈ 90 °); the modified weld is drawn with a very small flank angle (≈ 15°)

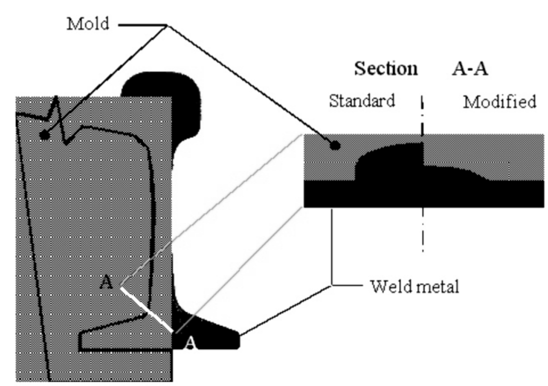

Figure 1. (*left*) Section through a Rail with Part of a Thermite Welding Mold Mounted; (*right*) Section into Plane of the Page, through the Weld at the Web-Base Fillet

Figure 2. Modifications to a Standard Thermite Weld Mold to Reduce Weld-Toe Flank Angle and Increase Weld Toe Radius (mold modified using refractory cement)

Testing

A standard, four-point bending, fatigue-testing apparatus was fabricated in the NSEL machine shop to test the welds under cyclic-loading conditions.[2] Tests were carried out in ambient laboratory conditions, using constant amplitude zero-to-maximum loading (R ≈ 0) at a frequency of 2 to 3 Hz. To reduce the duration of the tests, initially a rather high load range (700 to 800kN) was chosen. However, at these high load ranges, both the standard and modified welds failed at around 20,000 cycles. Fatigue life improvement measures are expected to be most effective in the long-life regime because such measures retard the early growth of fatigue cracks. Thus, the applied load range was reduced to the lowest practicable value of 489 kN (110 kips), consistent with producing a fatigue failure in a reasonable length of time (less than one week; i.e., less than 2,000,000 cycles).

Additionally, the approximate bending stress in the base of 136RE rail on wood ties with typical subgrade conditions and a vehicle load of 286 kips is 11.4 ksi. The bending stress imparted by the 489 kN (110 kips) fatigue fixture loading produces a bending stress of 33.6 ksi or approximately 3 times the service loading. To better represent service conditions, a test load of approximately 160 kN (36 kips) would be used, but would subsequently require unreasonable test durations. Thus, the lower fatigue test loads are more representative of "real world" conditions.

TEST RESULTS

Fatigue Test Results for Standard Thermite Welds

The four-point-bending fatigue results for the standard thermite welds that failed at their web-to-base weld toe are plotted in the load-life diagram in Figure 3. The squares in the fatigue data (Figure 3) represent the control condition of standard welds for Manufacturer A. The standard welds of the other two manufacturers are diamonds. Also plotted with the standard welds are modified welds with standard flank angles. It was found that the presence or absence of small cold laps did not have much effect on the fatigue life of the web-to-base fillet of the standard thermite weld with a 80-degree flank angle. Thus, the results for modified weldments with the flank angle are plotted as solid triangles and included in the regression analysis as unmodified welds. The results for a specimen that did not fail 2,000,000 cycles of testing is identified by an arrow next to its symbol. The data for this unbroken specimen was not included in the regression analysis.

As is customary with weld fatigue data, a least-squares fit regression analysis curve was fitted to the data (solid line) and parallel lines plus or minus two standard deviations were plotted (dashed lines). The slope of the regression line is ≈ -0.33. The slope of the regression analysis curve is not significantly different from the expected slope of load-life curves for rail steel when fatigue crack growth dominates. This slope can be shown to be the reciprocal of the exponent of the Paris Power Law for fatigue crack growth, which for rail steel is 3.3.[3,4] Given the expected variation in fatigue results for weldments, there is little scatter in the data; and results suggest that the standard welds of all three manufacturers had about the same fatigue resistance under our test conditions.

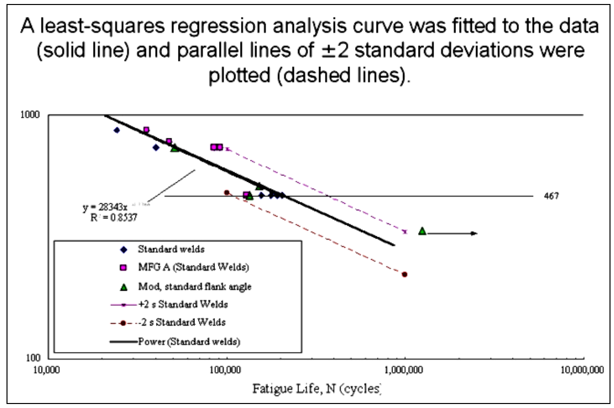

Figure 3. Load Range versus Cycles to Failure for Standard Thermite Welds of Various Manufacturers.

Fatigue Test Results for Modified Welds with Reduced Flank Angle

The test results for the modified welds with reduced flank angle are compared with the data for the welds with a standard flank angle in Table 1 and Figure 4. At the load range of 489 kN welds with a reduced flank collar angle (0-15 degrees) had an average fatigue life 3.5 times longer than welds with a standard flank angle of ≈ 80 degrees.

At the higher load ranges (>690 kN), the weldment with a reduced flank angle performed no better than weldments with a standard flank angle.

Table 1. Comparison of the Fatigue Life of Standard and Modified Flank-Angle Weldments (467 kN load range)

Flank Angle	Cycles to Failure (± 95% confidence interval, assuming a log-normal distribution of fatigue life)
Standard (ca.80°)	161,800, -19,800+22,200
Modified (0° –15°) Web-toe failures only	368,900, -187,900+304,000

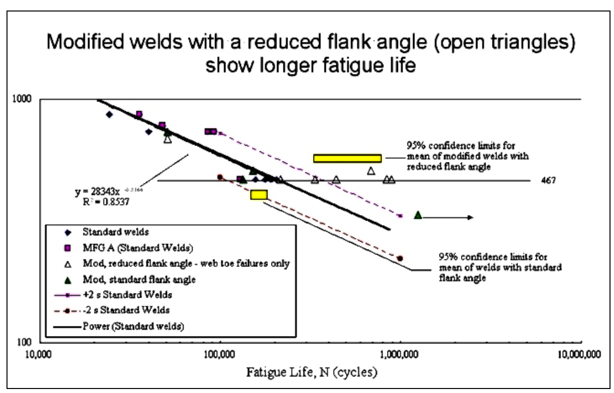

Figure 4. Load Range versus Cycles to Failure for the Standard and Modified Thermite Welds

DISCUSSION

Standard welds of all three manufacturers had web-base fillet weld-toe flank angles in the range of 70 to 80 degrees. All weldments had about the same fatigue life with little scatter in the fatigue data. This is frequently observed for weldments having severe weld geometries and weld residual stresses that lead to short fatigue lives. Weldments that have favorable weld geometries generally have longer fatigue lives, but exhibit a greater sensitivity to minor discontinuities such as surface finish, which with improved weld geometry may become more significant.

Experiments were performed at a load range of 489 kN or 110 kips to determine the relative effects of many design parameters quickly and efficiently. This level produces bending stress at the base of the rail approximately 3 times that under 286-kip cars. In-track proof testing of these welds at FAST under heavy axle loads will be conducted next.

The modified welds that performed best had the smallest weld toe defects and represented a fatigue life improvement of 5.5 times. The range in fatigue life for the modified welds with reduced flank angle is much greater than that of the welds with a standard flank angle for reasons discussed above.

Suggestions for Improving Fatigue Resistance

- Weld-toe flank angles should be reduced as much as possible. This change should be possible for any mold because it is only the local stresses at the notch root that matter.
- Increasing the weld-toe radius is of equal importance to reducing the flank angle. It should be increased as much as possible.
- Eliminate or reduce the size of cold laps in the web-base fillet region and in the rail base by making the molds conform as closely as possible to the rail in those areas. The molds can be altered so that they fit these regions snugly. If that is not sufficient, mold sealant can be applied to critical regions of the mold before being fitted to the rail.
- Problems with insufficient melt back that may contribute to the formation of cold laps can be reduced by increasing the gap between the rail ends from 1 inch to some larger value or by decreasing the collar dimension.

Acknowledgements

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