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High-Speed Rail IDEA Program

Improved Reliability of Thermite Field Welds Used on High Speed Rail Lines

Final Report for High-Speed Rail IDEA Project 24

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Improved Reliability of Thermite Field Welds Used on High Speed Rail Lines

IDEA Program Final Report

For the period September 2000 to January 2002

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1. EXECUTIVE SUMMARY

The fatigue life of thermite rail welds was increased by modifying standard thermite molds to improve their weld toe geometry and to avoid the formation of cold laps at the web-base fillet. The weld-toe flank angle was reduced by modifying the shape of the molds using a refractory molding compound. A diagram of the existing and modified contour of the mold can be seen in FIG. ES-1 below. Sealing the gap between the mold and the fillet with refractory paste prevented cold laps from forming. In this study, the rail gap width was increased form 1-in. to 1.4-in. Increasing the gap width between the rail ends insured melt-back beyond the dimensions of the mold collar.

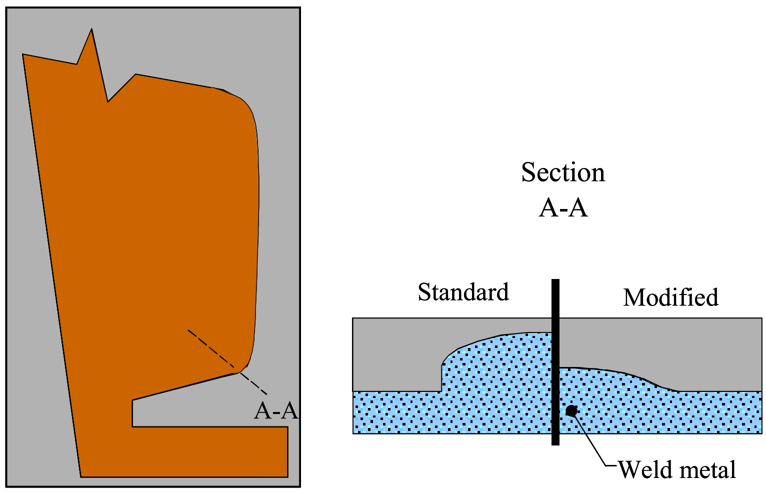

FIGURE ES-1 -- A portion of the thermite mold used in this study is shown on the left. The location of the web-base fillet region is indicated as section A-A. At the left is the standard and modified profile of the mold in the section A-A.

The improved fatigue resistance of the thermite welds was demonstrated through full-scale 4-point bending fatigue tests. No significant improvements were seen at higher load levels when comparing the fatigue life of modified to the un-modified welds. As seen in FIG. ES-2 below, there was considerable scatter to the data at low load ranges. Several modified welds failed prematurely at the 489 kN load range because of inadvertent gross defects. Other modified welds tested at the 489 kN load range failed at the same fatigue life as standard welds due to the existence of cold laps. However, many modified welds were free of cold laps; these specimens exhibited fatigue lives between 2 and 5 times greater than that of standard welds (dashed line).

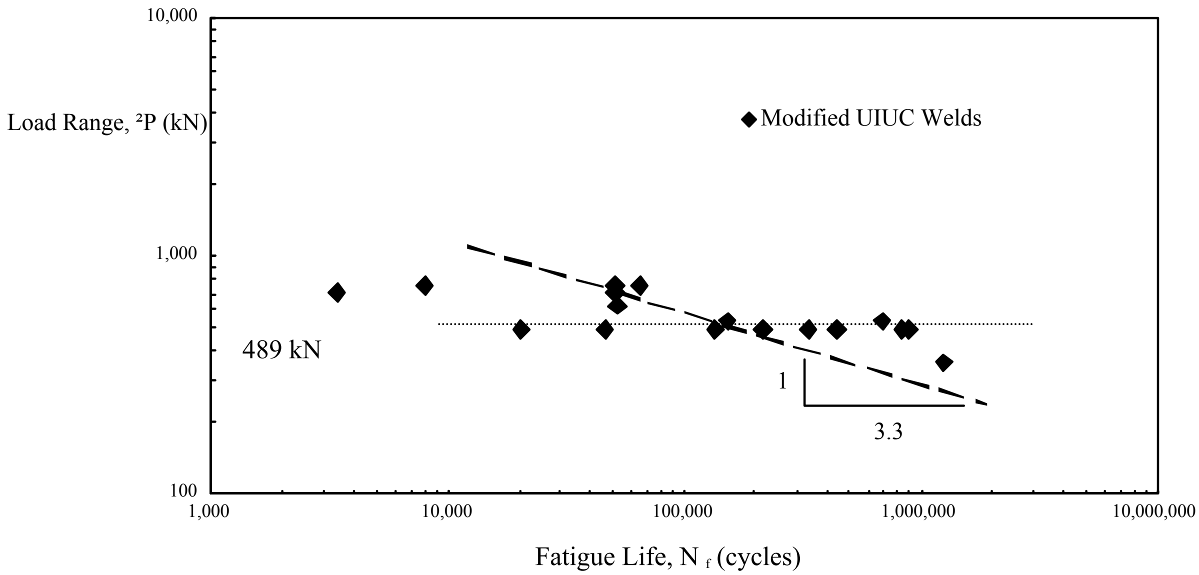

FIGURE ES-2 – Fatigue test results for modified thermite weldments. Dashed line represents the fatigue behavior of the base and web of standard thermite rail welds.

The results of this study indicate that the fatigue resistance of the web and base of thermite rail welds can be improved by:

- Eliminating cold laps in both the web-base fillet region and in the rail base by making the molds conform perfectly to the rail in these areas. The mold dimensions can be altered so that the mold always fit this region snugly and possibly fit less well in areas of lesser importance like the wide part of the base or the central parts of the web of the sides of the head. If that measure does not prove sufficient, small smears of mold sealant such as was used in this study can be applied to critical regions of the mold prior to being mounted on the rail. Problems with insufficient melt-back which 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. (1.4 inches was used in this study.)

- Reducing the flank angle to as small a practical value. It may be possible to effect this change even in molds in which the weld collar is very pronounced because it is only the local stresses at the notch root which matter.

- Increasing the weld toe radius to as large a value as possible. This alteration is of equal importance to reducing the flank angle.

Reducing the roughness of the as-cast thermite weld surface has not as yet been fully explored. It is possible that reducing the as-cast surface roughness in conjunction with the other improvements mentioned above (elimination of cold laps and improving the gross weld toe profile) may lead to even greater improvements in the fatigue life of the thermite weld web-base region.

2. PROJECT SUMMARY

2.1 IDEA PRODUCT

The IDEA product that will result from the completion of this investigation is an improved method of welding thermite rail welds that will cause a substantial improvement of the thermite-welded rail's fatigue resistance in the base and web region.

2.2 CONCEPT AND INNOVATION

The innovative principles which served as the basis of this IDEA product was the realization that thermite rail welds, like fusion welds in the past, were optimized to resist static loads rather than repeated loading. Viewed from the perspective of resisting fatigue crack initiation and growth, the lack of attention to the stress-raisers caused by the thermite weld toe caused serious fatigue problems. In this project, it was demonstrated that improving the geometry of the web-base weld toes can greatly lengthen the fatigue life of the thermite rail weld.

2.3 INVESTIGATION

Project Background

The problem posed by thermite welds:

Field welded rail joints are widely considered to be among the most frequent source of rail flaws in the North America (NA) railroad infrastructure; as such, they have a major impact on rail service reliability and safety. Recent studies have suggested that defective field welds are a major problem for most railways. For example, a Class I railroad reports 14 service failures per day of which 40% are due to thermite welds, 40% are due to transverse defects under shell and 20% are listed as other [1]. Broken field welds are reported as being a major cause of derailments. The increasingly heavy axle loads characteristic of current and future NA railroad freight operation will only make this problem worse. A practical and economic means of improving the fatigue-resistance of field welds is needed; this is particularly true for freight railroad lines over which high-speed passenger trains will operate. In these circumstances, failed welds will at a minimum pose service reliability problems and possibly a safety hazard.

Why do welds fail?

Fatigue is a process in which fatigue cracks are formed in regions of high stress or strain concentration and enlarge until the component finally breaks. FIGURE 1 illustrates the three critical locations where fatigue cracks develop in thermite field welds: Rail heads (H) where fatigue cracks initiate at internal inclusions and pores; Rail web (W) locations; and Rail base (B) locations where cracks initiate at weld toes because of the high stress concentrations there: see FIG. 1. Most broken field welds (service failures) initiate at cracks in either the rail web (W) or rail base locations (B). Railhead defects are actually more frequent than rail failures originating at the web and base locations, but railhead defects generally do not cause failure because they are usually found during inspection and repaired. Another Class I railroad reports that "mark-outs" (that is, detected and removed rail head flaws) exceed actual broken rails (failures) by a 2 to 1 ratio.

Scope of the project

The project developed means for improving the reliability and safety of thermite welds used in railroad rail by increasing the resistance of the rail web and base to fatigue failure by improving the local notch-root geometry and by developing new rail-mold sealant that will produce defect-free surfaces in these fatigue-critical locations. The improved fatigue resistance of the thermite welds was demonstrated through full-scale, fatigue tests using UIUC test facilities.

Project history

Phase I of the project began in September 2000. A project advisory panel was established that consisted of three experts on thermite welding:

- Dr. Kevin Sawley, of the Association of American Railroads is a research metallurgist with extensive experience with rail metallurgy and the production and behavior of thermite welds.
- Mr. Robert H. Kachik, Assistant Vice President Technology of Orgo-Thermit, Inc., gives the project a linkage to a major manufacturer of thermite welding equipment. The Orgo-Thermit Company has generously donated materials and expertise to the project.
- Mr. Hayden Newell, Manager, Innovative Research Norfolk Southern Corporation, is a valuable resource. The Norfolk Southern has made extensive surveys of the behavior of thermite welds in service and has provided the investigators at the UIUC with insights based on their experience.

Members of the panel contributed advice, information, and materials throughout the project and were kept informed of progress through monthly reports. One panel member contributed a database containing a major US railroad's four-year-experience with 244 thermite weld service failures. This data confirmed the hypothesis of the project namely that the geometry of thermite weld base-to-web fillet area and the existence of weld-toe cold laps aggravated the fatigue severity of those regions.

Phase II was begun in January 2001. A four-point bending test apparatus was designed based on the dimensions of a standard European test. Then, nominal thermite welded rails were produced and fatigue tested to establish their baseline fatigue resistance.

Phase III was begun in May 2001. Various schemes to improve the external weld geometry, to produce smoother as-cast surfaces and to eliminate weld toe defects such as cold laps were explored. Improved (modified) thermite welds were produced and fatigue tested. Many specimens showed a lengthened fatigue life. Starting in September 2001, the experimental data were analyzed; the skills obtained in the study were applied to thermite welding project at the Transportation Technology Center, Inc. (TTCI) in Pueblo, Co.; analytical models were developed; a poster presentation was made at the TRB meeting in January 2002; and this final report was submitted at the end of that month.

Observed Nature of Web-to-Base Fillet Weld Toes

A database containing 244 service failures from four year's experience was donated and analyzed. Most failures originated at the base to web fillet (FIGS. 2 and 3), and the most frequent defect causing failure was a cold lap; see FIGS. 2 and 3. Thus, the critical nature of the base-to-web fillet area and importance of cold laps frequently occurring there were confirmed by this information.

A polished section through a typical weld toe in the web-to-base fillet of a standard thermite rail weld is shown in FIG. 4 in which it can be seen that the angle at which the weld metal fairs in to the base metal (termed the flank angle) is obtuse and is roughly 70 to 90 degrees. A typical "cold lap" at the weld toe can also be seen. Cold laps are sometimes termed "flashing," "fins" or a "run out."

Theoretical Aspects

Damage model

Fatigue is a process in which fatigue cracks are formed in regions of high stress or strain concentration and enlarge until the component finally breaks. Fatigue damage is the imprecise but useful concept that each reversal of stress imparts a certain, constant amount of "fatigue damage." Thus by that definition, the fatigue damage per cycle is:

$$D = \frac{1}{N_T} \tag{1}$$

where:

D	=	Fatigue "damage" per cycle of load application
N_T	=	Fatigue life or cycles to failure

For applications in which the stresses and strains in the critical location or locations are quite small and the resulting fatigue lives are beyond, say, 500,000 cycles, plastic strains can be ignored; and the fatigue process can be modeled in terms of local (notch root) stresses by the Basquin-Morrow expression:

$$\frac{\Delta\sigma}{2} = \left(\sigma_f' - \sigma_o\right)\left(2N_T\right)^b \tag{2}$$

where:

$\Delta\sigma/2$	=	Local (notch root) stress range
σ_o	=	Local (notch root) mean stress
N_T	=	Fatigue life or cycles to failure
σ_f'	=	Material property – fatigue strength coefficient
b	=	Material property – fatigue strength exponent

Relating the local (notch root) stresses (σ) to the remote applied stresses (S) using a supposed, effect multiplying fatigue notch factor K_f:

$$\sigma = K_f \; S \tag{3}$$

The damage (D) per cycle would then be:

$$D \approx 2\left[\frac{\sigma'_f - \sigma_o}{K_f \dfrac{\Delta S}{2}}\right]^{\frac{1}{b}} \tag{4}$$

The thermite welds to be studied will be fatigue tested in four-point bending, thus the applied stress range (ΔS) will vary with distance from the rail neutral axis. The mean stress (σ_o) is a combination of applied mean stress and the welding residual stresses shown in FIG. 5.

FIGURE 6 is a estimate of the variation in fatigue damage (D) with elevation in the rail cross-section for three assumed values of fatigue notch factor (K_f):

- K_f = 10 which would correspond to a rather severe fatigue notch.
- K_f = 7 which would correspond to a moderately severe fatigue notch.
- K_f = 3 which would correspond to a more desirable, less severe notch.

The plotted curves were calculated using Eq. 4 assuming four-point bending under a 110 kip load, R = 0. The damage per cycle is plotted on the x-axis and increases to the right. The "S" shape of the damage versus distance curves below the neutral axis results from the large sudden variations in residual stress in the base of the rail (FIG. 5). The existence of fatigue damage above the neutral axis is a result of the very high tensile residual stresses in that area superposed on the fluctuating (compressive) bending stresses (FIG. 5). Several points on the calculated curves are labeled A through I to aid in discussion.

If the fatigue severity of the weld toe was the same in all locations, then the base of the rail would always be the location of failure because the damage for location I is greater than that of H and B. For fatigue failure to occur in the web-to-base fillet, that is location C in FIG. 6, the fatigue notch factor in that area must be larger than that of the base, for example the damage of H (K_f = 10) is larger than that of G (K_f = 7). If the fatigue notch factor of the web-to-head fillet is greater than that of both the web-to-base and base (B > E > D), then failure could occur under the rail head even though that would seem impossible given that the applied stresses in this region are compressive!

A model for the fatigue severity of a given weld-toe geometry

What determines the fatigue notch factor for a thermite weld toe? To answer this question models for the fatigue severity (fatigue notch factor (K_f) of thermite weld-toes with and without cold laps will be developed below. These models will be used to assess the influence of the many geometric parameters (flank angle, weld toe radius, etc.) which control the fatigue severity of the web-to-base fillet weld toes of the thermite weld.

To assess the effect of these geometric variables, one must recognize that small notches are less damaging (have longer fatigue lives) than large notches having the same geometry (elastic stress concentration factor – K_t). Petersons's equation provides a rough estimates of the apparent "fatigue notch factor" (K_f) for a notch having a given elastic stress concentration factor K_t.

$$K_f = 1 + \frac{K_t - 1}{1 + \frac{a}{r}} \qquad (5)$$

where:

K_f	=	Fatigue notch factor
K_t	=	Elastic stress concentration factor
a	=	Peterson's material parameter
r	=	Notch root radius

Thermite weld toes without cold laps

Thermite weld toes without cold laps were modeled as a compound notch (FIG. 7) in which a weld toe defect or the as-cast-surface roughness is considered to be a small, notch-root defect located in the stress field of a larger (global) notch - the weld reinforcement. The fatigue notch factor (K_f) in this case is modeled as the product of two terms:

$$K_f = K_{tG} * K_{fL} \qquad (6)$$

where:

K_f = Fatigue notch factor
K_{tG} = Global stress concentration factor
K_{fL} = Local fatigue notch factor

The model of Trufyakov and Dumka [**2**] was used for the global stress concentration factor, K_{tG} (FIG. 8) for the web-to-base fillet weld toes of the thermite weld.

$$K_{tG} = 1 + \left[\frac{R\cos\theta}{g\sin\theta} + \frac{4R}{t} + \frac{5R}{l+R} \right]^{-\frac{1}{3}} \qquad (7)$$

where:

K_{tG}	=	Global stress concentration factor		
g	=	Height of weld reinforcement	≈	7.5 mm
l	=	Width of weld reinforcement	≈	50.8 mm
θ	=	Flank angle	≈	80˚
R	=	Weld toe radius	≈	1.25 mm
T	=	Specimen thickness	≈	25.4 mm

For the typical values of g, l, θ, R and t indicated above, the K_{tG} is ≈ 2.41. According to this model, doubling the gap width (L) from 50 mm to 100 mm would result in a very small increase in K_{tG} from 2.41 to 2.50. This result indicates that the increase in global stress concentration resulting from the use of wide-gap weldments is probably not too important.

The local stress concentration factor, K_{tL} depends on the nature of the notch-root defect present. The stress concentration factor K_{tL} for the surface roughness or other similar weld defect was modeled by Eq. 8:

$$K_{tL} = 1 + \alpha\sqrt{\frac{d}{r}} \qquad (8)$$

where:

K_{tL} = Local stress concentration factor for surface roughness
α = A constant varying with the nature of the notch
d = Surface roughness or notch depth
r = Notch root radius

Thus, the K_f of a specimen without cold laps becomes:

$$K_f = \left[1 + \left[\frac{R\cos\theta}{g\sin\theta} + \frac{4R}{t} + \frac{5R}{l+R} \right]^{-\frac{1}{3}} \right] * \left[1 + \frac{\alpha\sqrt{\frac{d}{r}}}{1+\frac{a}{r}} \right] \qquad (9)$$

Thermite weld toes with cold laps

Dimitrakis [3] studied the effect of cold laps on the fatigue resistance of fusion welds using the finite element method. FIGURE 9 shows the geometry studied. Dimitrakis determined the geometry correction factor M_k which influences the stress intensity factor (range) of a crack emanating from a cold lap embedded in the weld toe of a butt weld (FIG. 10).

$$\Delta K = M_k \, \Delta S \sqrt{\pi a} \qquad (10)$$

Since the models for thermite welds are based on the elastic stress concentration factor (K_t) and values of K_f estimated using Peterson's equation (Eq. 5), the fracture mechanics relationships for a crack of finite radius were used to estimate the crack tip (notch root) stress and from this, K_t and finally K_f. For a crack having a finite tip radius:

$$\sigma_x = \frac{K_I}{\sqrt{2\pi R}} f_1(\theta) + \frac{K_I}{\sqrt{2\pi R}} \left[\frac{r}{2R}\right] f_2(\theta) \qquad (11)$$

From Eqs. 10 and 11 for $\theta = 0$ and $R = r = a$, notch root stress is:

$$\sigma_x = \sqrt{2}\, M_k\, S \qquad (12)$$

and K_t becomes

$$K_t = \frac{\sigma_x}{S} = \sqrt{2}\, M_k \qquad (13)$$

As seen in FIG. 11 the cold laps seen at thermite weld toes are different from the cold laps observed in normal fusions welds in that the cold lap in a thermite weld can extend for great distances as the weld metal runs between mold and the rail. Such great extensions of the cold lap cannot much worsen the stress state at the apex of the cold lap; and so for that reason, we considered the maximum depth of cold lap to be no greater than 1mm even when their actual depth was greater than 1 mm: see TABLE 1. Cold lap depths as great as 5 mm were observed.

The analysis of Dimitrakis includes the effect of the global geometry. Thus, the fatigue notch factor for thermite welds with cold laps was obtained by combining Eqs. 5 and 13:

$$K_f = 1 + \frac{\sqrt{2}\, M_k - 1}{1 + \frac{a}{r}} \qquad (14)$$

If one assumes that a = r and for values of $M_k \approx 9$ and a flank angle of 60˚, $K_f \approx 7$.

Influence of geometric variables on the fatigue life of a thermite weld toe

The fatigue notch factor models developed in the previous section permits one to assess the influence of the many geometric parameters (g, l, θ, R, t, d, r, ρ – see Eq. 9) which control the fatigue severity of the web-to-base fillet weld toes of the thermite weld.

Influence of flank angle and weld toe radius for thermite welds without cold laps

In the absence of a cold lap, what is the influence of the main (global) geometric variables - Flank angle (θ) and weld toe radius (R) - on the fatigue notch factor for a thermite weld toe? The variation of K_f with flank angle (θ) and weld toe radius (R) predicted by Eq. 9 is shown in Fig. 11. In this figure, the values of g, t, l, d, and r are held constant:

g	=	Height of weld reinforcement	=	7.5 mm
l	=	Width of weld reinforcement	=	50.8 mm
t	=	Specimen thickness	=	25.4 mm
d	=	Surface roughness or notch depth	≈	1.19 mm
r	=	Notch root radius	=	Petersons constant a
a	=	Peterson's constant	≈	0.1 mm

The surface roughness (d) was taken as the size of a lutting sand particle (1.19 mm). Measurements of a mold contours indicate that a standard thermite weld will have a flank angle (θ) of approximately 80 degrees and a weld toe radius (R) of ≈ 1.25 mm. For these nominal dimensions, the fatigue notch factor (K_f) unmodified weld would be identified by the black circle labeled 1 in FIG. 11. Eq. 9 predicts that decreasing the flank angle from the standard 80˚ to 15˚ would decrease K_f from 3 to 2.5. From Eq. 15 below this decrease in K_f could result in fatigue life improvements (I) of ≈ at least 1.8 times.

$$I = \left[\frac{K_{fs}}{K_{fm}} \right]^x \tag{15}$$

where:

I	=	Fatigue life improvement factor
K_{fs}	=	Fatigue notch factor of standard thermite weld
K_{fm}	=	Fatigue notch factor of modified thermite weld
x	=	Exponent (3.3 for rail steel assuming dominance of fatigue crack growth [4,5].

Increasing the weld toe radius (R) from 1.25 mm to 4 mm would result in a decrease in K_f from 3 to ≈ 2.5 (circle 3) and fatigue life improvements (I) of at least ≈ 1.8 or greater. In this latter case, the reduction in K_f is (by chance) nearly the same as that effected by reducing the flank angle from 80 to 15 degrees. So each of these two changes result in about the same fatigue life improvement. However, both decreasing the flank angle and increasing the toe radius can have much greater effect. Circle 4 in FIG. 11 shows that reducing the flank angle from 80˚ to 15˚ and increasing the weld toe radius from 1.25 mm to 4 mm will reduce K_f from 3 to 2.2 and could result in fatigue life improvements (I) of at least ≈ 2.8 times.

Influence of the presence of cold laps

If there is a cold lap at the weld toe, what effect would its elimination have on the fatigue life? One can estimate the possible improvement resulting from the elimination of cold laps by noting that the K_f of a 60˚ flank angle weld with a cold lap was estimated above as $K_f \approx 7$. In the absence of a cold lap, the K_f can be estimated in FIG. 11 as ≈ 4.2. Thus, by Eq. 15, the elimination of the cold lap would change the K_f from 7 to 4.2 and thus could improve the fatigue live by a least a factor of 5.4! Eliminating the cold lap, reducing the flank angle to 15˚, and increasing the toe radius to 4 mm could reduce the K_f from 7 to 2.2 and thus could improve the fatigue life by at least a factor of 46 times!

Summary

- Other things being equal, fatigue failure should occur at the rail base. Fatigue failure at the web-base fillet implies that the fatigue notch in that location is substantially more severe than that of the rail base.
- Many factors influence the fatigue severity of the thermite weld toe: flank angle, weld toe radius, as-cast surface roughness and the presence of cold laps.
- It was estimated that the elimination of cold laps could increase the fatigue life of the web-base fillet by at least a factor of 5.
- Elimination of cold laps and improving the weld toe geometry could increase the fatigue life of the web-base fillet by at least a factor of 46 times.

Experimental Program

Materials and welding procedures for standard welds

Lengths of new 136 pound rail were donated by the Canadian National-Illinois Central Railroad Company. Thermite welding materials and equipment of all three of the common thermite welding procedures used in North American railroad practice were used. All welds were fabricated in the research facilities of the Department of Civil and Environmental Engineering (CEE) initially with the assistance of welding supervisors and welders from the CSX Transportation and the Canadian National-Illinois Central Railroad Companies, as well as representatives of some thermite welding companies, on occasion.

All welds were created indoors in the CEE welding shop using the welding jig shown in FIG 12**.** All rails were carefully aligned, and the molds were prepared using standard recommended industrial practice. Preheating was carried out using a propane-oxygen flame with a two row head torch. Premium (high alloy content) thermite charges were used. At the appropriate moment, the base risers were removed, the head riser was sheared using a hydraulic shear, and, lastly, the running surfaces were ground smooth follow standard industrial practices.

Fabrication of modified welds

Three modifications were made to the standard molds of one manufacturer to improve the weld toe geometry and to avoid the formation of cold laps at the web-base fillet. These modifications included:

- Sealing the gap between the mold and the web-base fillet with refractory pastes.
- Reducing the weld-toe flank angle with refractory molding compound.
- Increasing the gap width between the rail ends to avoid cold laps.

Sealing the gap between the mold and the fillet with refractory pastes had the purpose of preventing cold laps from forming. The sealing pate used in the study was the standard Railtech stemming paste. The paste sealed gap between mold and rail in the web-base fillet. The paste was applied by hand to the mold edges as shown in FIG. 13**,** and then the mold was pressed against the rail being careful to align the mold properly.

The weld-toe flank angle was reduced by modifying the shape of the molds using a refractory molding compound. A diagram of the existing and desired contour of the mold can be seen on FIG. 14. The molding compound was applied to the web-base fillet area of the silica sand mold as seen on FIG. 14. To ensure adequate bond between the molding compound and the mold, holes were drilled into the surface of the mold to provide a mechanical bond.

Increasing the gap width between the rail ends insured melt back beyond the dimensions of the mold collar. In this study, the rail gap width was increased from 1.0-in. to 1.4-in.

Testing

A European standard four-point bending fatigue-testing apparatus was fabricated in the CEE machine shop and was used for all fatigue tests. A drawing and photograph of the apparatus are shown on FIG. 15, respectively. Tests were carried out in ambient laboratory conditions, using constant amplitude zero-to-maximum loading ($R = 0$) at a frequency of 2 – 3 Hz. A safety harness seen in FIG. 15 prevented the broken rail sections from jumping out of the apparatus.

Post-test examination

Following testing, all fracture surfaces were photographed. Several welds were sectioned and polished and examined using optical microscopy (OM). Several un-fractured weld toes were cut out of welds and examined in a scanning electron microscope (SEM).

Test Results

Fatigue tests results for standard thermite welds

The four-point-bending fatigue results for the standard thermite welds are presented in the material fatigue life curve (SN diagram) of FIG. 16. A line having a slope of 1/3.3 has been drawn through the data. The slope of 1/3.3 represents the expected slope of SN curves for rail steel when fatigue crack growth dominates. Given the expected scatter in fatigue results for cast materials and weldments, there is very little scatter in the data; and it seems that of the welding systems of all manufacturers produce thermite welds having about the same fatigue resistance.

Fatigue test results for modified welds

The test results for the modified welds are shown in FIG. 17. No significant improvements were seen at higher load levels when comparing the fatigue life of modified to the un-modified welds. The 1/3.3 slope line of FIG. 16 has been reproduced in FIG. 17 for comparison. At low load ranges, there is considerable scatter to the data. Two modified welds failed prematurely at the 489 kN load range. Other modified welds tested at the at the 489 kN load range, failed at the same fatigue life as standard welds. However, at lower load levels (below 500 kN), many modified welds had fatigue lives between 2 and 5 times the typical standard welds. One test was discontinued after 1.2×10^6 cycles and the data point for this specimen is termed a "run out" and is denoted with an arrow.

A summary of the weld information and fatigue testing observations of all the specimens tested is contained in TABLE 1.

Discussion

Scatter in results for the modified welds

As seen in FIG. 17 there is a great deal of scatter in the fatigue test results for the modified weldments. The weld fatigue data plotted in FIG. 17 are grouped into three clusters in FIG. 18. The first cluster includes all the data that lie substantially to the left of the expected fatigue life of the standard thermite weld represented in FIG. 18 by the dashed SN curve. The second cluster includes data that lies on or close to the SN curve. The third cluster includes data that exceed the expectations for the standard thermite weld and lie substantially to the right of the S-N curve.

Cluster 1 includes all the data that lie substantially to the left of the expected fatigue life of the standard thermite weld. These welds exhibited premature failure and typically contained gross inclusions in the base of the weld, as shown in FIGS. 19 and 20. These two figures show the fracture surfaces for Specimens 30 and 36, respectively. FIG. 19 shows a slag inclusion that was the site of fatigue crack initiation. FIG. 20 shows a fracture surface of a weld in which a large piece of mold-modifying material (refractory molding compound) fell to the rail base - presumably during pre-heating or the thermite pour - and provided the site of fatigue crack initiation.

Cluster 2 includes data that lies on or close to the S-N curve. The welds and the fracture surfaces of the modified welds in this cluster were examined and found to contain discontinuities typical of standard thermite welds (namely cold laps). As a consequence, these weldments did not perform better than the standard thermite weld. These weldments all initiated fatigue cracks at the critical web-to-base fillet weld toe, just as did the standard thermite weldments. A fracture surface of Specimen 33, a modified weld which contained a cold lap, can be seen in FIG. 21. The cold lap probably resulted from the sealing paste bead having been damaged during the assembly and alignment of the molds.

Cluster 3 includes data that exceed the expected fatigue life for a standard thermite weld and lie substantially to the right of the SN curve. These welds initiated fatigue cracks at discontinuities on the as-cast surface, as can be seen in FIG. 22. These welds all exhibited longer fatigue lives than the standard welds. The longer lives were obtained because of a significant reduction in the stress concentration at the web-base fillet weld toe.

Reasons for the observed improvement of fatigue life

FIGURE 23 shows the ideas that were employed in this study to improve the fatigue life of the web-base fillet area of the thermite weld. FIGURE 23(A) shows the typical weld toe shape of a normal (good) thermite weld. The weld toe and the melt back coincide and no cold lap is present; however, the flank angle is large (≈ 80˚) and the weld toe radius is small. FIGURE 23(B) shows a frequently observed difficulty with thermite weld toes: the amount of melt back is less than the dimension width of the collar leading to a situation in which weld metal runs out onto an un-melted, highly-oxidized base metal surface. This condition promotes the formation of a cold lap as discussed by Dimitrakis and Lawrence [6]. The frequency of this condition observed in a recent study by the authors is shown in FIG. 24.

FIGURE 23(C) shows a further complication of FIG. 23(B) in which there was a gap between the mold and the rail causing a large fin-like cold lap. These cold laps may frequently be as large as 5 mm but in the fatigue severity analysis of Section 2.3 only a maximal length of 1 mm was considered to be fully effective.

Thus, the improvements effected in this study are ascribed to:

- The elimination of cold laps
- Reductions in weld toe flank angle from ≈ 80˚ to ≈ 15˚
- Increases in weld toe radius

In this study, the fatigue life was improved by as much as factor of 5. This improvement is more than would be expected from an improvement of flank angle and weld toe radius alone and is thus ascribed to both the near elimination of cold laps and the improvement of the basic weld geometry by reducing the flank angle and increasing the weld toe radius. It is felt that further improvements are possible through the modifications mentioned above coupled with an improvement in the as-cast surface roughness.

While attempts were made to improve the as-cast surface roughness through the use of mold washes, none of the measures tried in this study seemed to much improve the as-cast surface roughness. Further study of this point could produce additional large improvements of the thermite weld fatigue resistance.

2.4 PLANS FOR IMPLEMENTATION

The ideas and concepts of this study have already been implemented in several field trials at the TTCI, and the outcome of these experiments will be known before long.

- The idea of eliminating cold laps was used to improve the fatigue resistance of weldments of rails having dissimilar height.
- One manufacturer has recently developed an experimental thermite weld having an improved weld toe geometry that is consistent with the recommendations of this study.

The plan for implementation is to suggest to manufacturers of thermite welding kits that they redesign their molds and welding systems as follows:

- Eliminate cold laps in both the web-base fillet region and in the rail base by making the molds conform perfectly to the rail in these areas. The mold dimensions can be altered so that the molds always fit this region snugly and fit less well in areas of lesser importance like the wide part of the base or the central parts of the web of the sides of the head. If that measure does not prove sufficient, small smears of mold sealant such as was used in this study can be applied to critical regions of the mold prior to being fitted to the rail. Problems with insufficient melt back which 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. (1.4 inches was used in this study.)
- Reducing the flank angle to as small a practical value should be carried out. It may be possible to effect this change even in systems in which the weld collar is very pronounced 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, and it should be increased to as large a value as possible.
- Reducing the roughness of the as-cast surface is a fatigue life improvement strategy which has not as yet been fully explored. It is possible that reducing the as-cast surface roughness in conjunction with the other improvements mentioned above (elimination of cold laps and improving the gross weld toe profile) may lead to further improvements in the fatigue life of the thermite weld web-base region.

3. CONCLUSIONS

- The web-base fillet area is a frequent location of thermite rail weld service failures.
- Cold laps are the most frequent fatigue-causing stress concentration in the web-base region of thermite rail welds.
- Theoretical studies indicate that elimination of cold laps and improvement of weld toe profile can greatly lengthen the fatigue life of thermite welds failing in the web-base area.
- Fatigue tests confirmed the theoretical predictions and showed that when cold laps were eliminated and the weld toe profiles were improved that five-fold increases in thermite weld fatigue life could be achieved.

4. INVESTIGATOR PROFILES

Professor **Frederick V. Lawrence** entered Haverford College in 1956 and received a B. S. in Civil Engineering in 1960 from Swarthmore College. He attended graduate school at the Massachusetts Institute of Technology where he specialized in Civil Engineering receiving an S. M. degree in 1962 and a Civil Engineer's Degree (C. E.) in 1965. In 1968, Professor Lawrence obtained a doctorate (Sc.D.) from M. I. T. in the area of Materials Science.

Professor Lawrence joined the faculties of Metallurgy and Mining Engineering and Civil Engineering at the University of Illinois in 1968 as an assistant professor. He was promoted to the rank of associate professor in 1973 and to full professor in 1977. Professor Lawrence has taught courses in welding and materials engineering and science. His research activities have been concentrated on the topic of mechanical properties of welds, and he has written numerous technical articles on the influence of weld discontinuities on their tensile and fatigue properties. He has published over one hundred reports and technical papers.

From 1976 to 1989, Professor Lawrence was the Director of the UIUC Materials Engineering Research Laboratory. He was the Co-editor of the ASCE Journal of Materials in Civil Engineering from 1998 to 1996. Since August 1996, Prof. Lawrence has been an Associate Head of the Department of Civil Engineering at the University of Illinois at UC. In September 2000, Prof. Lawrence was appointed the Director of the Newmark Structural Engineering Laboratory.

Professor Lawrence has studied the factors that control the fatigue behavior of welded components, and he has developed analytical methods for estimating the total fatigue life of welds. Recent studies include development of improved thermite welding procedures, fatigue life of weldments with longitudinal attachments, modeling the effects of crack closure in weldments.

Jeffrey P. Cyre was born and raised in Edmonton, Alberta, Canada. In 1996 he entered into the University of Alberta, where he went on to receive a B.S. in Civil Engineering degree in May 2000. He will be graduating with a M.S. in Civil Engineering degree in May of 2002 from the University of Illinois with a specialization in construction materials.

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TABLE 1 – Fatigue test results for standard and modified thermite welds

ID	Welding System	Load Range (kN)	Fatigue Life (cycles)	Fracture Surface Observations and General Comments	Crack Depth (mm)	Distance from NA to Location of Crack Initiation (mm)
1	A	867	784	Failure caused by insufficient fusion of the web and head, some fusion at the base.	-	-
2	A	868	35,624	Brittle fracture, head riser to early and caused V-notch in head, small indication of failure at web-base interface, very little fatigue crack growth before failure.	0	62
3	A	-	-	Weld blow out!	-	-
4	B	868	24,267	~2 mm crack propagation site. Indication of failure at web-base interface, very little crack growth before brittle fracture.	2	58
5	A	735	91,801	~6 mm crack growth. Indication of failure at web-base interface, very little crack growth before brittle fracture. The growth was kept to one out of the two toes.	6	63
6	A	779	47,570	~5 mm crack growth site. Indication of failure at base of weld, very little crack growth before brittle fracture. Large cold laps present in base of weld	5	80
7	C	734	40,070	~3 mm crack growth site. Indication of failure at web-base interface, very little crack growth before brittle fracture. Presence of cold laps	3	61
8	Mod A	734	65,163	~4 mm crack growth site at one of the toes on the fracture surface and ~ 2 mm at the base. Small cold lap on toe side that has crack growth. Small cold lap at base bottom where cracks initiated.	4	58
9	C	734	18,550	Very small amount of cracking from one of the weld toes on the fracture surface. Large cold lap at center of web, smaller cold lap at base bottom, small porosity hole near base, off center.		54
10	C	-	-	Weld blow out	-	-
11	A	734	84,943	Fatigue Crack initiated from at weld toe.	4	60
12	B	690	24,872	Failure initiated at web-base fillet. No cold lap or inclusion present. May have initiated from packing mud particle.	1	62
13	New A	689	21,118	No cold laps present, no crack initiation. Packing material present at location of failure initiation.	<1	57
14	Mod A	0	-	No test, specimen Sectioned.	-	-
15	Mod A	0	-	No test, specimen Sectioned.	-	-

ID	Welding System	Load Range (kN)	Fatigue Life (cycles)	Fracture Surface Observations and General Comments	Crack Depth (mm)	Distance from NA to Location of Crack Initiation (mm)
16	Mod A	734	50,969	Dominant fatigue crack initiated from cold lap at web-base fillet. Cold lap present in web area.	3	55
17	Mod A	734	8,017	Fatigue crack initiated from inclusion at the base, close to web-base fillet.	<1	60
18	Mod A	690	51,043	Failure initiated from indentation which caused inclusion at the base.	1	60
19	Mod A	690	3,417	Failure due to incomplete fusion at the base.	-	75
20	Mod A	601	52,091	Failure initiated from indentation caused by inclusion at the base.	<1	65
21	Mod A	334	2,000,000+	Run-out.	-	-
22	C	467	177,888	Multiple cold laps present. Cold lap present at location of fatigue crack initiation.	16	60
23	C	467	204,481	Multiple cold laps present. Failure crack initiation at cold lap.	17	61
24	C	467	156,405	Multiple cold laps present. Failure initiation at cold lap location	19	61
25	New A	0	0	No test. Melt back measurements.	-	-
26	C	467	192,061	Multiple fatigue cracks preset. Failure initiation at cold lap location.	15	59
27	New A	0	0	No test, melt back measurements.	-	-
28	Mod A	467	440,640	Multiple cold laps present. Fatigue crack initiation at cold laps. Stemming paste shifted along the surface both cold laps towards the base.	11	61
29	A	467	129,400	Multiple cold laps present. Fatigue crack initiation at cold lap.	5	61
30	Mod A	467	20,482	Large slag inclusion in center of base of weld.	-	-
31	Mod A	467	840,326	Failure at large slag inclusion, trapped by mold modifying material.	12	63
32	Mod A	512	685,410	Failure at small slag inclusion trapped below mold modification material.	7	61
33	Mod A	512	152,616	Cold laps on both sides of rail base. Stemming paste was not located at the correct spot for cold lap that initiated failure. Other location of cold lap was shifted downward because of the stemming paste.	13	62

ID	Welding System	Load Range (kN)	Fatigue Life (cycles)	Fracture Surface Observations and General Comments	Crack Depth (mm)	Distance from NA to Location of Crack Initiation (mm)
34	Mod A	467	889,514	Very small cold lap at initiation point. Cold lap is at location where stemming paste missed.	11	65
35	Mod A	467	333,678	Failure at large inclusion trapped by mold modification material at surface of weld.	1	60
36	Mod A	467	46,540	Large inclusion at the off-center base of weld. Mold modification material caused inclusion.	-	-
37	Mod A	467	214,292	Cold lap at failure point. Inclusion located vertically opposite of cold lap. Small amount of crack from inclusion. Inclusion located 2 mm below surface. Hot tear in head.	4	62
38	Mod A	467	134,455	Crack initiated at the web-base fillet area. No cold lap present. Crack initiated at the surface of the weld. Possibly caused by small particle(s) trapped by stemming paste.	<1	59

6. LIST OF FIGURES

FIGURE **PAGE**