

**Innovations Deserving
Exploratory Analysis Programs**

High-Speed Rail IDEA Program

Reliability of Improved Thermite Welds

Final Report for High-Speed Rail IDEA Project 41

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Reliability of Improved Thermite Welds

IDEA Program Final Report
For the Period January 2002 Through June 2004
HSR-41

Prepared for
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Transportation Research Board
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ABSTRACT

This IDEA program study (HSR-41) confirms the results of its prior IDEA program study (HSR-24) that thermite-weld fatigue resistance can be significantly and reliably increased by improving the shape of the weld-toe in the web-base fillet and rail-base regions of the weld and by suppressing common weld-toe defects found there. Laboratory 4-point bending fatigue tests were carried out on five series of thermite welds: three series had a standard external shape currently in use and two series had an improved shape developed in this study. Test laboratory results show that improved welds have a fatigue life approximately 2 times that of standard welds.

Twenty-one (21) welds with the improved shape were installed in the TTCI FAST track facility in Pueblo Colorado. Several of the 21 welds failed prematurely; and thus, all of the remaining 21 were removed from the track. A small fabrication fault in the web of the improved welds was identified and has been corrected, new molds are being manufactured and a second series of improved welds will be installed in the FAST track.

KEY WORDS

Weldment Fatigue, Thermite Rail Welding, Fatigue Life Improvement, Thermite Welding, Welding

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EXECUTIVE SUMMARY

A previous concept-exploration project funded by the High-Speed Rail IDEA program (HSR-24) determined that thermite-weld fatigue resistance can be significantly increased by improving the shape of the weld-toe in the web-base fillet and rail base regions of the weld and by suppressing common weld-toe defects found there (FIGURES 1 and 2).

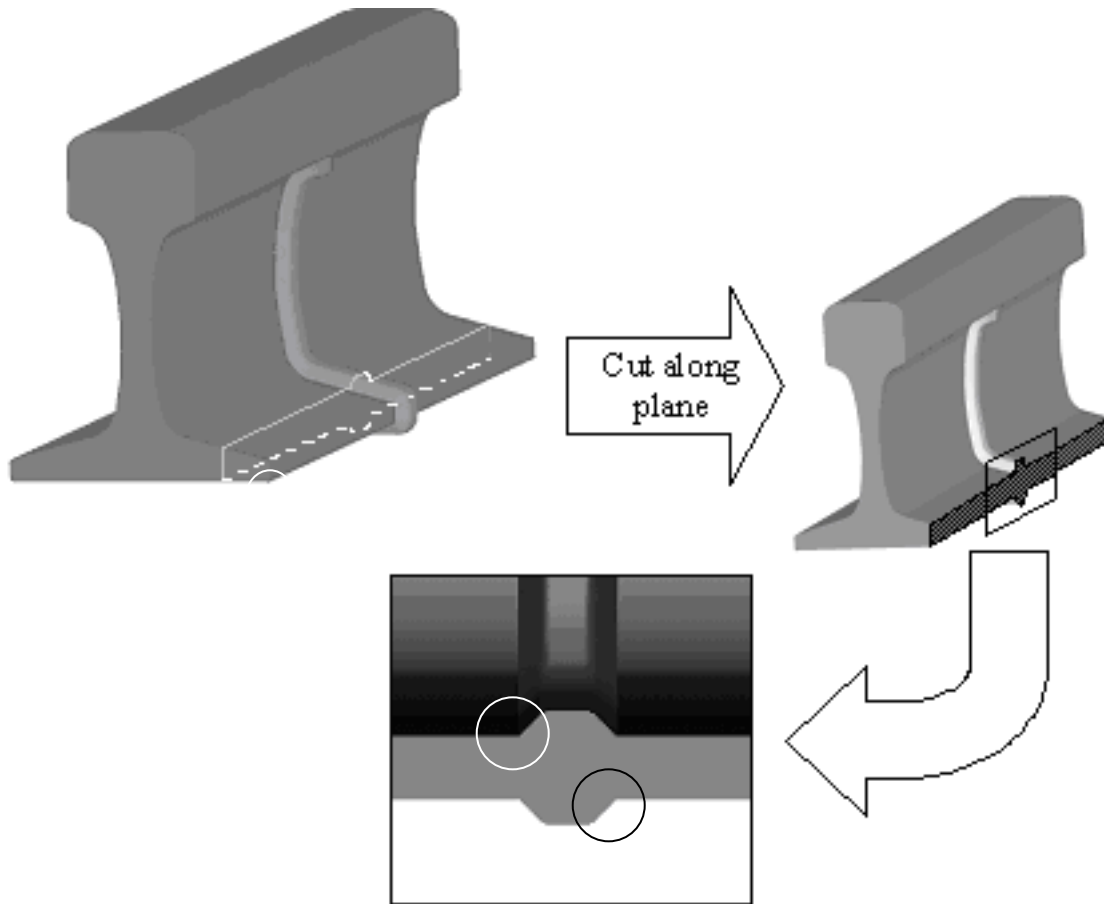


FIGURE 1 The thermite rail-weld weld-toe. Section of a thermite weld in the rail base. The circled regions are at weld-toes.

The objectives of this follow-on study were to confirm the fatigue life improvement and to assess its reliability in service. To these ends, laboratory 4-point bending fatigue tests were carried out on five series of thermite welds: three series (A, B and C) had standard shapes currently in use, and two series (D and E) had an improved shape developed in this study. To enable the study to be carried out in a reasonable period of time, a load of 628 kN was used for all tests. This load is equal to 148 kips and is about 6 times greater than the wheel load of a 100 ton car (25 kips). Test results showed that improved welds have a fatigue life approximately 2.0 to 2.5 times that of the standard welds under laboratory test loads (FIGURE 3). The effect of mold washes was studied, but no systematic improvement in fatigue life could be attributed to the use of mold washes. A thermal simulation model of thermite weld solidification was developed in partnership with the TTCI, and some results of that study are presented in this report. A more comprehensive report will be available in the fall of 2004.

Twenty-one (21) “improved” welds similar to Series D and E were installed in curved sections of the TTCI FAST track facility in Pueblo Colorado (FIGURE 4). Five of the 21 welds failed at an unacceptably short fatigue life (<30 mgt); and to avoid further difficulties, all 21 welds were removed from the track. It is possible that the state of stress in the FAST track is characteristic of over-balanced curves and causes different regions of the weld to be more highly stressed than in this study’s laboratory 4-point bending tests. A small fabrication fault found in the web of all the improved welds - in a region remote from the improved regions in the base - caused the premature failures. The small

fault in the web of the improved weld molds has been corrected, new molds are being manufactured and a second series of improved welds will be installed in the FAST track to determine whether the results and observed improvements found in the laboratory studies hold true in the field.

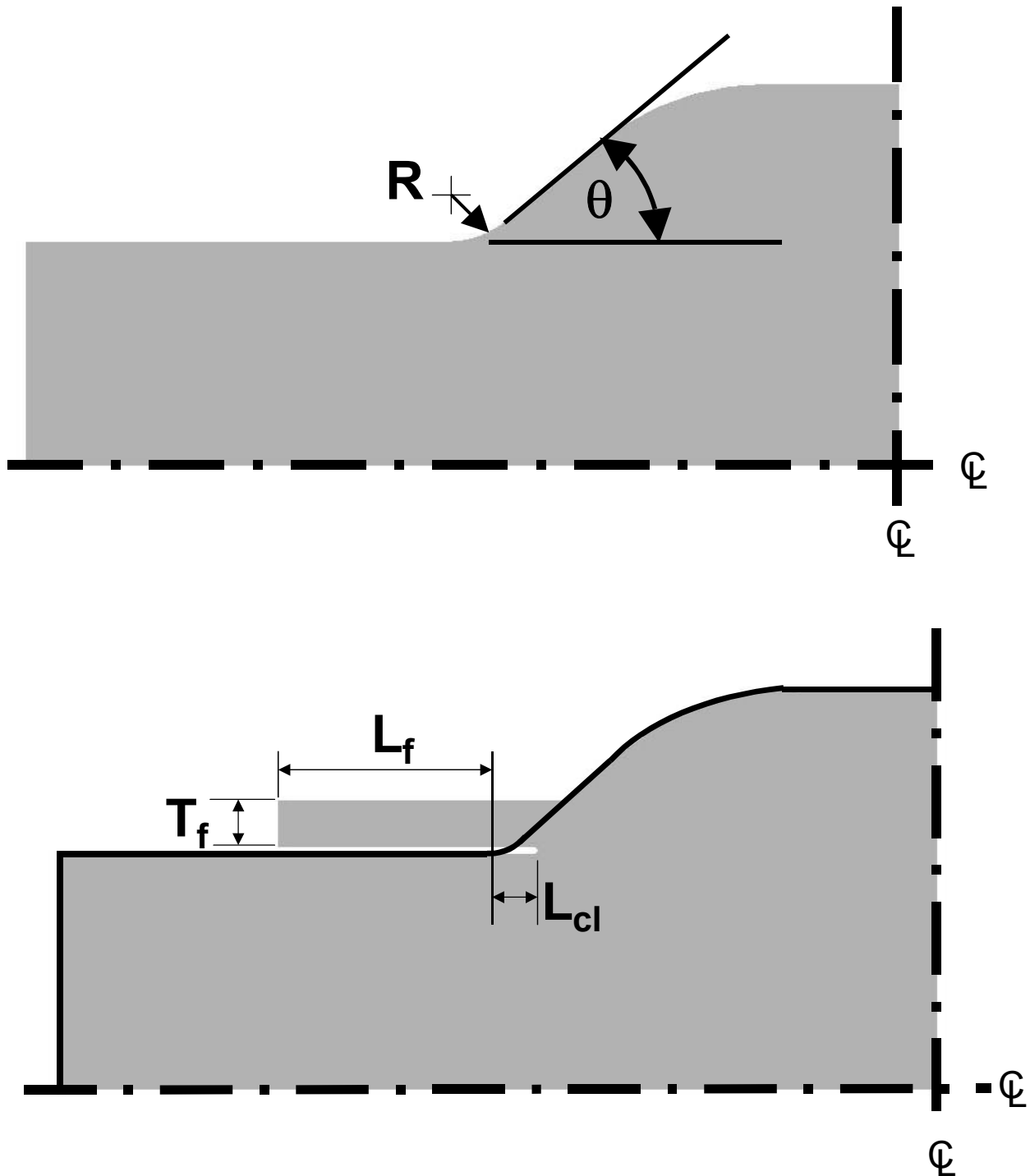


FIGURE 2 (above) Geometry of a thermite weld-toe without fins or cold laps: R is the weld toe radius and θ is the flank angle. (below) Geometry of a thermite weld-toe with both a fin and cold lap defect: T_f is the fin thickness, L_f is the fin length and L_{cl} is the cold lap length. All measurements originate at the point of tangency between the weld reinforcement and the rail. The solid outline indicates the defect-free geometry.

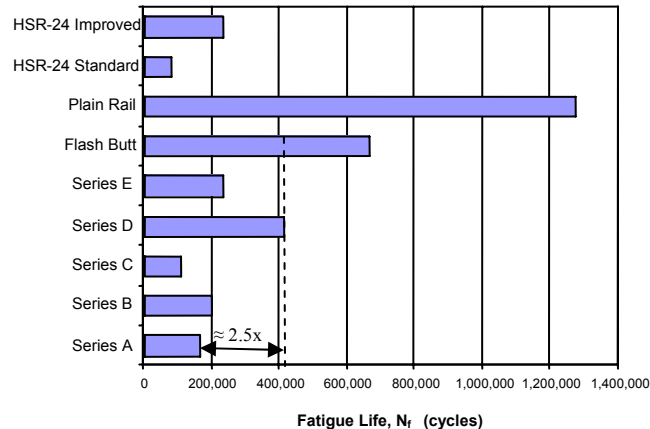


FIGURE 3 Fatigue lifetimes from laboratory tests for various weld types at an equivalent load range of 628 kN. (Extrapolated) HSR-24 results [1, 2], plain rail data from [3] and flash-butt data from [4]. Improved welds (Series D) had an average life time approximately 2.5 times longer than the average for the standard welds (Series A).



FIGURE 4 A thermite weld being fabricated at the Transportation Technology Center Inc. at Pueblo, Colorado. The weld is being produced using a single-use crucible. Picture taken shortly after ignition of the thermite charge and prior to self-tapping.

IDEA PRODUCT

The IDEA product that will result from this investigation is improvements in the standard method of welding thermite rail welds that will increase the thermite-welded rail's fatigue life in the base and web region. The findings of the project will provide thermite welding system manufacturers and railroads with the data and information needed to determine the cost-effectiveness of the new techniques and to implement the concept.

CONCEPT AND INNOVATION

The innovative principles which served as the basis of this IDEA product was the concept that thermite rail welds, like fusion welds in the past, were optimized to resist static loads rather than repeated (fatigue) loading. Viewed from the perspective of resisting fatigue crack initiation and growth, the stress-raiser caused by the standard thermite web-base and rail-base weld toe is a serious fatigue notch. In this project, it was demonstrated that improving the geometry of the web-base weld toes can substantially reduce the severity of the fatigue notch there and consequently lengthen the fatigue life of the thermite rail-weld.

1 INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

Field welded rail joints are a frequent source of service failures in the North America (NA) railroad infrastructure; as such, they have a major impact on rail service reliability and safety. For example, a Class I railroad reports 14 rail 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.

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.

1.1.1 Why do thermite welds fail in fatigue?

Fatigue is a process in which cracks are formed in regions of high stress or strain concentration and enlarge until the component finally breaks. FIGURE 5 illustrates the three stress-concentrating locations in thermite field welds where fatigue cracks commonly develop:

- Rail heads where fatigue cracks initiate at *internal* stress concentrations - inclusions and pores.
- Rail web locations where cracks initiate at *external* stress concentrations - weld toes.
- Rail base locations where cracks initiate at *external* stress concentrations - weld toes.

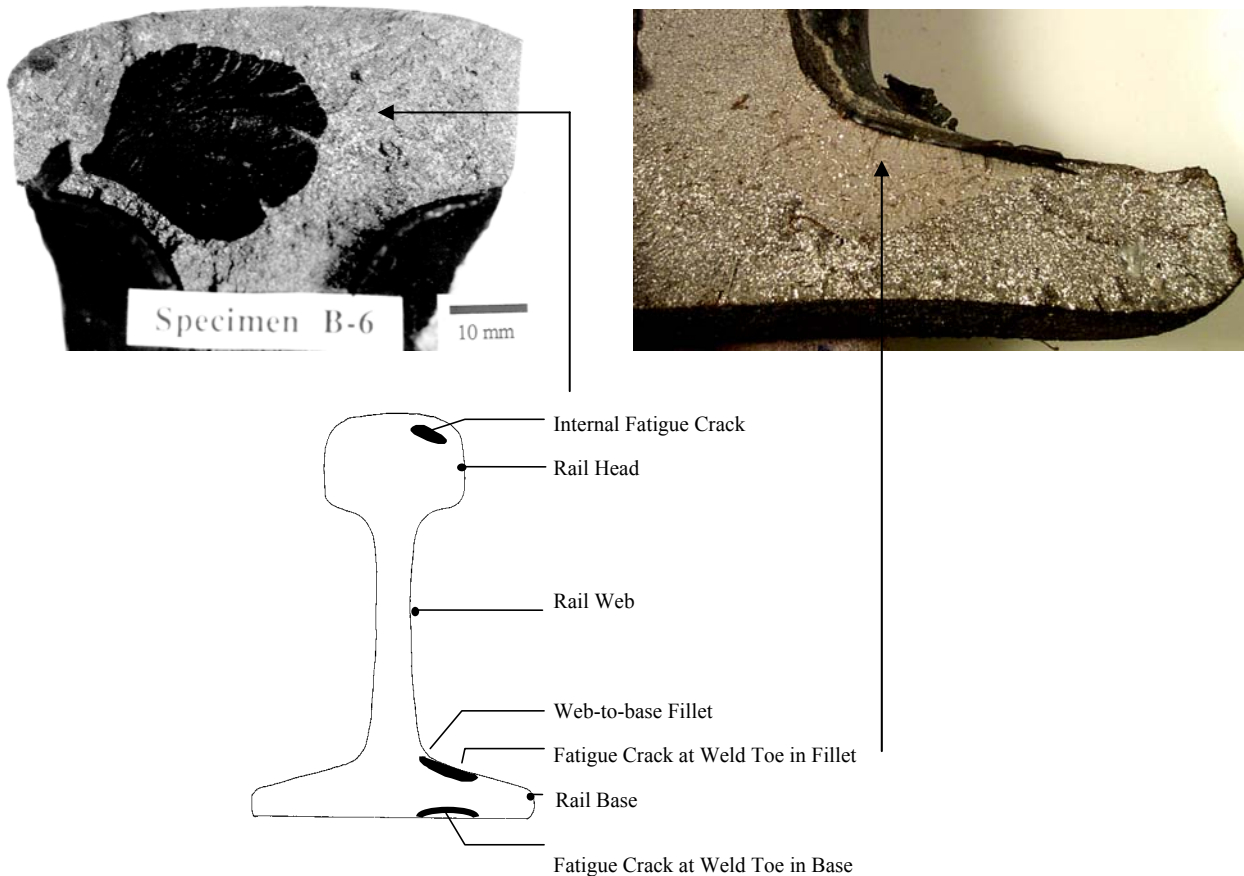


FIGURE 5 Locations of common sites for fatigue crack initiation in thermite rail welds. (Above, left) Detail fracture initiating at shell defect in rail head. (Above, right) Fatigue failure originating at cold lap located in the web-base fillet. (Below) Locations of common sites in a thermite weld cross-section.

Railhead defects are actually more frequent than rail failures originating in the web and base locations, but railhead defects and associated fatigue cracks generally do not cause failure because they are usually detected and repaired. Another Class I railroad reports that “mark-outs” (that is, detected and removed rail head flaws) exceed actual broken rails (service failures) by a 2 to 1 ratio. Thus, most service failures initiate at cracks in either the rail web-base fillet or rail-base locations. These observations are confirmed by a study in which 244 thermite service failures reported by a Class I railroad were analyzed [5]. This study suggests that the majority of failures occur in the web (28%), base (30%), and web-base fillet (30%) regions (FIGURE 6). However, experience prior to 1995 at the Transportation Technology Center Inc. (TTCI) in Pueblo, Colorado, at the Facility for Accelerated Service Testing (FAST) suggests that the principal failure modes are not the base and web regions but shelling and web cracking [6]. Since 1997 to date, 90 percent or more thermite weld failures initiate at the base or base-web fillet [7].

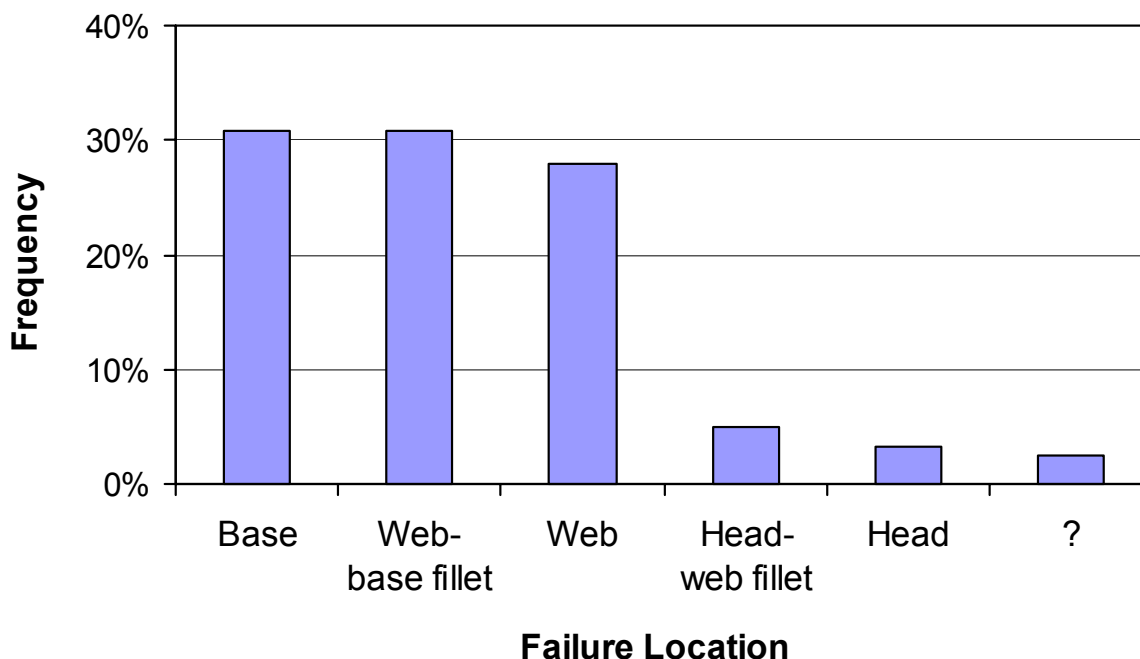


FIGURE 6 Histogram of failure locations for 244 service failures reported by a Class I rail-road to have been caused by thermite welds. [1, 5].

1.1.2 Fins and cold laps: common fatigue-crack- initiating, rail-base weld defects.

The mentioned study of 244 service failures also indicated that the most common welding defect associated with these thermite weld service failures (FIGURE 7) is “fins.” Fins (sometimes called flashing or run-out) are a common thermite weld defect that arises when the sand molds do not perfectly fit the rails and allow molten steel to flow into the consequent gap. In some cases, a fin fuses to the rail surface for most of its length; however, in many cases it does not causing a “cold lap.” The dimension of a fin and its associated “cold lap” are defined in FIGURE 2. Cold laps occur when there is insufficient heat input to melt the steel at the surface of the rail, but may also occur because the rail surface is badly contaminated with oxides or other foreign materials. The result is a notch defect that could possibly extend into (under) the weld reinforcement (collar); and for that reason, it is convenient to think of “fins” and “cold laps” as somewhat independent weld defects.

Fins can be avoided or reduced in size by improving the fit-up of the molds to the rail. The production welds of Series A and B of this study both utilized 2-piece molds – molds consisting of two pieces that each fit one half of the rail. For the improved welds of Series D and E of this study, 3-piece molds were used – molds consisting of two pieces that fit either side of the rail and a third, separate, bottom piece that fits the base of the rail. With the 2-piece molds, it is nearly impossible to eliminate gaps between the molds and the rails for two reasons:

- The manufacture of the molds requires a draft angle where the molds mate with the flat under base area.
- It is difficult and time consuming to cause the molds to closely fit the rail in *both* the base and the web-base fillet regions.

The 3-piece mold design allows the welder to attach the upper two mold pieces such that they fit snug at the web-base fillet without compromising the fit at the base.

Despite their being very frequently associated with fatigue failures in the base and web regions of the thermite weld, it is controversial as to whether or not fins are serious defects and actually decrease weldment fatigue life.

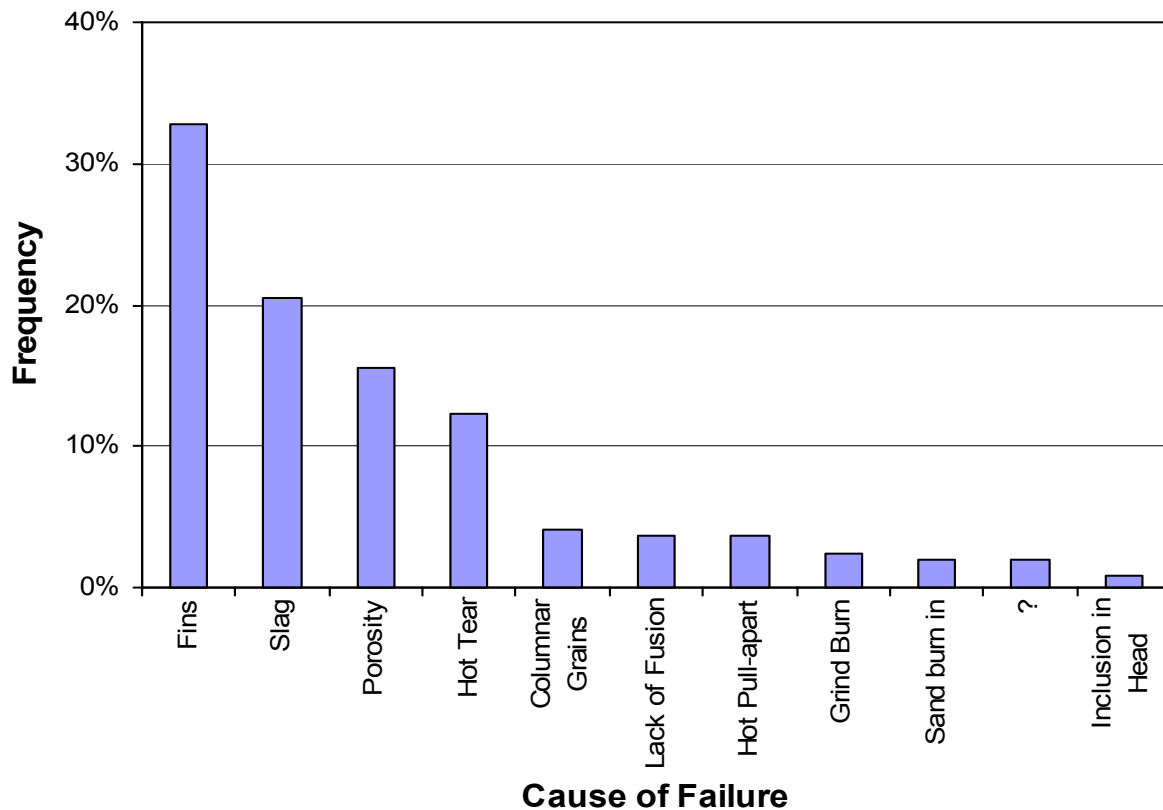


FIGURE 7 Histogram of defect type for 244 service failures reported by a Class I railroad to have been caused by thermite welds. [1, 5].

1.2 PRIOR STUDY (HSR-24) RESULTS

In the prior HSR-24 study, it was shown that the fatigue life of thermite rail welds could be increased by modifying standard thermite molds to improve the weld toe geometry in the fatigue-critical web-base-fillet and to avoid the formation of cold laps there. The weld-toe flank angle was reduced in experimental thermite welds by modifying the shape of the molds using a refractory molding compound. Other modifications to the standard thermite welding procedure included: sealing the gap between the mold and the fillet with refractory paste to prevent large fins from forming; and increasing the rail gap width from 25 mm. to 35 mm to ensure melt-back beyond the dimensions of the mold collar. The fatigue resistance of the experimental thermite welds is shown in FIGURES 3 and 8. No significant improvements were seen at higher load levels (short lives). However, at the load level corresponding to a 110 kip load (467 kN), welds having a reduced flank angle and being free of large cold laps had a mean fatigue life approximately 3 times greater than that of standard welds.

1.3 SCOPE OF THE PRESENT STUDY (HSR-41)

The scope of current project – HSR-41 “*Reliability of Improved Thermite Welds*” will be to perform full-scale laboratory tests on thermite welds using weld molds produced by mold manufacturers based on the concepts of HSR-24. The intent of HSR-41 is to confirm the fatigue life improvement and to assess its reliability in practice. Full-scale field tests at the TTCI test track facility using the most promising new mold designs and welding procedures will be carried out to demonstrate their effectiveness in service. The effect of mold washes on the as-cast surface roughness was to be studied, and a model of the solidification of thermite welds being developed in a parallel study was to be used to suggest optimum welding conditions for the new mold designs.

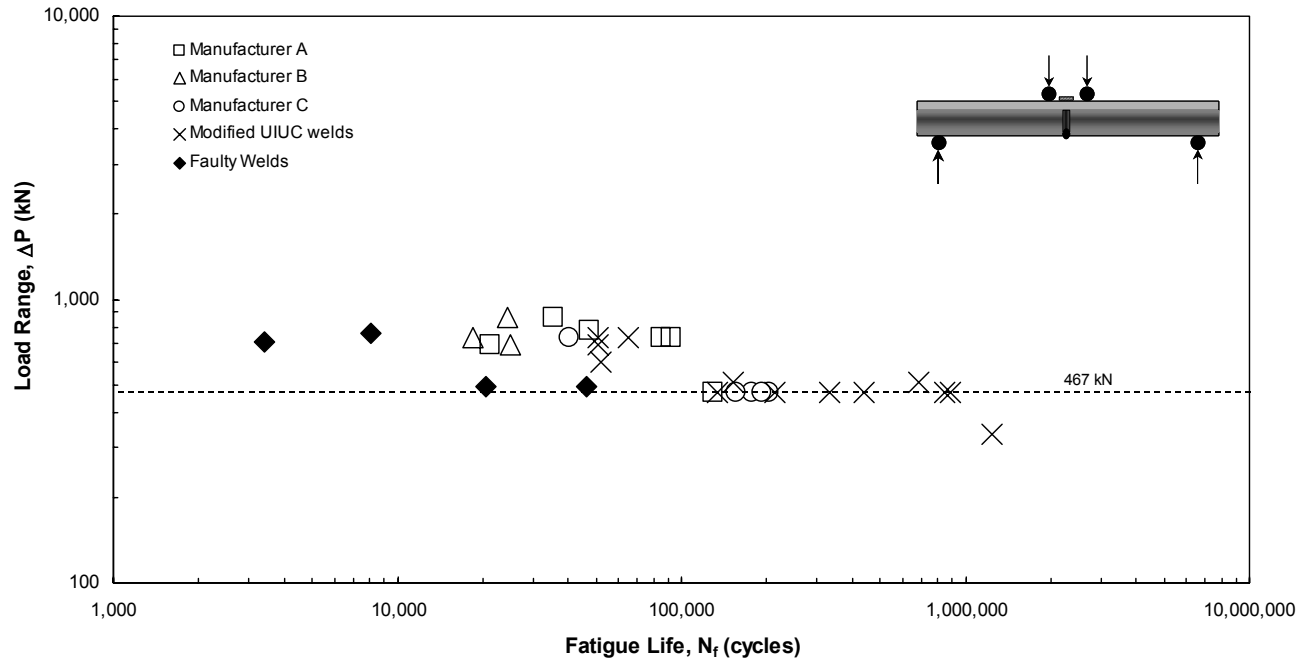


FIGURE 8 HSR-24 study fatigue test results [1]. Manufacturers A-C indicate standard welds from three different companies that chose to participate in the pilot study, all of which are comparable to Series A of the present study.

2 LABORATORY PROCEDURES

2.1 CREATION OF OPTIMIZED WELD-TOE SHAPES

In this study, a thermite weld manufacturer produced molds having improved weld-toe geometry and supplied ready-to-test weldments fabricated with these molds. Because all molds were made from the same pattern and no post-production modifications were made to the molds, the variability in shape from weld to weld was nearly eliminated thus preventing most problems experienced in the HSR-24 study, such as grossly defective welds resulting from the detachment of the refractory compounds applied to the mold interior. FIGURE 9 shows a comparison of the molds used in the HSR-24 study and in the present study. Because of the use of 3-piece molds, there was no need to utilize the sealing paste used in the HSR-24 study, seen as the dark patches near the toes in FIGURE 9a.

The modified sand molds were created in three steps:

- The web-base fillet of a standard aluminum mold pattern was modified. A toe radius along the edge of the collar of the aluminum mold pattern was machined using a 3 mm radius round end-mill tool.
- The weld-toe flank to an angle of 30° was decreased and made tangent to the milled weld-toe radius.
- A pattern for the base mold was made. No pattern was available for this; so it was machined from aluminum. The drawings for the base pattern are shown in FIGURE 10.

Once finished, the patterns were returned to the manufacturer for mold production and weld fabrication.

The silica sand and binder used for the molds of the improved welds were the same as for the standard production welds. Most molds were given a coating of zircon mold wash. In addition to having a much finer particle size than the usual silica sand, the zircon mold wash has a higher melting point and prevented the mold material from becoming fused to the weld surface. A potential disadvantage of using the mold wash is its extremely low gas-permeability, which can inhibit the escape of gases evolved during solidification and lead to surface porosity. This difficulty was largely avoided by applying the mold wash only locally in a stripe along the weld-toe of the mold.

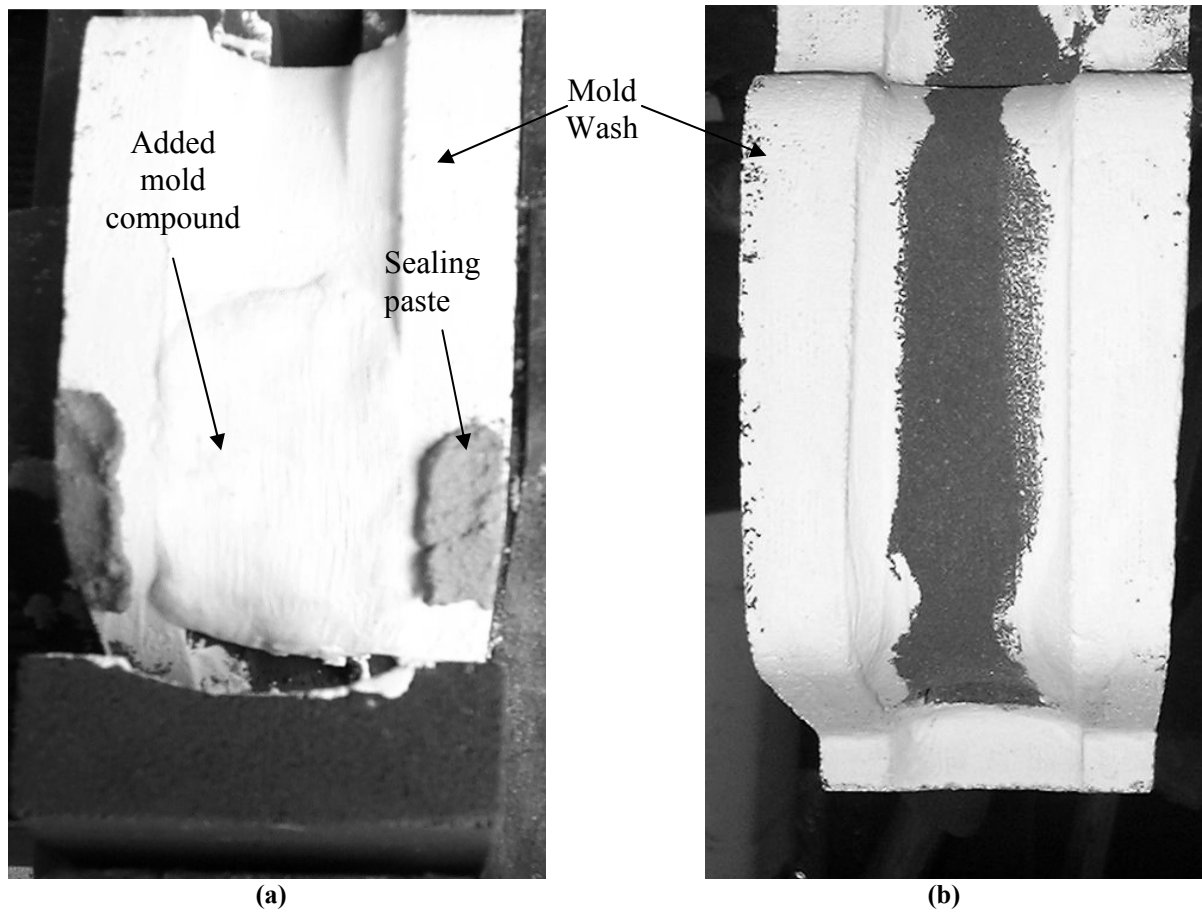


FIGURE 9 Mold halves from (a) HSR-24 [1, 2] and (b) the present study.

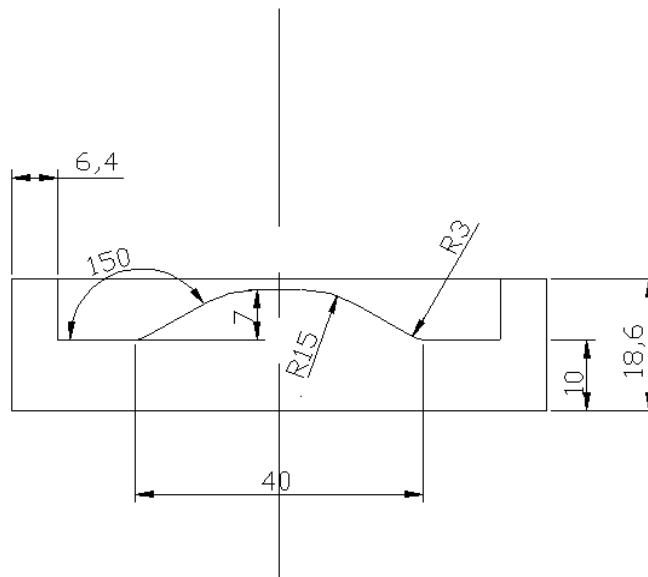


FIGURE 10 Section through the base-core pattern. All dimensions in millimeters.

2.2 FABRICATION OF WELDS

All welds employed in this study were fabricated using AREA 136 lb/yard RE carbon steel rail and were supplied to the investigators in a ready-to-test condition. The welds were made using a single-use crucible system and a premium composition thermite charge that matched the rail hardness. Five series each consisting of 10 weldments were created. Standard welding procedures were followed except as noted. Each of the five series had a different weld geometry and/or welding procedure: see TABLE 1.

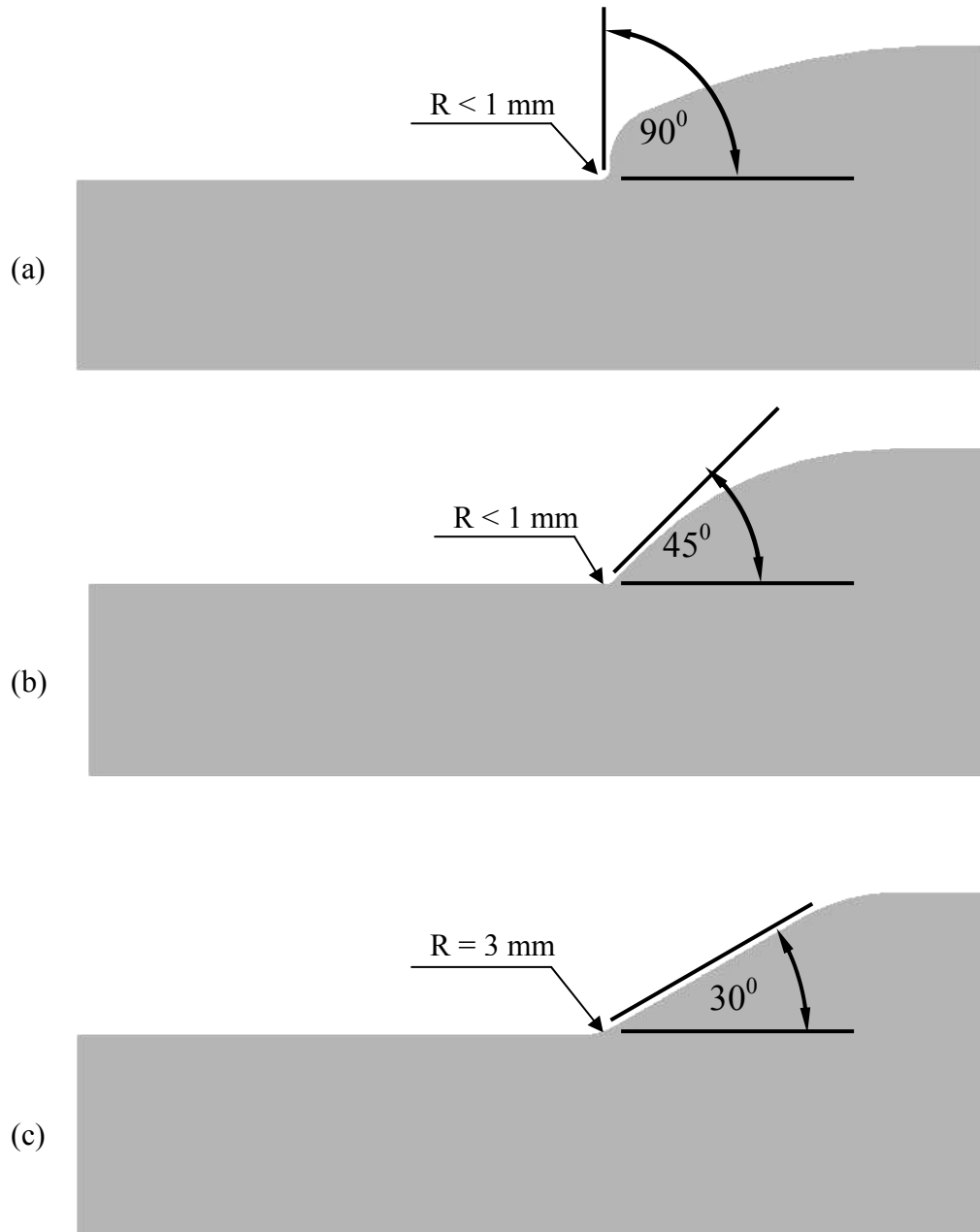


FIGURE 11 Weld geometries for (a) Series A, (b) Series B and C, and (c) Series D and E.

2.2.1 Series A: Standard Production Welds

Series A welds were made using a former standard thermite weld mold. This series served as a baseline for this study. The shape of the Series A weld-toe is shown in FIGURE 11a. A 2-piece mold was used for this series. The flank angle of the weld toes approaches 90° , and the mold does not have a significant weld-toe radius. Mold wash was applied to the entire mold face.

2.2.2 Series B: Reduced Flank Angle Production Welds

Series B welds were made using a newer style of thermite mold now in standard use. The flank angle of the Series B weld-toe has been significantly reduced to about 45°, but no finite weld-toe radius was incorporated into the design. The shape of the Series B weld-toe is seen in FIGURE 11b. A 2-piece mold was used for this series. The riser design is different from that in Series A. No mold wash was applied to the Series B molds.

2.2.3 Series C: 3-Piece Reduced Flank Angle Welds

The Series C welds were identical to those of Series B except that they used a 3-piece mold system. The collar cross-section of the base is slightly different from the web-base fillet area, but the weld-toe profile is very nearly the same, having a 45° flank angle and little to no weld-toe radius. A number of different mold wash strategies were tried with this series. In all cases, the base mold piece was entirely coated with mold wash; but the upper part of the mold had several different mold wash treatments. One mold set had mold wash applied to its entire surface, two mold sets had mold wash only at the weld-toe area, and the remaining seven mold sets had no mold wash applied to the upper pieces.

2.2.4 Series D: University of Illinois (Improved) Design Weld

Series D welds were made using molds modified to reduce substantially the weld-toe stress concentration. The mold modifications were suggested by the HSR-24 study and the FEM results of [8] (FIGURE 12). The weld-toe geometry of the Series D welds is shown in FIGURE 11c. The weld-toe had a flank angle of 30° and a weld-toe radius of 3 mm. As in Series C, a 3-piece mold design was used to achieve tight fit-up between mold and rail. The rail gap was 25 mm, as in Series A, B and C, but the preheat time was increased to 7 minutes to enhance melt-back.

2.2.5 Series E: University of Illinois (Improved) Design Weld with a Larger Gap

The Series E welds were identical in shape to those of series D. The single difference was an increase in the rail end-gap from 25 mm to 31 mm. Support for this idea is provided by the work of Ashton [9], who found through a multi-variable factorial experiment that optimal conditions for fatigue resistant welds includes a gap width of about 30 mm. The larger gap was intended to further increase melt-back by increasing the volume of superheated weld metal and thus the heat input to avoid cold laps. In hindsight, the increased weld gap was probably unnecessary. Over the course of this study, only a few (under collar) cold laps were found, and the majority of these occurred only at the extreme outer edge of the base. Also, Series E welds exhibited a much lower fatigue life than Series D (See FIGURE 3)

Table 1. Nominal welding conditions for the five series of thermite welds.

Series	Flank Angle, θ (Deg)	Toe Radius, R (mm)	Gap, G (mm)	Mold Pieces	Preheat (min)
A	80-90	<1	25	2	6
B	45	<1	25	2	6
C	45	<1	25	3	6
D	30	3	25	3	7
E	30	3	31	3	7

2.3 FATIGUE TESTING

Fatigue testing was carried out using the industry-standard 4-point bending fixture, shown schematically in FIGURE 13. The servo-hydraulic load frame used is rated at 2,600 kN and in all tests applied a sine wave cyclic load at a frequency of 2 Hz under load control. A minimum load of 22.4 kN was used in all tests. After a few initial tests at various load ranges, one maximum load of 650 kN was utilized for all remaining tests. Thus, the load range for nearly all tests was 628 kN. This load is equal to 148 kips and is about 6 times greater than the wheel load of a 100 ton car (25 kips). A strain gage (FIGURE 13) was affixed to each weldment to check the applied loads. The strain readings were generally slightly lower than the strain range calculated for the section of the rail, presumably because the weld reinforcement locally increased the moment of inertia above that assumed in the calculations.

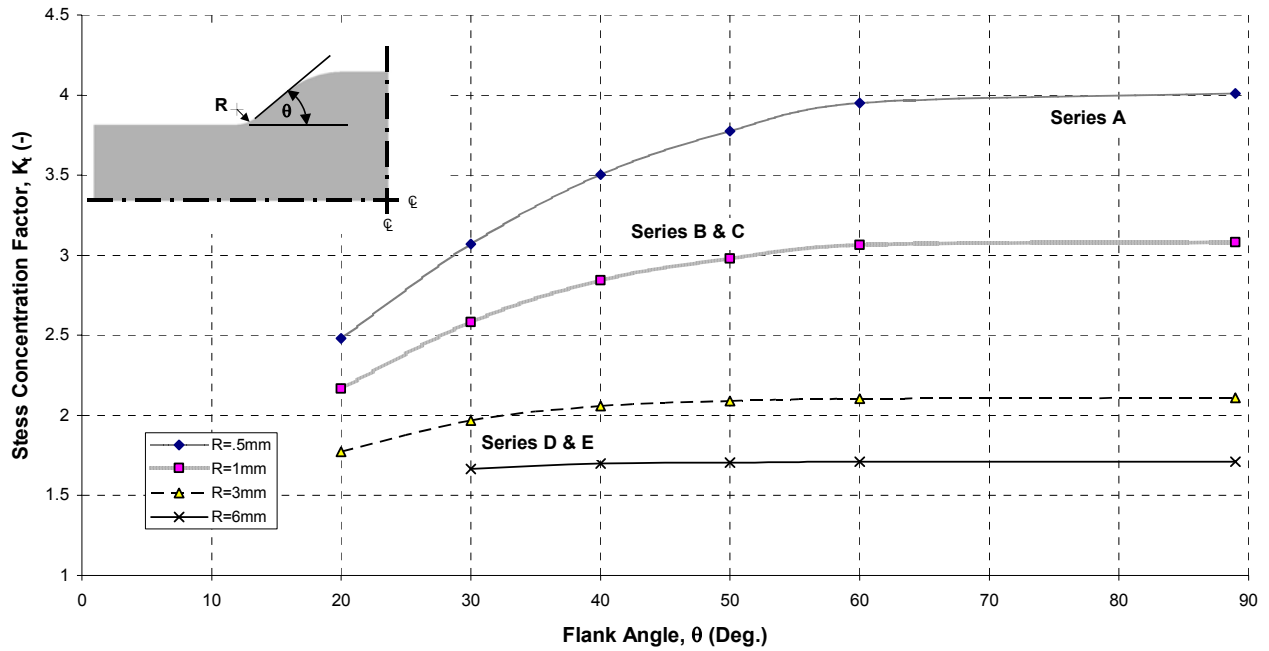


FIGURE 12 FEM predictions for the effect of flank angle and weld-toe radius on the stresses at the outer surface of the weld toe – the elastic stress concentration factor, K_t . Surface roughness effects are not considered [8].

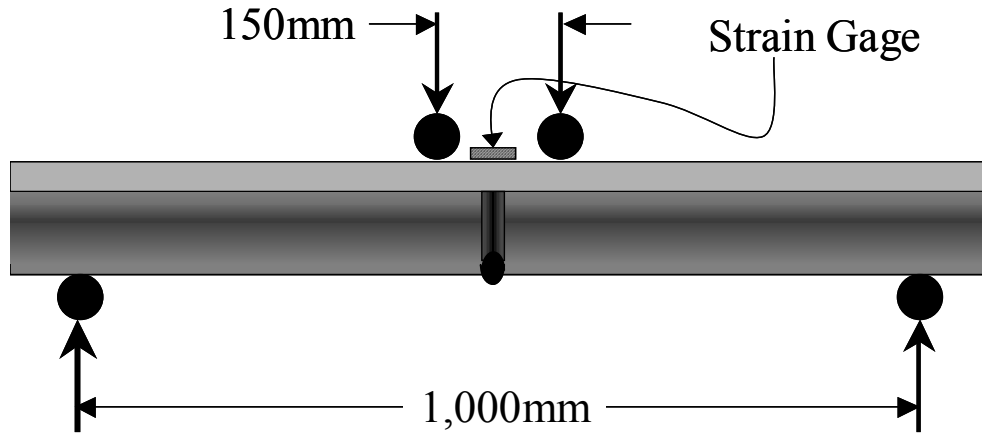


FIGURE 13 Schematic and dimensions of the 4-point bend test fixture used for fatigue testing. Due to the small separation of the points of load application, the stress state is in-between that of a true 4-point bend test and a 3-point bend test.

2.4 FRACTURE SURFACE EXAMINATION

The location of the crack initiation site was measured on the fracture surface using the coordinate system shown in FIGURE 14. Then each fracture surface was longitudinally sectioned through the fatigue crack initiation site to determine the fin size, the plane of fatigue crack initiation relative to the weld-toe and the location of the line-of-fusion relative to the weld-toe. FIGURE 15 shows a section taken longitudinally through a typical crack initiation site and indicates the measured quantities. All measurements were made using the weld centerline as the origin of coordinates.

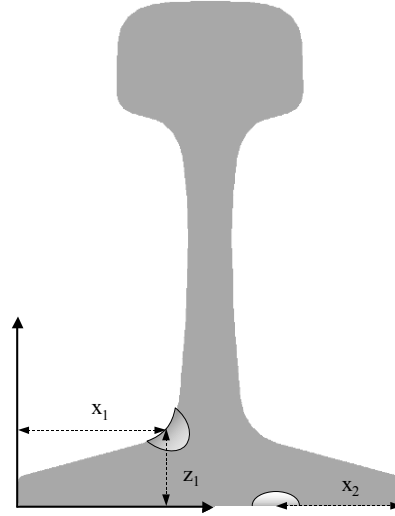


FIGURE 14 Measurement of the fatigue crack initiation sites. The origin of the coordinate system is the bottom corner of the rail base. Measurements are always taken from the corner nearer the fatigue crack initiation site. Two common locations are shown: site 1 is in the web-base fillet and is located at $(x=x_1, z=z_1)$ and site 2 is in the base and is located at $(x=x_2, z=0)$.

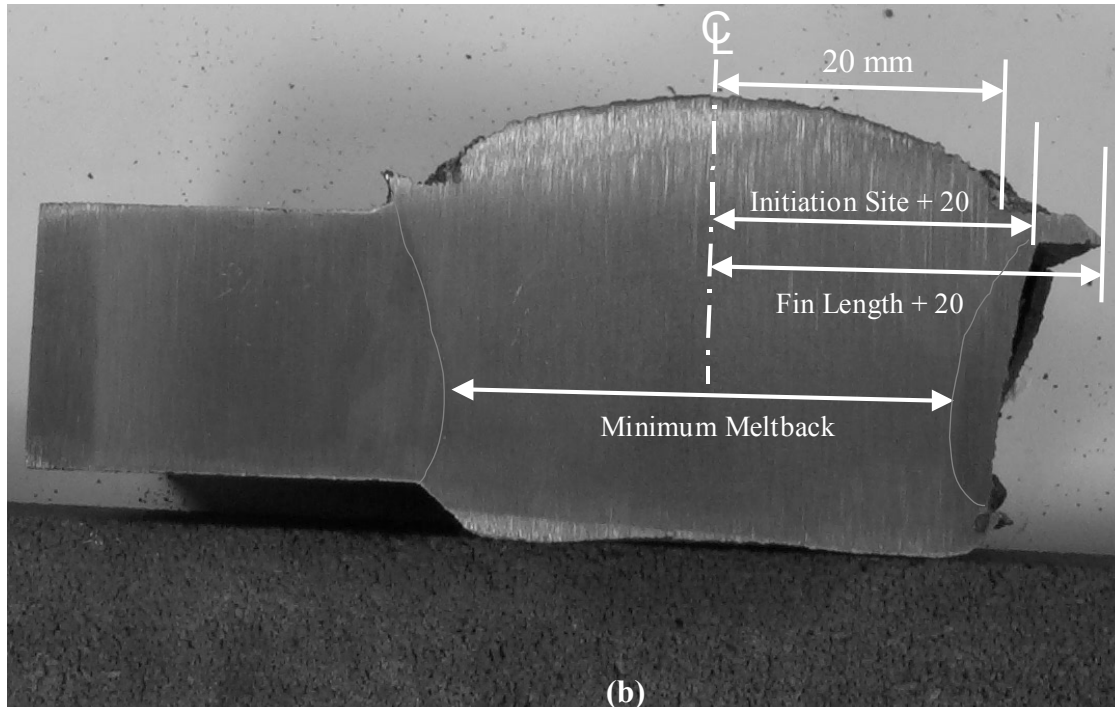


FIGURE 15 Typical section (cut through the crack initiation site for metallographic examination and measurements recorded,

3 RESULTS

3.1 FATIGUE TEST RESULTS

The experimental results for Series A-E are summarized in Table 2, which lists the fatigue lives of each specimen, the location of failure, and the nature and size of any fin present at the site of crack initiation. FIGURE 16 is a plot of the cumulative probability distribution of failure for the five test series as a function of fatigue life. The probability of failure

was calculated using a small-sample correction factor [8]. Table 3 summarizes the statistics of the test results for the five series based on a log-normal distribution. Indicated are the log-normal distribution parameters, estimates of the 95% confidence limits and the statistics for the natural log of the fatigue lives, $\ln(N_f)$, for all series.

Table 2a. Experimental data for Series A.

ID Number	Load, ΔP (kN)	Fatigue Life, N_f (cycles)	Failure Location				Fin Size		
			Base or Fillet?	Material	Distance from foot, x (mm)	Height, z (mm)	Thickness (mm)	Length (mm)	Crack Initiation Site (mm)
8740	748	84,498	B	HAZ	60.2	0	3	16.5	-1.3
8726	628	95,642	B	HAZ	73.9	0	1.7	16.7	-4.7
8725	628	124,388	B	HAZ	63.0	0.0	0.4	6.8	-4.7
8716	628	128,710	B	HAZ	68.1	0	2.5	14.8	-9.7
8739	628	128,881	B	HAZ	74.4	0	1.9	14.9	-7.2
8717	628	138,386	B	HAZ	55.6, 62.2, 72.1	0	1.1	9.6	-4.4
8730	628	224,868	F	HAZ	62.0	27.9	1.4	9	-4.4
8734	628	225,380	B	HAZ	73.7	0	1.8	15.2	-8.8
8731	628	228,726	F	HAZ	53.6	27.2	0.8	12.2	-2.3
8736	467	1,685,959	F	HAZ	37.3	20.3	0.8	6	-0.8

Table 2b. Experimental data for Series B.

ID Number	Load, ΔP (kN)	Fatigue Life, N_f (cycles)	Failure Location				Fin Size		
			Base or Fillet?	Material	Distance from foot, x (mm)	Height, z (mm)	Thickness (mm)	Length (mm)	Crack Initiation Site (mm)
8756	628	104,798	B	HAZ	75.9	0	2.7	19.5	-9.5
8741	628	120,212	B	WELD	69.6	0	2	20.3	-6.7
8761	628	135,136	F	WELD	52.3	26.2	0.8	3	-1.8
8765	628	141,535	B/F	WELD	71.4(B), 49.5(F)	0(B), 23.1(F)	1.4(B), 0(F)	7.7(B), 0(F)	-6(B), 0.7(F)
8766	628	144,743	F	WELD	48.3	22.9	-	-	1.4
8748	628	145,047	B	HAZ	74.7	0	3.8	Broke off	-5.6
8760	628	194,592	F	WELD	49.5	27.4	-	-	0.9
8757	628	197,742	B	HAZ	74.9	0	2.4	16.8	-8.1
8749	628	207,541	F	WELD	53.3, 52.6	30.5	-	-	0
8742	628	608,964	B	WELD	42.4, 74.7	0	-	-	0.8

Table 2c. Experimental data for Series C.

ID Number	Load, ΔP (kN)	Fatigue Life, N_f (cycles)	Failure Location				Fin Size		Crack Initiation Site (mm)
			Base or Fillet?	Material	Distance from foot, x (mm)	Height, z (mm)	Thickness (mm)	Length (mm)	
8953	628	70,939	F	HAZ	45.4	22	2.5	9.4	-4.4
8958	628	72,344	F	WELD	55.5	26	-	-	0
8945	628	75,961	F	HAZ	47.7	22.2	1.7	4.8	-3.1
8957	628	104,364	F	WELD	51.8, 50.5	25.1, 24.7	-	-	0
8940	628	104,999	B/F	HAZ	70.8(B), 36.3(F)	21	.5(B), 0(F)	2.3(B), 0(F)	0
8952	628	111,501	F	HAZ	40.8	20.5	2.7	12	-7.2
8947	628	117,264	F	HAZ	41.5	21.9	1.3	2.1	-1.2
8951	628	123,213	F	HAZ	44.1	22.4	1.8	5.9	-3.9
8946	628	129,066	F	HAZ	28.4, 53.3	18.5, 25.3	1.7	6.6	-2.7
8960	628	147,454	F	HAZ	40.7	21.6	2	3.3	-1.6

Table 2d. Experimental data for Series D.

ID Number	Load, ΔP (kN)	Fatigue Life, N_f (cycles)	Failure Location				Fin Size		Crack Initiation Site (mm)
			Base or Fillet?	Material	Distance from foot, x (mm)	Height, z (mm)	Thickness (mm)	Length (mm)	
9057	628	167,328	B	HAZ	69.7	0	-	-	0
9044	628	296,861	F	WELD	53.4	25.1	-	-	2.1
9046	628	309,485	F	WELD	37.3	20.0	-	-	1
9047	628	339,957	F	WELD	34.7	19.3	-	-	0
9043	628	346,952	F	HAZ	44.0, 23.0	21.8, 17.0	-	-	2
9055	628	347,417	F	HAZ	33.8	20.2	-	-	0.5
9054	628	372,090	B	HAZ	74.9	0	-	-	-0.5
9051	628	454,658	F	HAZ	31.2	19	-	-	0
9050	628	669,821	F	HAZ	27.5	18.7	-	-	0.9
9052	628	814,176	B	BASE	49.5	0	-	-	-

Table 2c. Experimental data for Series E. Entries with N/A indicate that the measurement could not be performed.

ID	Load, ΔP	Fatigue Life, N _f	Failure Location				Fin Size		Crack Initiation Site
			Base or Fillet?	Material	Distance from foot, x	Height, z	Thickness	Length	
	(kN)	(cycles)			(mm)	(mm)	(mm)	(mm)	(mm)
9208	628	160,396	F	WELD	51.9	25.1	-	-	3.3
9215	628	172,943	F	HAZ	44.8	22.1	0.5	1.5	0
9207	628	184,838	B	WELD	70.8	0	-	-	-0.4
9214	628	205,969	F	WELD	52.3	24.7	-	-	N/A
9211	628	217,218	F	WELD	56.06	26.3	-	-	1
9222	628	239,120	F	N/A	N/A	N/A	N/A	N/A	N/A
9224	628	269,666	F	HAZ	27.1	17.9	0.4	N/A	1.8
9212	628	274,574	F	HAZ	41.9	21.9	-	-	1.2
9210	628	291,947	F	HAZ	40.3	21	0.3	3.9	-2.9
9218	628	321,380	F	WELD	45	23.4	-	-	1.1

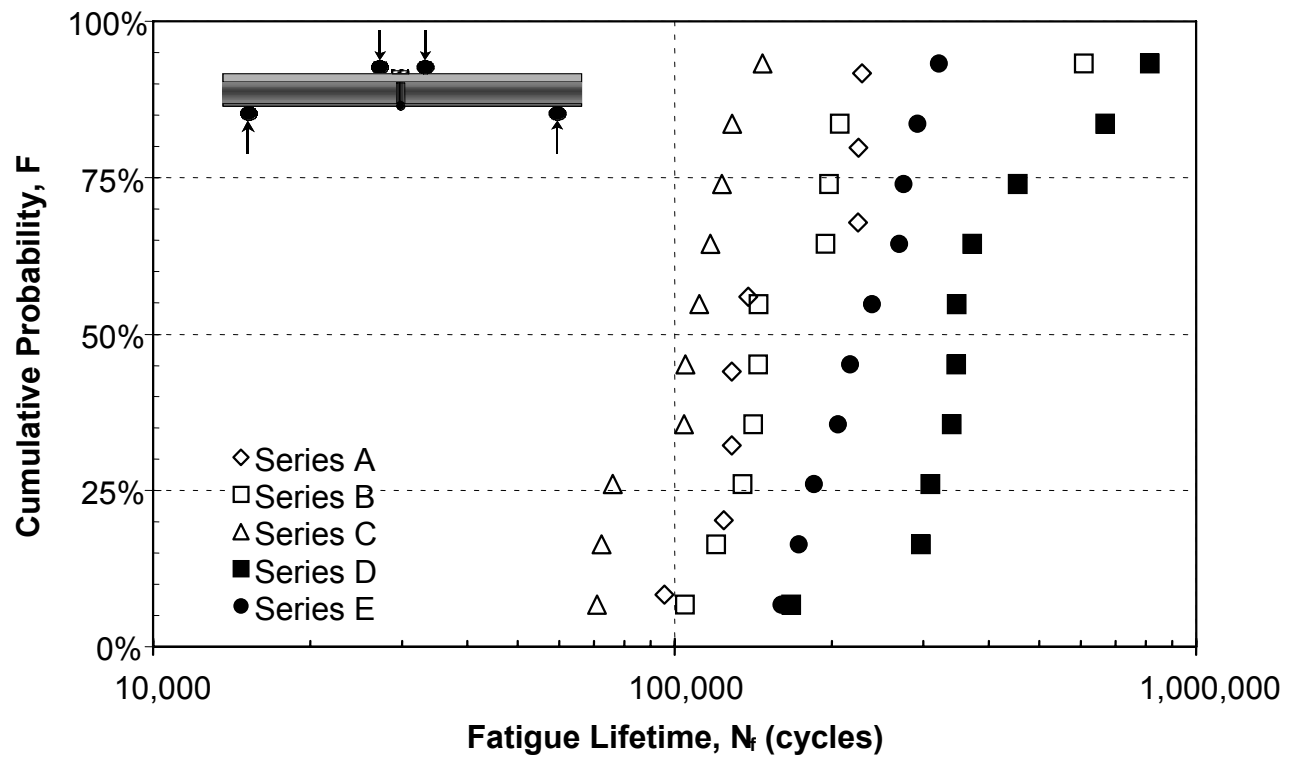


FIGURE 16 Cumulative probability distribution of fatigue lives of all welds of the five series tested at a load range, $\Delta P = 628$ kN.

3.1.1 Series A: Standard Production Welds

Statistical analysis of all Series A tests (at the nominal load range of 628 kN) indicates a mean lifetime of approximately 163,000 cycles with lower and upper 95% confidence limits of 122,000 cycles and 194,000 cycles, respectively. Table 2a shows that all Series A specimens had fin defects; and, consequently, the crack initiation sites were all located in the heat affected zone (HAZ). For Series A, most failures occurred in the base, and welds initiating fatigue cracks at the web-base fillet had longer lives than welds that initiated fatigue cracks at their base.

3.1.2 Series B: Reduced Flank Angle Production Welds

Statistical analysis of Series B tests indicates a mean fatigue lifetime of approximately 195,000 cycles with lower and upper 95% confidence limits of 128,000 cycles and 236,000 cycles, respectively. Series B had a longer average fatigue life than did Series A, although the confidence limits overlap considerably. Table 2b shows that Series B had far fewer failures originating at fins than did Series A and that welds failing at fins generally had shorter fatigue lives. Series B exhibits failures in both the base and web-base fillet area and neither region seems to give distinguishably different fatigue lives.

3.1.3 Series C: 3-Piece Reduced Flank Angle Welds

Statistical analysis of Series C tests indicates a mean lifetime of approximately 106,000 cycles with lower and upper 95% confidence limits of 88,000 cycles and 120,000 cycles, respectively. Table 2c shows that most Series C specimens had fin defects and consequently initiated the fatigue cracks in the HAZ material and that all failures occurred in the web-base fillet. Series C had a lower average fatigue lifetime than did Series A.

3.1.4 Series D: University of Illinois (Improved) Design Weld

Statistical analysis of Series D tests indicates a mean lifetime of approximately 415,000 cycles with lower and upper 95% confidence limits of 287,000 cycles and 495,000 cycles, respectively. Table 2d shows that all Series D welds contained no fins defects, that fatigue cracks initiated principally in the web-base fillet and that fatigue cracks were present in both the HAZ and weld metal. One weldment contained a large pore and exhibited the lowest fatigue lifetime and another specimen failed in the base rail prior to failure of the weld: both data points were included in the analysis. The mean fatigue life for Series D was 2.5 times that of Series A.

3.1.5 Series E: University of Illinois (Improved) Design Weld with a Larger Gap

Statistical analysis of Series E tests indicates a mean lifetime of approximately 235,000 cycles with lower and upper 95% confidence limits of 197,000 cycles and 264,000 cycles, respectively. Table 2e indicates that Series E had a few failures originating at fins, that most fatigue cracks initiated in the web-base fillet, and that weld metal failures exhibited shorter fatigue lives. The thickness of the fins was very small. The mean fatigue life for Series E was 1.4 times that of Series A.

Table 3. Statistical analysis of the fatigue lives for the five series of thermite weldments at $\Delta P = 628$ kN. Confidence interval estimates based on a log-normal distribution of the data.

Series	Lognormal Distribution Parameters		Fatigue Life 95% Confidence Interval		Statistics of $\ln(N_f)$	
	Mean, $E(N_f)$	Standard Deviation	Lower	Upper	Mean, μ	Std. Dev, σ
A	162,985	56,435	121,980	194,460	11.94	0.337
B	195,926	103,008	127,678	235,546	12.06	0.494
C	106,170	27,682	87,637	120,434	11.54	0.256
D	415,316	191,717	287,160	495,152	12.84	0.440
E	234,522	56,097	197,064	263,994	12.34	0.236

3.2 STATISTICAL INDEPENDENCE OF THE TEST RESULTS

Most experiments conducted in this study were all carried out using the same load range. This practice allows inferences to be made between the five series without the need for a model of the stress-fatigue life behavior or many tests. One-sided student's t-tests assuming unequal variances were performed to compare the five series. These statistical analyses indicate which, if any, of the test series have significantly different fatigue lives. Table 4 presents the probability that any two of the test series might share a common true mean. Taking the comparison between Series B and Series E as an example, there is a 7% chance that Series B has a true mean fatigue life equal to or greater than the true mean fatigue life of Series E even though the average life of the Series E specimens was greater than that of Series B specimens. There are two combinations, which are boxed in Table 4 that cannot be considered different from one another: Series A and B, and Series B and E. For all other comparisons, there is a high degree of confidence that they are independent of one another. It is also possible to see from the cumulative probability distribution plots of FIGURE 16 that Series A and B appear to

be very similar. The possibility of Series B and E belonging to the same population is much lower and a result primarily of scatter in the data.

Table 4. Student's t-test probability that the series in the row and column share a common mean (that the null hypothesis is true). Cells boxed indicate a high probability ($P > 5\%$) of an alpha type error.

	Series A	Series B	Series C	Series D	Series E
Series A		28%	<1%	<1%	<1%
Series B			<1%	<1%	7%
Series C				<1%	<1%
Series D					<1%
Series E					

3.3 FRACTURE SURFACE EXAMINATION

Each fracture surface was examined and all measurements are recorded in Table 2. Although the measurements were taken with respect to the centerline of the weld, Table 2 reports the distances with respect to the weld-toe. The weld-toe was defined as the point of tangency between the weld and rail in the design, which is 20 mm from the centerline for all series. The plane of crack initiation is a measure of where the fatigue crack initiated relative to toe of the weld. A negative value of crack initiation site indicates that the crack began in the rail, away from the weld-toe and a positive number indicates crack initiation in the weld reinforcement. This concept is shown for a positive value of crack initiation site in FIGURE 15.

4 DISCUSSION

4.1 COMPARISON WITH HSR-24 RESULTS

The HSR-24 results showed a fatigue life improvement of close to 3.5 times at a load range of $\Delta P = 467$ kN. It may seem, at first glance, that the present study did not fully realize the potential the HSR-24 study suggests; however, the difference in standard load range used in the two studies accounts for the apparent difference. FIGURE 16 shows that the results of the present study are, in fact, similar to those of HSR-24 when the data is converted to an equivalent load range of 628 kN (assuming a $-1/3$ slope of the load vs. cycles).

When the load ranges are all converted to the same level, the welds of the HSR-24 study tend to have a shorter fatigue lifetime than the welds of the present study. The most likely cause of this difference lies in the manufacture of the welds themselves. In the HSR-24 study, all welds were manufactured at the University of Illinois and employed a reusable crucible system. In contrast, the welds used in the present study were fabricated by a leading thermite weld manufacturer, were carried out by trained welders, and employed a single-use crucible. Moreover, the HSR-24 study utilized individually hand-modified molds to make the improved geometry welds; whereas, the present study developed a modified pattern to create identical molds for all tests.

The increases in fatigue live suggested by the HSR-24 study have been confirmed in the present study. Although the two studies did not use identical geometries, they were fundamentally similar – a smooth transition from the weld reinforcement to the rail surface. Both studies confirm that fatigue life can be improved through improvements in weld-toe geometry.

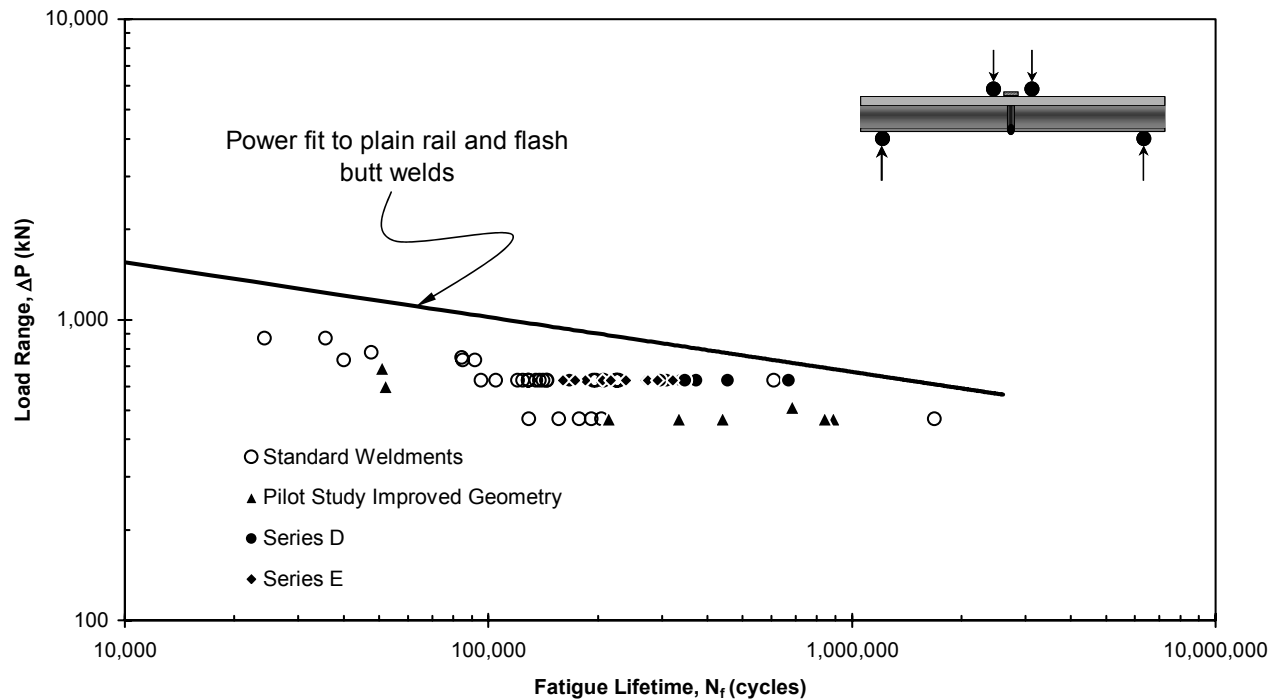


FIGURE 17 Fatigue performance of standard (production) thermite welds and improved geometry welds. Data for pilot study standard and improved geometry welds from [1, 2] and plain rail and flash-butt welds taken from [3, 4].

4.2 FATIGUE PERFORMANCE OF THE FIVE TEST SERIES

4.2.1 Predicted Behavior

Ross [8] used an analytical model to predict the fatigue behavior of the five test series and the effects of cold laps on each. The model considered both fatigue crack initiation and growth and was able to predict the experimental values of fatigue life of all specimens of all five series within a factor of 2. The model is reasonably accurate. The presence of either surface roughness (assumed to be the depth of the mold sand particles ≈ 0.1 mm) and/or the presence of a fin virtually eliminated any contribution to the fatigue life from fatigue crack initiation. Thus, the model's predictions reflect only crack growth from an assumed initial crack length of 0.025 mm and therefore do not depend much on surface roughness but do reflect the contributions of weld geometry and the presence of fins. Due to the fact that the residual stresses are compressive in both the web-base fillet and base regions, the estimation of residual stresses and their effect on crack growth through crack closure is very important. FIGURE 18 shows the model's predictions for Series A, B, C, D and E in the absence of fins. The model studies suggest:

- As discussed below, the improvements in weld shape of Series B and C do not effect much of an improvement, but the shape of welds in Series D and E are expected to show a fatigue life improvement of 2.5 times (FIGURE 18) at the test loads and as much as 3.3 under service loads of 70 Mpa or about 20 kips.
- The model [8] predicts that fins do not affect the fatigue life of Series A weldments but diminish the fatigue life of Series D. So the presence or absence of fins is not too important for Series A but quite important for welds having an improved weld shape (Series D). Fins can reduce the performance of Series D weldments to that of Series A. Ross [8] also showed that the severity of a fin was independent of its length but highly dependent on its thickness. The severity of the stress concentration provided by a fin increases linearly with its thickness. In the standard welds of this study, the fins ranged from 1 to 3 mm in thickness.

We believe Ross's model study and its conclusions above [8] agree with the experimental results and provide a succinct summary of the results of this study and their meaning.

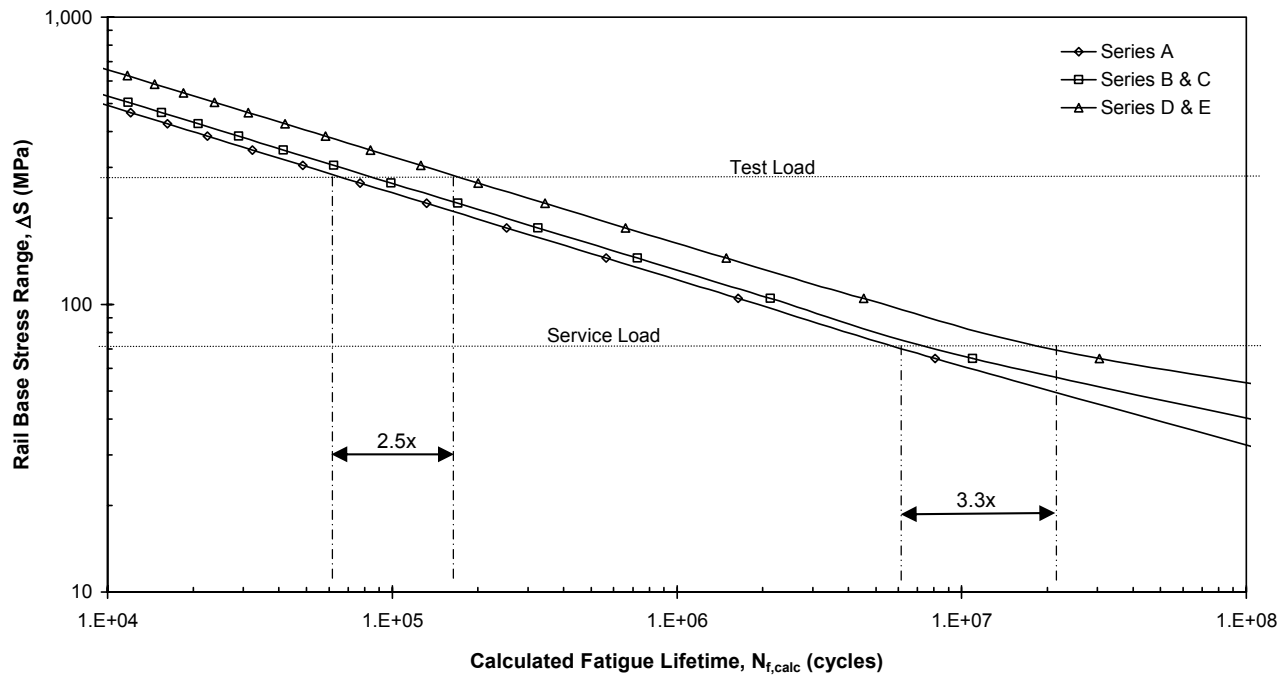


FIGURE 18 Stress-life predictions for the five thermite weld series [8]. The analysis is for welds without fins. Horizontal lines indicate the stresses from test loading and service loading. Vertical lines indicate the expected lifetimes at the aforementioned loading conditions for Series A and Series D. Crack initiation life predictions for a surface roughness depth of 0.1 mm. Crack growth life predictions for an initial crack size of 0.025 mm and final crack size of 5 mm.

4.2.2 Experimental performance of the standard welds (Series A, B and C)

Series A was the baseline for this study, and had an average fatigue life of 163,000 cycles at $\Delta P = 628$ kN. Series B had a marginally better average fatigue lifetime, but overall Series B was very similar to Series A, as evidenced by the overlap in their data in FIGURE 16. There are two major differences between Series A and Series B:

- Series B has a lower flank angle (45° versus 90°).
- Series A weld fabrication employed a mold wash treatment.

The effect of reducing the flank angle from 90° to 45° lowers the stress concentration factor by only about 10 – 15% [8]. It is not until θ is decreased to below 45° to about 30° that substantial improvements in the stress concentration are realized as is shown in FIGURE 12. The effect of the different mold wash treatments on fatigue life is not entirely clear due to the presence of fins at all failure sites of Series A. Cross-sections do reveal that Series B welds have a noticeable, but small toe radius, possibly from the silica mold material melting locally and wetting. This phenomenon does not appear in Series A when sections are taken at places that fins were not present. For this reason Series A stress concentrations were estimated for a toe radius of ≈ 0.5 mm and Series B for a toe radius of ≈ 1 mm. Series C was produced under the same fabrication conditions as Series B and has the same geometry as Series B, but has a significantly shorter fatigue lifetime than either Series A or Series B. No definitive explanation for this shorter life is available at the present time; however, one possibility is a difference in the residual stresses. Hardness testing did not reveal any difference between either the weld metal or the metal in the HAZ, where failures tended to initiate.

Series C utilized different mold washing strategies on 3 welds, but the results suggest no significant effect. Specimens 8958 and 8960 both had the mold wash at the toes only and Specimen 8957 had mold wash over the entire mold interior. Specimen 8960 did have the longest lifetime of the 10 specimens, but an identically treated specimen (8958) was one of the worst and specimen 8957 had an average fatigue life. Thus, all three series of standard welds seemed to behave about the same and neither the use of mold wash, differences in weld geometry, differences in failure

location, differences in material properties, nor presence or absence of fins seemed to influence the results in a systematic way.

4.2.3 Performance of the improved welds of Series D

The largest fatigue life improvement relative to the baseline Series A was achieved by Series D. Analysis of the test results reveals a fatigue life improvement of about 2.5 times that of Series A. This improvement can be attributed to:

- Series D welds have a much more favorable weld-toe stress concentration factor than either Series A, B or C. It should be noted that the improved stress concentration is due both the reduction in flank angle and the incorporation of a generous toe root radius.
- Series D welds did not have any fins. The stress concentration calculated by the FEM was approximately 50% lower than Series A.

4.2.4 Performance of the improved welds of Series E

Series E was intended to confirm the results of Series D and possibly show even greater improvements by completely avoiding the formation of cold laps. The concept was to increase the weld gap and thus increase the heat input to produce more melt-back, thereby avoiding cold lap formation: see FIGURE 19. This figure shows the results from a computer simulation of solidification in the center plane of thermite rail welds [10]. This simulation program was partly developed in this study and in a concurrent project with the TTCL. Predicted thermal profiles at the moment at which the head freezes (right) and predicted weld profile for a 25 mm and 38 mm weld gap (left) are shown in FIGURE 19.

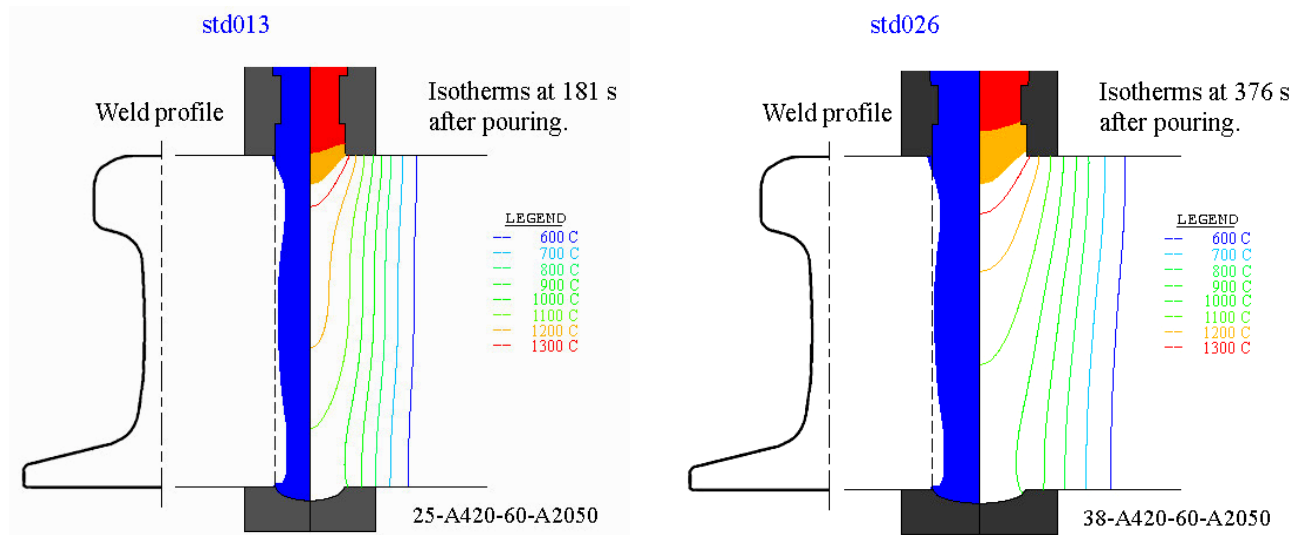


FIGURE 19 Results from a computer simulation of solidification in center plane of thermite rail welds. Predicted thermal profiles at the moment at which the head freezes (right) and predicted weld profile for a 25 mm and 38 mm weld gap (left) [10].

4.3 PERFORMANCE OF SERIES E

Much effort was expended in trying to explain why Series E did not perform identically to Series D, but, finally, no conclusive answer could be found. Series E had a higher heat input and thus a greater tendency to melt back to or beyond the edge of the collar. Any difference in performance between Series D and E might have resulted from:

- **Differences in weld toe geometry** - Series D and E were made from the same molds!
- **Differences in surface roughness** - Surface roughness was finally an uncontrolled and unmeasured variable in this study. It was what it was. Mold washes did not seem to make any difference. In any case, there would seem to be no reason for differences in surface roughness between Series D and E.

- **Presence of fins** – There were a few fins present in Series E, and none in Series D. The Series E fins were very thin, and thus did not cause the specimens in question to have noticeably shorter fatigue lives than other welds in Series E.
- **Differences in material properties** - The wider weld gap of Series E resulted in a greater heat input and presumably greater melt back. FIGURE 20 shows the observed effect of the various thermal conditions on the position of the line of fusion relative to the weld toe in Series A, D, and E. The line of fusion is nearly vertical in Series E weldments, and this may frequently result in fatigue cracks both initiating and growing to failure in weld metal. However as Tables 2d and 2e show the frequency of HAZ and weld metal involvement was the same in both series. Both Rockwell hardness (HRC) and Vickers hardness were measured in the sites of crack initiation but no large difference was found between the sites initiating cracks in Series D and E. Results from a study in progress [10] indicate that there is probably little difference in hardness between the HAZ close to the line of fusion and weld metal close to the line of fusion FIGURE 21; also, rotating bending specimen fatigue tests on smooth specimens of these materials taken from the rail base of similar thermite welds [10] indicate that the HAZ and weld metal near the line of fusion may have about the same fatigue resistance; but weld metal from the near the weld centerline has a significantly lower fatigue resistance (FIGURE 22).
- **Differences in residual stresses** - It was thought that there might be a difference in residual stresses between Series D and E due to the different thermal conditions resulting from differences in heat input (weld gap). Thus weld toe residual stresses in the fillets and base of Series B, C, D, and E welds were measured by X-ray diffraction. FIGURE 23 shows that the weld toe residual stresses prior to fatigue testing differ somewhat from series to series. In the fillet region, the pattern of residual stresses for Series B and C differ somewhat from the pattern for Series D and E. The residual stress patterns in the base show that series B has the least favorable (least compressive) residual stresses. FIGURE 24 plots the estimated fatigue damage in the fillet and base of each of the Series B, C, D, and E. Damage is the reciprocal of fatigue life. Series B and C have the highest values. Series D and E show similar behavior, so the measured residual stresses do not provide an explanation for the difference in performance for Series D and E.

Thus, no entirely satisfactory explanation for the difference in behavior between Series D and E can be offered.

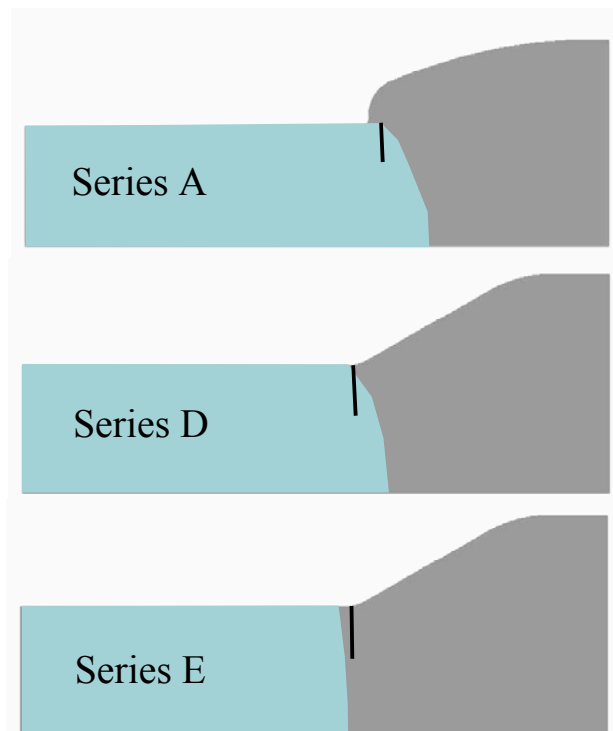


FIGURE 20 Schematic (roughly to scale) drawings showing the general effects of geometry and thermal conditions in Series A, D and E. The dark shaded region is weld metal. In Series E fatigue cracks may have both initiated and grown in weld metal.

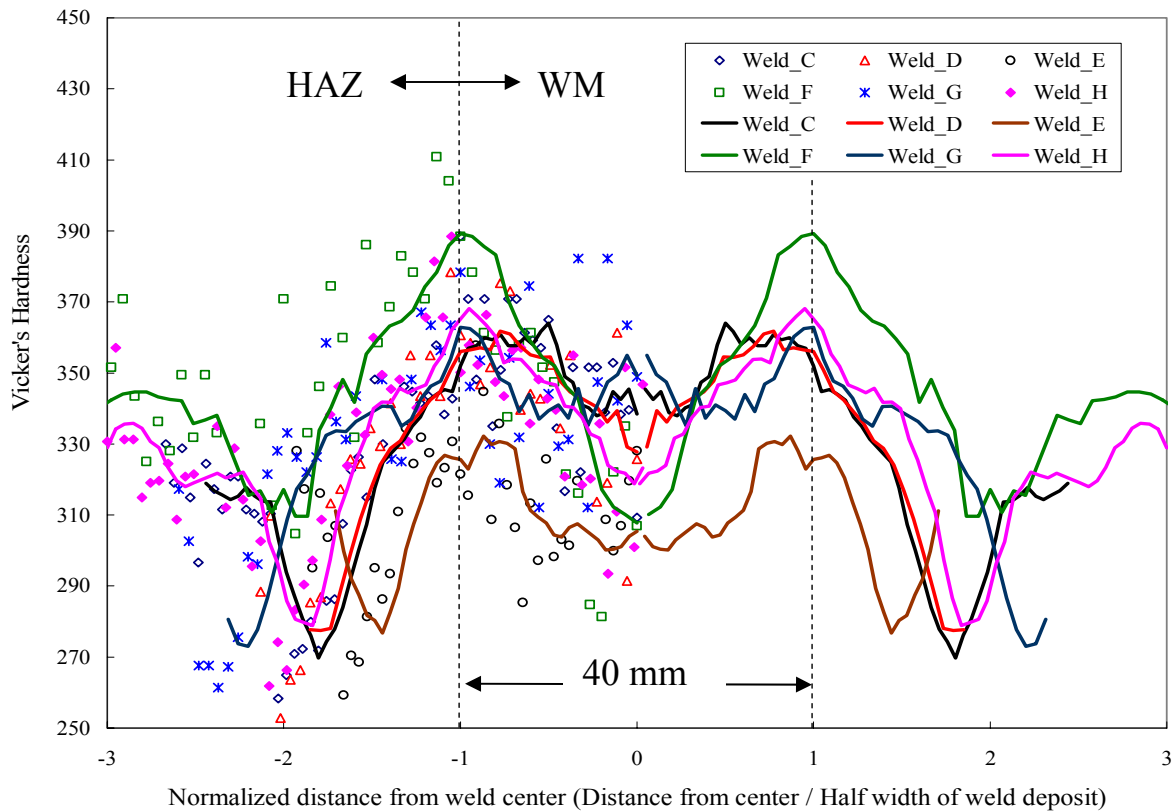


FIGURE 21 Vickers hardness measurements just below the toe of several standard thermite welds. The coordinate -1 is the line of fusion [10]. Note a peak in hardness at the line of fusion. HAZ and WM near the line of fusion appear to have about the same levels of Vickers micro-hardness.

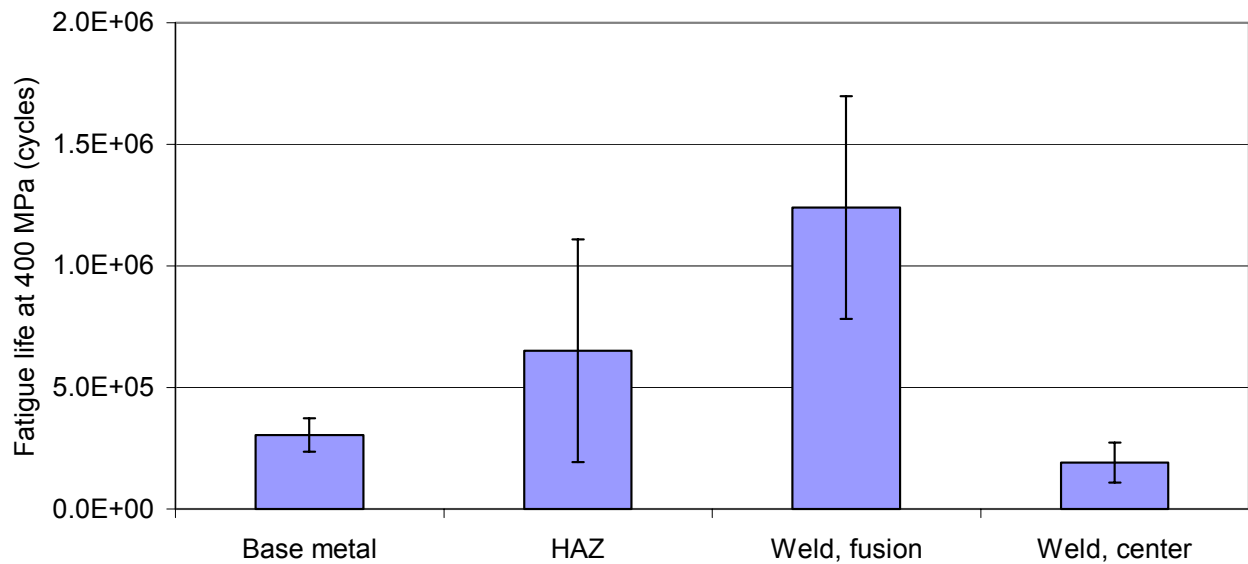


FIGURE 22 Rotating bending fatigue results for base metal, HAZ near the line of fusion, weld metal near the line of fusion, and weld metal near the weld centerline. Specimens taken from base of standard thermite weld [10].

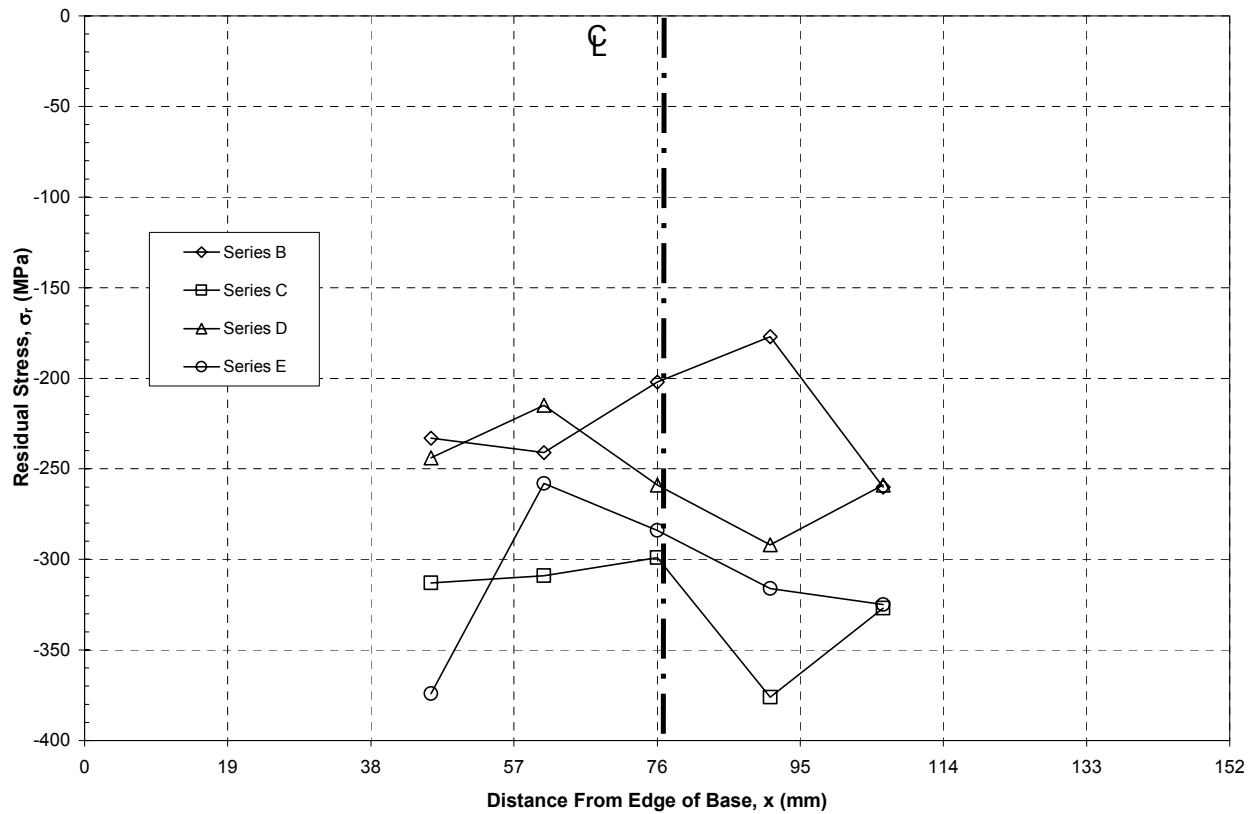
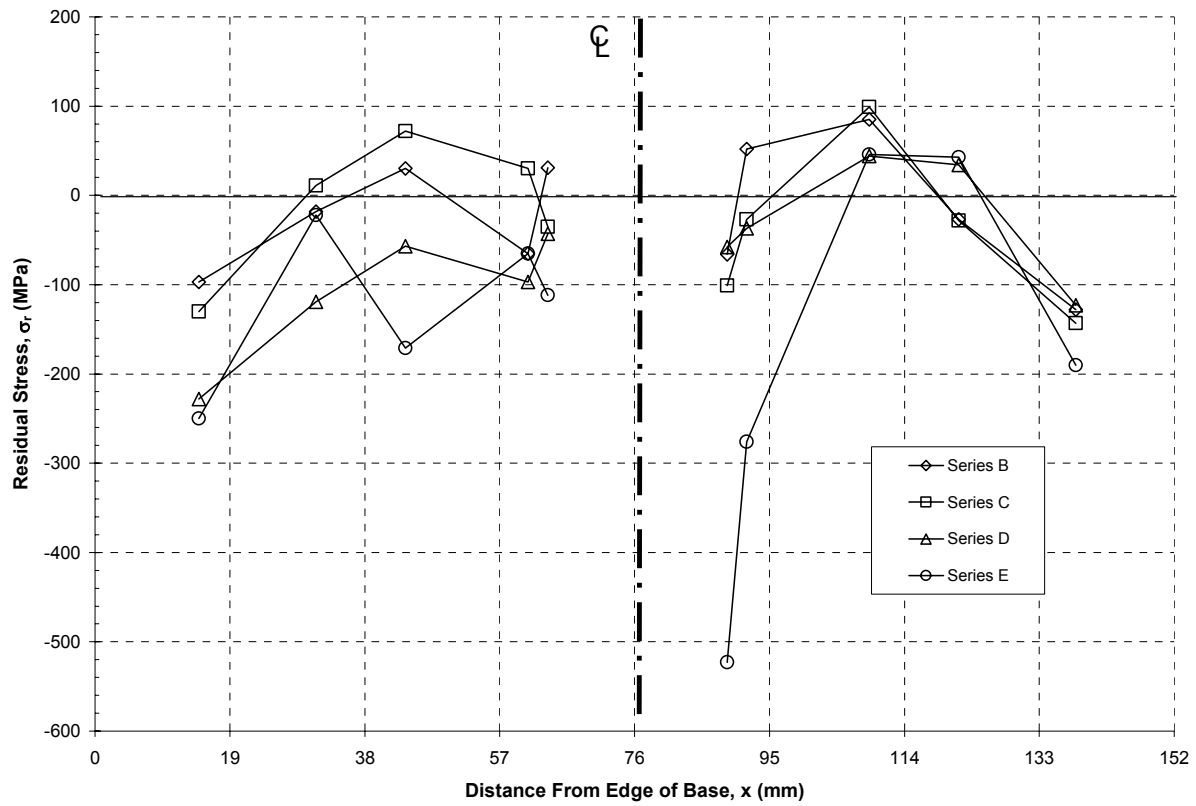


FIGURE 23 Residual stresses measured at the welds toes in the fillet and base of Series B, C, D and E weldments using X-ray diffraction. (above) Right and left fillets. (below) Base of weld near the center line.

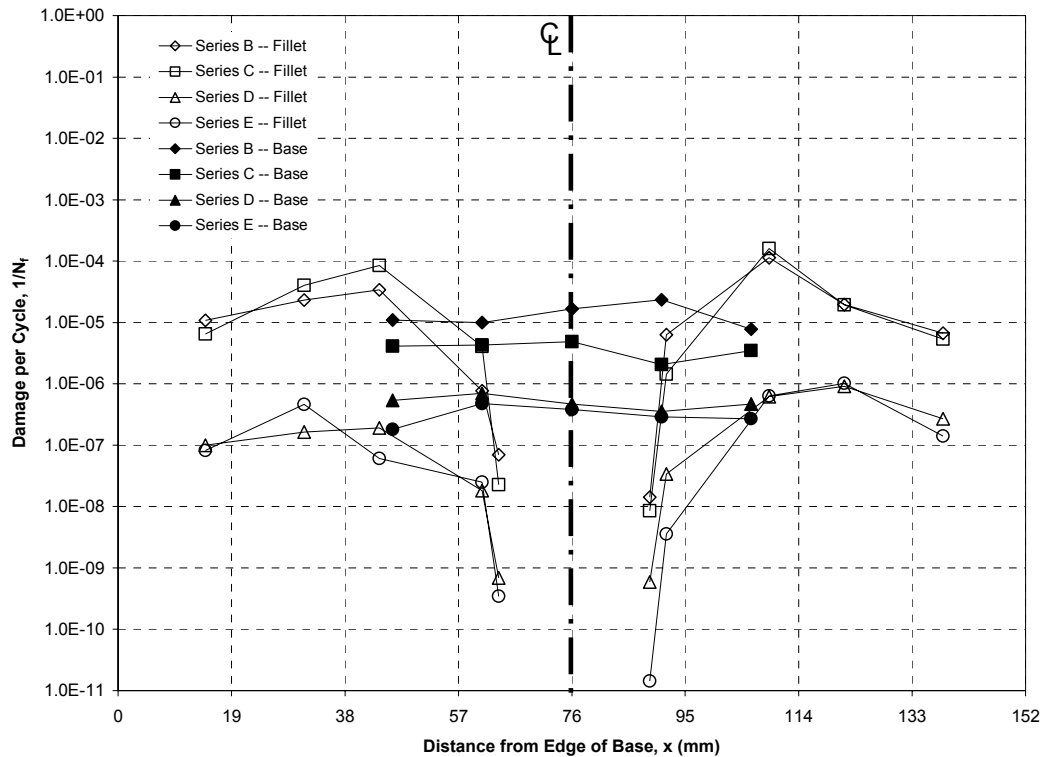


FIGURE 24 Estimated fatigue damage per cycle at the weld toes in the fillet and base of Series B, C, D, and E weldments. Highest values would give the shortest fatigue lives.

4.4 IN-TRACK EXPERIMENTS AT TTCI

Twenty-one (21) “improved” welds were installed in curved sections of the TTCI FAST track facility in Pueblo Colorado in November 2003 (FIGURE 4) using the welding parameters for Series D. After installation and before testing was begun, one of the 21 failed spontaneously. Soon after testing was begun in January 2004, 4 other welds failed: see FIGURE 25. In all cases, the failures did not involve the improved portions of the improved welds. Nonetheless, because of these premature failures, all 21 welds were removed from the track in April 2004.

Inspection of the welds that failed at the TTCI suggests that the state of stress in the FAST track is characteristic of over-balanced curves and causes the web of the weld to be more highly stressed than would be the case in this study’s laboratory tests. Thus, a small (unintentional) un-machined region of the weld toe in the web of the improved welds (FIGURE 26) may have caused these premature failures. The small fault in the design of the improved welds was corrected in late May 2004, new molds are currently being manufactured, and a second series of improved welds will be installed in the FAST track to determine whether the improvements found in the laboratory studies hold true in the field.

Four of the welds removed from track were shipped to the UIUC for fatigue testing. The four were tested using the same loading conditions used previously for Series A-E. The test results are given in Table 5. The average fatigue laboratory life of the four specimens was 215,000 cycles or 1.3 times that of Series A. Three specimens failed at the web-base fillet weld toe. One failed in the base from a partially fused fin. No web failures like those seen in the field tests (FIGURE 25) occurred.

Table 5. Laboratory 4-point bending test results for the four field welds removed from the TTCI FAST facility and shipped to the UIUC for testing.

ID Number	Load, ΔP (kN)	Fatigue Life, N_f (cycles)	Base or Fillet?
241-03	628	171,040	F
245-03	628	220,531	B
244-03	628	281,596	F
243-03	628	200,171	



FIGURE 25 Photograph of one of 4 improved welds that failed shortly after the beginning of testing at the TTCI FAST test facility [4].

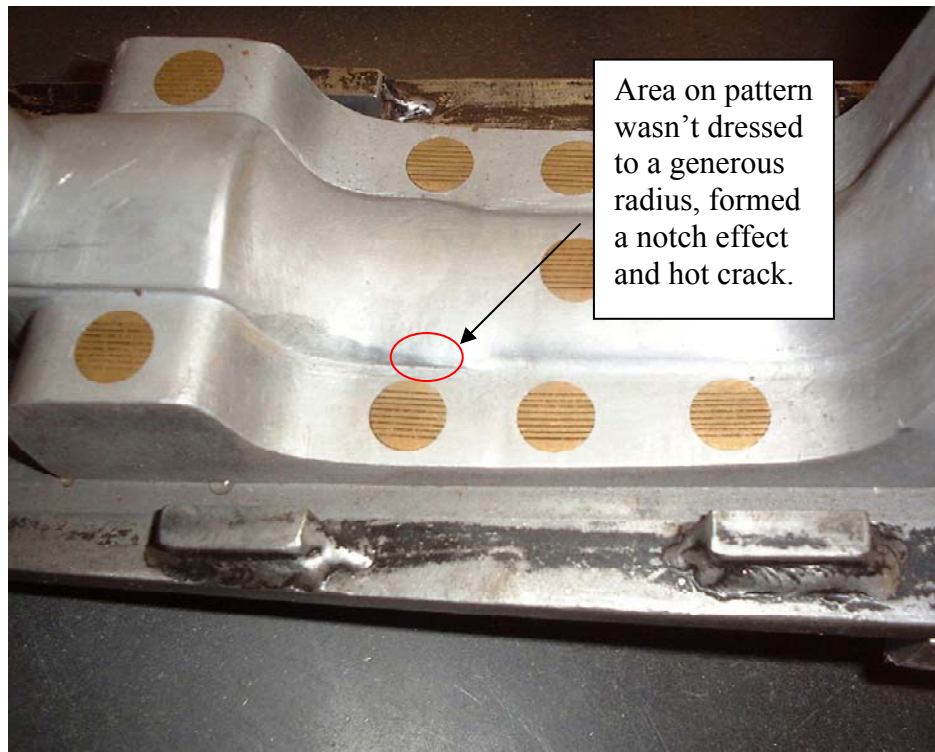


FIGURE 26 Weld mold pattern as modified by the investigators to produce the improved welds of Series D and E. Indicated weld toe region in web is approximately the location of the web failure observed in FIGURE 22. Area on pattern that was not dressed to a generous radius formed a notch and a hot crack. [11].

4.5 AMOUNT OF IMPROVEMENT

Despite the differing results for Series D and E, it seems certain that reducing the flank angle and introducing a generous radius at the weld toe will improve the fatigue resistance of the base and fillet region of the thermite rail weld. It is possible that the results for Series D and E reflect normal series-to-series variations. Likewise, the difference between Series A, B and C are really so small that one might lump their data together. If one combines all the results for the standard welds without a generous toe radius and a substantial reduction in flank angle (Series A, B, and C) and compares them with the combined results for all the improved welds (Series D and E plus the laboratory results for the four TTCI field welds) one obtains the frequency diagram of FIGURE 27. Given the many experimental variables, it would seem reasonable at this time to claim no more than the factor of 2 improvement in fatigue life indicated in FIGURE 27 even though greater improvements may be possible if as-cast surface roughness can be reduced and if the residual stresses that develop in the fatigue critical regions can be made even more favorable.

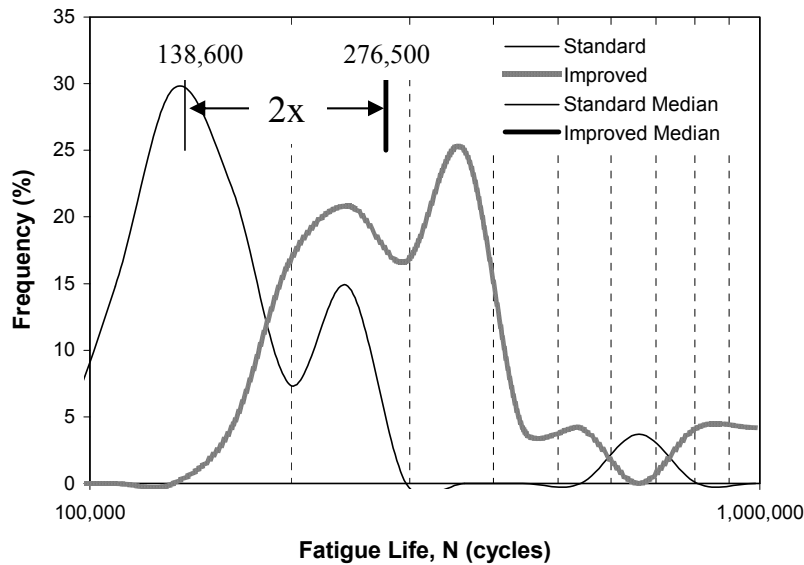


FIGURE 27 Frequency diagram resulting from grouping the standard Series A, B and C results and all “improved” weldment results (Series D and E plus the four improved welds removed from the TTCI field tests). It is clear that the improved welds perform better than the standard. The median lives of the two groups differ by a factor of 2.

5 CONCLUSIONS

- The laboratory tests results confirm the results of the previous IDEA program study that the fatigue life of thermite welds can be improved by a factor of 2 or more by improving the weld toe profile in the base and web-base fillet regions.
- Fins reduce the fatigue life of welds having improved geometry but do not much affect the current standard welds unless their thickness is much in excess of 1 mm. The length of a fin is generally so large that its actual value doesn’t matter.
- Mold washes did not seem to greatly influence the fatigue life of the welds considered in this study. Nonetheless surface roughness remains an important fatigue variable particularly if fins can be eliminated and improved weld toe profiles are used.
- Residual stresses are a major fatigue variable. Measurements of this study suggested that there was a basic similarity between the values and distribution of residual stress in the four weld series whose residual stresses were measured, but some small and possibly important differences were observed: the improved series (D and E) had lower tensile residual stresses in the fatigue-critical base-web fillet region.

- Field tests of the improved welds have not yet confirmed the laboratory results due to the unintentional unmachined region of the weld toe in the web. A second series of improved welds will be installed in the FAST track to determine whether the observed improvements found in the laboratory tests hold true in the field.

6 PLANS FOR IMPLEMENTATION

Much depends upon the outcome of the field tests planned at the TTCI. If it can be shown that the improved welds of this study do in fact perform better in service, then the test results from the TTCI will be made known to railroads and they in turn will likely ask thermite welding kit producers to consider providing this type of weld. One major thermite weld producer has been involved in this study and is thoroughly familiar with the concepts proposed.

Future studies should focus on the effects of residual stresses and the effect of heat input and other thermal conditions on their development. Ways to improve the surface roughness in the fatigue critical weld toes should be sought. Given the experience gained from testing at TTCI, optimizing thermite welds to resist fatigue damage in curves should be studied.

7 INVESTIGATOR PROFILES

Frederick V. Lawrence is a Professor (Emeritus) of Civil and Environmental Engineering at the University of Illinois at Urbana. 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.

Eric T. Ross was a research assistant in the Department of Civil and Environmental Engineering. He received his Master of Science degree from the Department of Mechanical Engineering in May 2004 and now is an engineer at the Caterpillar, Inc. in Aurora, Illinois.

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