Application of Translational Friction Welding for Rail Assembly and Repair

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ABSTRACT
Joining new rails end-to-end or inserting repair sections is most often performed using thermite welding or flash butt welding. This study examined the use of an alternative technology, translational friction welding (TFW) for attaching rail. This process offers potential for minimal shortening of the rail during welding, with equipment comparable to the flash butt welding used today. Translational friction welds are formed by oscillating one part relative to the other while a force is applied. This oscillation under load creates in interfacial heating, enabling upsetting the workpieces creating a solid-state joint. For the work done here, initial weld parameters were derived from published work. Specific practices were explored in an iterative fashion. Full area rail sections were welded, achieving near parent metal strength with low hardness levels for the rail head and the rail web. The specific equipment employed necessitated the use of low friction forces. These low friction forces resulted in non-uniform heating of the rail interfaces, with variations in properties. While TFW of rail sections has been demonstrated, next
generation systems will be required to demonstrate the performance necessary for implementation.

INTRODUCTION

Welding of rail is conventionally done by two technologies. These include thermite welding and flash butt welding. Thermite welding has the demonstrated advantages of portability and low capital costs. However, thermite welding can be time consuming, and is subject to a range of casting related defects. Flash butt welding was introduced into the rail assembly in 1955. Flash butt welding is a forge welding process that can be fully automated for rail assembly. Flash welding is used for both assembly of rail strings, and (with portable welding systems) installation of those strings in the field. While reliability of flash welded joints is excellent, there have been concerns about fracture toughness. Further, for repair applications loss of metal (due to flashing and upsetting) is a concern. These concerns have led the rail industry to continuously investigate new methods for welding rail.

Translational friction welding, also known as linear friction welding (LFW) is a new technology capable of creating butt joints similar to flash butt welding. This technology was created in the 1960’s as an extension of rotary friction welding, and was conceived as a way of creating solid-state welds on parts with not-round sections. Translational friction welds are made by creating relative oscillation between workpieces while a perpendicular force is applied. This oscillation under load creates heat from friction and mechanical working between the two parts. The combination results in the plastic deformation at the interface with subsequent localized heating. Once sufficient
temperatures are achieved, the oscillation is stopped and the force increased, resulting in forging. The combination of heat and deformation then results in a solid-state joint.

A key aspect of translational friction welds is the mechanism creating the oscillating motion. Through the development of translational friction welds, various means were proposed to create the oscillation, including offset rotating spindles, rotating fixed stroke cranks or cams, and hydraulic linear actuators.\(^5\) The vast majority of large Translational friction welding systems today employ hydraulic oscillators. These oscillators use fluids at high pressure that are alternately diverted into two opposing cylinders using a directional valve. Such systems operate in the range of 50 to 100 hertz (Hz), at loads ranging up to 100 tons.\(^7\) Hydraulic translational friction welding systems are very large – estimated to be 10 to 20 times the size of the current translational friction welding welder under study.\(^7,8\) These hydraulic machines require significant investment capital, are extremely large and complex to operate, and expensive to maintain.

Recently, a unique mechanically-based oscillator for translational friction welding has been developed.\(^9\) This oscillator translates the parts by using a motor drive and continuously variable stroke crank. The rotation of the motor drives the crank which translates the rotary motion into linear oscillation. Frequency can then be varied simply by changing the motor speed. Variable amplitude is achieved by a second rotating cam that changes the reference location of the driving crank. The system can finish with precise and specific workpiece alignment by driving the offset at the end of the cycle to
zero. Actual process variables and sequencing are similar to other linear friction systems.

This newly designed oscillator system offers the potential for portable systems. Such systems could be conceptually similar to existing flash butt mobile welding systems. Such a translational friction welding based system would offer many of the properties benefits of solid-state welding, with reduced rail shortening compared to flash butt welding. In this work, some initial efforts have been made to make translational friction welds to 136RE rail. Work was done on an existing system at APCI in South Bend, Indiana. The trials conducted were used to evaluate processing conditions, and were supported with both metallographic inspection and mechanical testing.

**EXPERIMENTAL PROCEDURE**

The rail used in this study as a standard 136RE, with a cross section of 13.33 in$^2$. Test coupons were cut from rail sections removed from service to a length of about four inches. Weld specimens were machined flat with surface perpendicular to rail long axis. Typical samples for these welding trials are shown in Figure 1. Welding was done on an APCI 100-ton translational friction welding machine located in South Bend, Indiana. The unit is shown in Figure 2. This machine is oriented in a pedestal configuration, with axial force supplied by a hydraulic system, and translational forces supplied by two 75-hp motors. In this study, two 4-in. long specimens of rail were joined to produce evaluation samples that were about 8-in. long (less the burn-off during weld). Tooling was designed and manufactured to fixture these short rail samples in the machine.
All welding trials employed preheating to prevent the formation of untempered martensite during cooling. Samples were pre-heated alternatively through furnace treatment or locally with torches. Furnace samples were cleaned, removing machining fluids, then pre-heated above 900°F. Heated samples were then placed into the welder tooling, clamped, and the welder cycle initiated. Heating with torches was done locally in the welding machine. In either case, welded samples were removed and allowed to cool, either in air or in a particulate insulation (enabling slower cooling rates).

The APCI translational friction welding system also allows dynamic collection of several operational parameters. These include variations in axial (weld) force, as well as axial and translational motion of the workpiece. Typical process data for rail joined with TFW is shown in Figure 3. Translational motion is shown in orange, burn-off and upset (lost length) in green, and the normal weld force in purple. In addition, this plot shows the motor speed in blue.
Selected samples were also evaluated through metallographic inspection and mechanical testing. In all cases, samples for evaluation were removed from the head, web, and base sections of the rail. Metallographic sections were then taken across the bond line, and prepared using standard techniques. All samples were etched in Nital, and examined using optical microscopy. Hardness traverses were done with a LECO micro hardness tester, with step spacing ranging from 0.04- to 0.12-inch. Mechanical testing included both tensile and bend evaluations. Bend testing was done to AWS B4.0:2007. Tensile testing was done to ASTM E8-09 on round specimens with a 0.5-in. diameter gage section.

**Results**

Data for all welding trials is provided in Table 1. Trial identification numbers shown in the table are reflective of individual welds made on the welder, and are not specific to this program, but fall in a series with other weld programs. After some initial set-up
Table 1. Weld Data for 136RE Rail Samples Welded on APCI 100-ton Welder

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Weld Date</th>
<th>Special Conditions Testing Objective</th>
<th>Weld Area in²</th>
<th>Weld Pressure * (ksi)</th>
<th>Time (Sec)</th>
<th>Forge Pressure * (ksi)</th>
<th>Amplitude (in)</th>
<th>Frequency (Hz)</th>
<th>Pre-Heat Used</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>548</td>
<td>6/10/2011</td>
<td>Initial weld trials 546 thru 552</td>
<td>13.33</td>
<td>4.0</td>
<td>8</td>
<td>11.0</td>
<td>0.20</td>
<td>60</td>
<td>Furnace 932 F</td>
<td>partial weld (in web)</td>
</tr>
<tr>
<td>549</td>
<td>6/13/2011</td>
<td></td>
<td>13.33</td>
<td>7.0</td>
<td>4</td>
<td>11.0</td>
<td>0.20</td>
<td>60</td>
<td>Furnace 932 F</td>
<td>no weld...machine stopped</td>
</tr>
<tr>
<td>550</td>
<td>6/13/2011</td>
<td></td>
<td>13.33</td>
<td>2.0</td>
<td>15</td>
<td>11.0</td>
<td>0.20</td>
<td>60</td>
<td>Furnace 932 F</td>
<td>broke after 3 hours</td>
</tr>
<tr>
<td>551</td>
<td>6/13/2011</td>
<td>Reduced area</td>
<td>4.80</td>
<td>6.0</td>
<td>3</td>
<td>14.0</td>
<td>0.20</td>
<td>60</td>
<td>Furnace 932 F</td>
<td>Oscillation ceased in last step before forge</td>
</tr>
<tr>
<td>552</td>
<td>6/14/2011</td>
<td></td>
<td>4.80</td>
<td>7.0</td>
<td>3</td>
<td>14.0</td>
<td>0.20</td>
<td>60</td>
<td>Furnace 932 F</td>
<td>Assembly fractured while aging</td>
</tr>
<tr>
<td>753</td>
<td>6/14/2011</td>
<td>Testing after Oscillator mods - new oscillator forward</td>
<td>2.68</td>
<td>7.0</td>
<td>2.5</td>
<td>18.0</td>
<td>0.24</td>
<td>50</td>
<td>Furnace 932 F</td>
<td>Assembly fractured while aging</td>
</tr>
<tr>
<td>754</td>
<td>6/15/2011</td>
<td>Reduced area</td>
<td>4.80</td>
<td>7.0</td>
<td>3.2</td>
<td>14.5</td>
<td>0.24</td>
<td>50</td>
<td>Furnace 932 F</td>
<td>fixture clamp hydraulic pressure 2.5 ksi</td>
</tr>
<tr>
<td>755</td>
<td>11/3/2011</td>
<td>Testing after Oscillator mods - new oscillator forward</td>
<td>4.80</td>
<td>7.0</td>
<td>3</td>
<td>14.5</td>
<td>0.24</td>
<td>50</td>
<td>Furnace 932 F</td>
<td>fixture clamp hydraulic pressure 2.5 ksi</td>
</tr>
<tr>
<td>756</td>
<td>11/4/2011</td>
<td>Reduced area</td>
<td>4.80</td>
<td>6.0</td>
<td>3.2</td>
<td>14.5</td>
<td>0.29</td>
<td>50</td>
<td>Furnace 932 F</td>
<td>fixture clamp hydraulic pressure 3.0 ksi</td>
</tr>
<tr>
<td>757</td>
<td>11/4/2011</td>
<td>Reduced area</td>
<td>4.80</td>
<td>2.2</td>
<td>10</td>
<td>14.5</td>
<td>0.29</td>
<td>50</td>
<td>Furnace 932 F</td>
<td>fixture clamp hydraulic pressure 3.0 ksi</td>
</tr>
<tr>
<td>758</td>
<td>11/4/2011</td>
<td>Begin use of manual clamp tie bolts, increase rigidity of tooling</td>
<td>13.33</td>
<td>2.0</td>
<td>15</td>
<td>14.5</td>
<td>0.29</td>
<td>50</td>
<td>Furnace 932 F</td>
<td></td>
</tr>
<tr>
<td>759</td>
<td>11/4/2011</td>
<td>Special end shape to one rail</td>
<td>13.33</td>
<td>0.5 to 2</td>
<td>22</td>
<td>14.5</td>
<td>0.29</td>
<td>50</td>
<td>Furnace 932 F</td>
<td></td>
</tr>
<tr>
<td>760</td>
<td>11/7/2011</td>
<td>Same as 759</td>
<td>13.33</td>
<td>0.5 to 1.9</td>
<td>25</td>
<td>14.5</td>
<td>0.29</td>
<td>50</td>
<td>Not Recorded</td>
<td></td>
</tr>
<tr>
<td>780</td>
<td>11/8/2011</td>
<td>Same as 759</td>
<td>13.33</td>
<td>2.0</td>
<td>30</td>
<td>14.5</td>
<td>0.29</td>
<td>50</td>
<td>Not Recorded</td>
<td>weld cycle terminated</td>
</tr>
<tr>
<td>781</td>
<td>11/8/2011</td>
<td>Same as 759</td>
<td>13.33</td>
<td>2.0</td>
<td>30</td>
<td>14.5</td>
<td>0.29</td>
<td>50</td>
<td>Not Recorded</td>
<td>cycle terminated, 85% of interface, at EWI</td>
</tr>
<tr>
<td>782</td>
<td>11/14/2011</td>
<td>Reduced area</td>
<td>1.80</td>
<td>7.0</td>
<td>3.2</td>
<td>14.5</td>
<td>0.24</td>
<td>50</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>783</td>
<td>11/15/2011</td>
<td>Same as 759</td>
<td>13.33</td>
<td>2.2</td>
<td>40</td>
<td>14.5</td>
<td>0.29</td>
<td>50</td>
<td>Furnace 932 F</td>
<td>90% of full interface, see met, at EWI</td>
</tr>
<tr>
<td>848</td>
<td>11/15/2011</td>
<td>After testing of 783 at EWI more trials with longer times to get full interface</td>
<td>13.33</td>
<td>1 to 1.9</td>
<td>60 - 20</td>
<td>11.5</td>
<td>0.29</td>
<td>50</td>
<td>None</td>
<td>cycle stopped no forge, upset 0.232,</td>
</tr>
<tr>
<td>849</td>
<td>12/9/2011</td>
<td>After testing of 783 at EWI more trials with longer times to get full interface</td>
<td>13.33</td>
<td>1.0</td>
<td>80</td>
<td>11.5</td>
<td>0.29</td>
<td>50</td>
<td>None</td>
<td>near full interface, upset 0.4 in, see met &amp; mech, at EWI</td>
</tr>
<tr>
<td>850</td>
<td>12/9/2011</td>
<td></td>
<td>13.33</td>
<td>1.0</td>
<td>70</td>
<td>11.5</td>
<td>0.29</td>
<td>50</td>
<td>None</td>
<td>cycle stopped, no forge, fixture loose on bottom</td>
</tr>
<tr>
<td>851</td>
<td>12/9/2011</td>
<td>Center area relieved 0.020 in</td>
<td>13.33</td>
<td>1.0</td>
<td>70</td>
<td>11.5</td>
<td>0.29</td>
<td>50</td>
<td>None</td>
<td>cycle stopped, no forge, fixture loose on bottom</td>
</tr>
<tr>
<td>852</td>
<td>12/10/2011</td>
<td>Center area relieved 0.005 in</td>
<td>13.33</td>
<td>1.0</td>
<td>70</td>
<td>11.5</td>
<td>0.29</td>
<td>50</td>
<td>Furnace 932 F</td>
<td>At EWI weld fractured after 1 week aging</td>
</tr>
<tr>
<td>853</td>
<td>12/10/2011</td>
<td>Center area relieved 0.005 in</td>
<td>13.33</td>
<td>1.0</td>
<td>70</td>
<td>11.5</td>
<td>0.29</td>
<td>50</td>
<td>None</td>
<td>cycle stopped, no weld, idler broke</td>
</tr>
<tr>
<td>854</td>
<td>12/10/2011</td>
<td>Center area relieved 0.005 in</td>
<td>13.33</td>
<td>1.0</td>
<td>70</td>
<td>11.5</td>
<td>0.29</td>
<td>50</td>
<td>Torch 1000 F</td>
<td>cycle stopped, no forge, upset 14.3 mm</td>
</tr>
<tr>
<td>919</td>
<td>1/16/2012</td>
<td>Repeating process of 849, weld cycle held until reach burnoff distance 0.15 in.</td>
<td>13.33</td>
<td>1.0</td>
<td>3.8-mm dist</td>
<td>11.5</td>
<td>0.29</td>
<td>50</td>
<td>Torch 1000 F</td>
<td>full interface, upset 0.35 in, forge held 10 sec, at EWI, see met &amp; mech Damaged Welder</td>
</tr>
<tr>
<td>944</td>
<td>1/31/2012</td>
<td>One additional weld, weld cycle held until reach burnoff distance 0.16 in.</td>
<td>13.33</td>
<td>1.0</td>
<td>4.1-mm dist</td>
<td>11.0</td>
<td>0.29</td>
<td>50</td>
<td>Torch 1000 F</td>
<td>upset 0.35, full interface, forge held 10 sec, at EWI, see met &amp; mech Damaged Welder</td>
</tr>
</tbody>
</table>

* Weld and Forge Pressure are the compressive stress for the weld interface applied by hydraulic force normal to weld plane.
trials a series of process iterations were examined. These included varying the actual weld area (by reducing the section size) as well as weld normal force. The combination was used to create variations in weld interface contact stresses. Weld stresses up to 7-ksi and weld times as short as three seconds were attempted on reduced areas. Ultimately, longer weld cycles with full-area weld interfaces were incorporated into these joining trials. Weld Trial 783 finished with about 85% of the interface joined and was sectioned through the rail head, web, and base. Metallographic sections were taken from the three rail regions of the welded assembly.

The third distinct set of weld trials, 848 through 854, were made using reduced weld stress (about 1-ksi) and long weld times (about 70 seconds). Weld 849 was not preheated but was held in friction heating phase for 80 seconds. Observation of the weld process and others like it showed that the friction heating began early in the web and continued next into the head and finally into the rail base. Observation of the welded assembly showed the best flash profile in the web and least developed flash in the rail base. Segments removed from 849 were subjected to tensile and bend testing. Table 2 lists the strength test results. The web and head specimen failed in a softened zone after significant necking. Metallographic sections were also prepared and evaluated. These results are described below.
Table 2. Destructive Test Results for Welds

<table>
<thead>
<tr>
<th>Weld Number &amp; Rail Section</th>
<th>Tensile 0.2% Yield</th>
<th>Ultimate Strength Mode &amp; Stress</th>
<th>Bend Test Set 15% Elongation</th>
<th>Bend Test Set 10% Elongation</th>
<th>Met Section</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ksi</td>
<td>Angle Deg</td>
<td>Angle Deg</td>
<td>Quantity</td>
<td></td>
</tr>
<tr>
<td>849</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head</td>
<td>78</td>
<td>Softened Zone 140</td>
<td>Parent 28° &lt; na</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Web</td>
<td>90</td>
<td>Softened Zone 146</td>
<td>Parent 28° &lt; na</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td>88</td>
<td>Near BL 128</td>
<td>Weld 60° na</td>
<td></td>
<td></td>
</tr>
<tr>
<td>919</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head</td>
<td>110</td>
<td>Near BL 137</td>
<td>na</td>
<td>Parent 25° &lt; 1</td>
<td>1</td>
</tr>
<tr>
<td>Web</td>
<td>103</td>
<td>Softened Zone 161</td>
<td>na</td>
<td>Weld 80° 1</td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td>110</td>
<td>Near BL 119</td>
<td>na</td>
<td>Weld 80° 1</td>
<td>1</td>
</tr>
<tr>
<td>944</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head</td>
<td>107</td>
<td>Near BL 148</td>
<td>na</td>
<td>Weld 80° 1</td>
<td>1</td>
</tr>
<tr>
<td>Web</td>
<td>96</td>
<td>Softened Zone 154</td>
<td>na</td>
<td>Weld 80° 1</td>
<td>1</td>
</tr>
<tr>
<td>Base</td>
<td>107</td>
<td>Near BL 144</td>
<td>na</td>
<td>Weld 80° 1</td>
<td>1</td>
</tr>
<tr>
<td>Base Metal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head</td>
<td>106</td>
<td>188</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Web</td>
<td>110</td>
<td>175</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Base</td>
<td>102</td>
<td>177</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
</tbody>
</table>

Two additional welds were made using parameter sets similar to Weld Trial 849, though with burn-off rather than time control. In these trials, allowable burn-off set at 0.15-in. before forging. The first of these welds (Trial 919) was preheated to 1000°F in the tooling using a torch. The heat generation during the weld cycle evolved starting in the web, moving to the head and then to the rail base. The flash from the weld was very good, having improved significantly in the base of the rail compared to previous efforts. Weld 944 was made to replicate Weld 919 with similar results. Figure 4 is a photograph of the complete weld (Trial 944) prior to removal of test specimen. Tensile test specimens and bend test specimens were removed from Weld Samples 849, 919, and 944 along with metallographic sections. These results follow in the below descriptions.

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The base metal tensile testing of the head, web, and base sections of the rail were processed as described in experimental procedure. The results were very similar among the three showing a 0.2% yield of about 106-ksi. (See Table 2 for details.) The tensile specimen failed with an ultimate strength of about 180-ksi. Bend and tensile testing of the weld from Sample 849 were again performed as described in experimental procedure, with the results again presented in Table 2. The yield and tensile strengths were lower than that of the base metal, with values of about 85.6-ksi, and 138-ksi, respectively. The failure modes of the tensile samples from the head and web were in the softened zone about 0.39-inch from the bond line. The base section failed near the bond line with very little necking in the softened zone. The bend tests for Part 849 were processed using a bend radius providing a designed strain of 15%. The specimens failed in the parent metal after only a 28° bend, indicating that the expectation of
elongation was too high. Subsequent parts were bend-tested at an expanded radius providing a designed elongation of 10%.

Additionally, bend and tensile specimens were removed from welded parts 919 and 944 at each of the rail head, rail web, and rail base. Mechanical testing was then performed as described above. The observed yield strengths were equal to that of the base metal. However, the ultimate strengths (139-ksi and 148-ksi for Trials 919 and 944, respectively) were below that of the base metal. The failure mode of the samples taken from the web was in the softened zone about 0.47-in. from the bond line. The head and base section failed near the bond line. See Figure 5 for the stress/strain curves of Part 944; weld tensile tests results for 919 were very similar. The bend tests for Part 919 and 944 were processed using the 10% elongation as described in experimental procedure above. Two of the specimens failed near the bond line after 80° of bend, indicating that the parent survived, but the maximum fiber tensile stress was too high at the bond line after 80° bend.
Microstructure and hardness results were then collected for Welds 849, 919 and 944. Data was collected for sections removed from the web, head, and base of each weld. Example results from the web section of Weld 849 are provided in Figure 6. In this figure, hardness data is superimposed over a micrograph of the weld area. Two hardness traces are shown, with different spacing of indents. The results show that the hardness of the parent base metal was about 300 to 320 Vickers. This hardness dropped below 300 to 270 Vickers about halfway into the heat affected zone, then rose to between 350 and 400 Vickers up to the bond line. Generally, the hardness traverse values were symmetric about the bond line.
A macro section from the base of Weld 944 is shown in Figure 7. Here it can be seen that the HAZ was about 0.39-in. on both sides of the bond line. The flash is relatively symmetric indicating material displacement in both directions of oscillation. The areas on the macrograph are also highlighted at locations where higher magnification microscopy was done. Figure 8 is a higher magnification micrograph of the bond line. This area was largely characterized by fine prior austenite grains that were transformed to an acicular ferrite/banitic microstructure. A stringer is also noted in this micrograph parallel to the bond line. Figure 9 is a similar micrograph in the softened heat affected zone. Location of the micrograph (seen in Figure 7) indicates peak temperatures are near the A3. This detailed microstructure (Figure 9) is seen to consist of a mixture of
fine prior austenite grains and untransformed ferrite grains. Finally, Figure 10 provides a micrograph of the base metal showing a coarser prior austenite grain size and a substructure of mixed bainite and pearlite.

Figure 7. Macro View of Weld 944 taken from Base of Rail
Figure 8. 200× Magnification of Bond Line Picric etch used instead of Nital

Figure 9. 200× Magnification of Fine Grain Heat Affected Zone

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DISCUSSION
The work here resulted in full-area or near full-area welds utilizing currently available equipment. These results showed that heating generally began in the web then moved to the head and finally the base of the rail as the process progressed. Ultimate tensile strengths were highest in the web, where all tensile test specimens failed in the softened heat affected zone. Conversely, most of the tensile specimen taken from the base and head regions fractured at the bond line at lower strengths. This change in mechanical behavior was related to the variations in heating (and forging) in the different regions as noted above. This variation in heating was to some degree an artifact of the processing conditions used to create these joints. As noted previously, best case welds used interfacial stresses during friction heating of less than 1-ksi. At those low stresses, thermal expansion during initial heating (concentrating at the center
of the rail) overcame the stress, resulting in loss of effective contact at the rail ends. As suggested above, heating tended to progress from the web to the heat and finally to the base. This progression appeared to be related to local section thickness, where the heavier rail head showed less deflection, and thus earlier contact compared to the base. This non-uniformity in the section heating rate, of course, led to residual stress in the welded rails. The level of residual stress depended on rates of heating in the different sections. Welds that employed longer heating times tended to achieve some balance to the temperature distribution, with apparent reduced residual stress. Welds made with shorter times usually failed by fracture during aging or on initial sectioning. It will be necessary to make changes to the process to reduce the heating difference between the head, base, and web for successful implementation of translational friction welding of rail sections.

The welding equipment used in this study was selected as the 100-ton weld capability was assumed sufficient for the 136RE section. A 100-ton axial force over the 13.33-in$^2$ weld interface area suggested a contact stress of roughly 15-ksi. Further, the amplitudes and frequencies from this system were comparable with previously published data on translational friction welding for steels.$^{(11-12)}$ The challenge seen when welding 136RE rail sections was in the loads placed on the oscillator. Experimental data collected as part of this study suggested that the translational friction welding oscillator ceased at axial welding loads between 10- and 20-kip. This demonstrated that the resulting friction forces at those loads exceeded the force capacity of the oscillator. The translational friction welding system used employed a 75-hp motor for oscillation. Working through a 0.128-in. amplitude crank at 50-Hz the
welder nominally generated about 12.4-kip of force. This suggests the oscillator must be designed to provide translational loads at least equal to necessary axial loads during friction heating. For steels, friction heating is typically done at a load of about 5-ksi.\(^{(13)}\) This would then translate to oscillator loads on the order of 65-kip, requiring a 400-hp drive. A key aspect in any rail system is development of an oscillator drive capable of delivering these loads to the system. Currently, that appears to be the limiting factor to adapting this technology to 136RE sections.

**CONCLUSIONS**

In this program, a preliminary investigation was conducted on the feasibility of using a new generation of translational friction welding systems to join full-scale rail sections. This new technology is based on a direct drive/programmable cam concept. The ability to replace hydraulic oscillators with servo-electric mechanical systems offers potential for making the equipment more compact (facilitating development of portable systems), broadening technical capability (through higher oscillation frequencies), and reducing implicit system costs. This work is part of a multi-phase initiative funded by the U.S. Department of Transportation, Federal Railroad Administration. In this phase, work was done to examine baseline feasibility of translational friction welding for rail sections, and design implications of welding rail with new generation systems. Specific conclusions from this work are described below.

(1) **Linear friction welds were made between two segments of 136RE rail with an area of 8597 mm\(^2\) (13.33 inch\(^2\)).** By applying low weld stresses for longer periods, the weld developed between the rail segments. Near full interface areas were completed. Strength testing and metallographic examination
showed that further development is required to improve strength at the bond line.

(2) **Inconsistent heating and forging was observed across the rail section.** Observations showed that at low contact pressures. Heating of the rail started in the web, and progressed out to the head and finally the base locations. This resulted in non-uniform heating and significant residual stresses. Longer times reduced this effect, but higher frictional forces are clearly needed.

(3) **Forces necessary for translational action at desired axial loads exceeded that available from the oscillator.** Forces estimated to be above 13,500 pounds reached the limit of the 75-hp oscillator drive. A larger oscillator force is required to overcome the effective high friction factors typical of the formation of microwelds early in the friction phase of translational friction welding. Given the welder forging capacity, a larger drive or modifications to add inertial energy storage would support the need for increased oscillation forces to overcome the high friction forces.

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Research and Demonstration Projects Supporting the Development of High Speed and Intercity Passenger Rail Service

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Figures

Figure 1. Two 4-in. Long Rail Test Samples of 136RE
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Figure 9. 200× Magnification of Fine Grain Heat Affected Zone
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Tables

Table 1. Weld Data for 136RE Rail Samples Welded on APCI 100-ton Welder
Table 2. Destructive Test Results for Welds
Application of Translational Friction Welding for Rail Assembly and Repair

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Technology Leader
Resistance & Solid-State Welding
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Rail Welding Technology
Widely Used Today

• Thermite Welding
  – Pyrotechnic composition
  – Oxidation reduction action
  – Exothermic reaction
  – Short bursts of very high temperatures in short time

• Considerations
  – Low capital cost
  – High portability
  – Long weld times
    • Between 30 and 45 min per weld
    • High operating cost
  – Weld quality limitations
    • Casting related defects
Rail Flash Butt Welding
Widely Used Today

- Flash butt welding introduced into the rail assembly in 1955
- Flash welding is used for both assembly of rail strings and repair
- Reliability of flash welded joints is excellent
- There have been concerns about fracture toughness plus loss of metal due to flashing & upsetting
- After flashing the heated ends are forced together
- Forging action forces plastic material out of interface
History of LFW

• Inertia Rotational
  – 1960's first real applications
  – One part in spindle other part fixed
  – Energy stored in rotating flywheel
  – Parts pressed together - heat and forge

• Direct Friction Drive
  – Similar to Inertia but continuous motor drive
  – Stopping is usually by brake and clutch

• Orbital welding machines
  – Demonstrated but not known to be applied in production

• Hydraulic oscillators – without stored energy

• Mechanical oscillators – fixed amplitude
Newer TFW Technologies

- Hydraulic Stored Energy TFW
  - Very high cost compatible with only high value added parts
  - Very large incompatible with in-field applications

- Mechanical Programmable TFW
  - Low physical and operating cost
  - Small compatible with in-field applications

100 Ton Hydraulic System
Moog Thompson Linear Friction Welder E100

100 Ton Mechanical System
APCI Translational Friction Welder
Process Mechanical System

- Top component is translated back and forth
- The bottom component is held fixed and pushed up
- The oscillation frequency is rotation rate
- Amplitude is controlled by the cam
  secondary to primary drive relationship
- Translation force is generated by the rotation through the amplitude
- The friction force is the opposing force that the primary oscillator drive must overcome
- Microwelds form - the friction force is equivalent to the force required to shear the connections
Welder Process Chart

- This is a normal cycle recorded during weld trials
- Horizontal axis in seconds
- Vertical axis is relative to controller scaling
- Orange trace is the position of the arm
- Top blue trace is primary drive rotation rate
- Green trace is the upsetting distance
- Lower purple trace is the load (vertical force)
Typical Weld Trial Processing

- 136RE Rail two parts each 4-inches long
- Machined flat and perpendicular to rail base
- Preheating to about 900°F
- Placed into lower tool first and then upper tool
- Press raises lower tool with part against upper part
Weld Trials

- Weld trials included varying
  - Weld area
  - Weld normal force
- Weld stresses up to 7-ksi and weld times as short as 3 seconds
- Longer weld cycles with full-area weld interfaces were added
- Weld Trial 783 finished
  - In 40 seconds
  - About 85% of the interface
- Unfinished base weld caused high residual stress
Observations During Weld

- Start with heating in center of web
- Slight opening at head and base
- Continued web heating
- Continued flash forming
- Contact and heating of head/base
- Flash formation at head and base
- Flash growth from web center to head and base
## Weld Trial Data

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Weld Date</th>
<th>Special Conditions Testing Objective</th>
<th>Weld Area in²</th>
<th>Weld Pressure $p$ (ksi)</th>
<th>Time (Sec)</th>
<th>Forge Pressure $s$ (ksi)</th>
<th>Amplitude (in)</th>
<th>Frequency (Hz)</th>
<th>PreHeat Used</th>
<th>COMMENTS</th>
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<tbody>
<tr>
<td>548</td>
<td>6/10/2011</td>
<td>Initial weld trials 548 thru 552</td>
<td>12.33</td>
<td>4.0</td>
<td>6</td>
<td>11.0</td>
<td>0.20</td>
<td>60</td>
<td>Furnace 932 F</td>
<td>Partial weld (in web)</td>
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<tr>
<td>549</td>
<td>6/13/2011</td>
<td></td>
<td>18.33</td>
<td>7.0</td>
<td>4</td>
<td>11.0</td>
<td>0.20</td>
<td>60</td>
<td>Furnace 932 F</td>
<td>No weld, machined</td>
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<tr>
<td>550</td>
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<td></td>
<td>15.55</td>
<td>2.0</td>
<td>3</td>
<td>11.0</td>
<td>0.20</td>
<td>60</td>
<td>Furnace 932 F</td>
<td>Broke after 5 hours</td>
</tr>
<tr>
<td>551</td>
<td>6/17/2011</td>
<td>Reduced area</td>
<td>4.60</td>
<td>6.0</td>
<td>3</td>
<td>14.0</td>
<td>0.20</td>
<td>60</td>
<td>Furnace 932 F</td>
<td>Oscillation ceased in last step before forge</td>
</tr>
<tr>
<td>552</td>
<td>6/17/2011</td>
<td></td>
<td>4.60</td>
<td>7.0</td>
<td>3</td>
<td>14.0</td>
<td>0.20</td>
<td>60</td>
<td>Furnace 932 F</td>
<td>Assembly fractured while aging</td>
</tr>
<tr>
<td>753</td>
<td>6/14/2011</td>
<td>Testing after Oscillator mods - new oscillator forward</td>
<td>2.60</td>
<td>7.0</td>
<td>2.5</td>
<td>13.0</td>
<td>0.24</td>
<td>30</td>
<td>Furnace 932 F</td>
<td>Assembly fractured while aging</td>
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<tr>
<td>744</td>
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<td>4.60</td>
<td>7.0</td>
<td>2</td>
<td>14.5</td>
<td>0.24</td>
<td>30</td>
<td>Furnace 932 F</td>
<td>Fixtured clamp hydraulic pressure 2.8 ksi</td>
</tr>
<tr>
<td>753</td>
<td>7/8/2011</td>
<td>Testing after Oscillator mods - new oscillator forward</td>
<td>4.60</td>
<td>7.0</td>
<td>3</td>
<td>14.5</td>
<td>0.24</td>
<td>30</td>
<td>Furnace 932 F</td>
<td>Fixtured clamp hydraulic pressure 2.8 ksi</td>
</tr>
<tr>
<td>756</td>
<td>7/8/2011</td>
<td>Reduced area</td>
<td>4.60</td>
<td>6.0</td>
<td>5</td>
<td>14.5</td>
<td>0.29</td>
<td>30</td>
<td>Furnace 932 F</td>
<td>Fixtured clamp hydraulic pressure 5.0 ksi</td>
</tr>
<tr>
<td>757</td>
<td>7/8/2011</td>
<td>Reduced area</td>
<td>4.60</td>
<td>7.0</td>
<td>4</td>
<td>14.5</td>
<td>0.28</td>
<td>30</td>
<td>Furnace 932 F</td>
<td>Fixtured clamp hydraulic pressure 5.0 ksi</td>
</tr>
<tr>
<td>758</td>
<td>7/12/2011</td>
<td>Beginning use of manual clamp tie bolts, increase rigidity of tooling</td>
<td>13.33</td>
<td>2.0</td>
<td>15</td>
<td>14.5</td>
<td>0.28</td>
<td>30</td>
<td>Furnace 932 F</td>
<td></td>
</tr>
<tr>
<td>759</td>
<td>7/14/2011</td>
<td>Special end shape to one rail</td>
<td>12.33</td>
<td>0.3 to 2</td>
<td>22</td>
<td>14.5</td>
<td>0.29</td>
<td>30</td>
<td>Furnace 932 F</td>
<td></td>
</tr>
<tr>
<td>760</td>
<td>7/17/2011</td>
<td>Same as 750</td>
<td>13.33</td>
<td>0.8 to 2.5</td>
<td>28</td>
<td>14.5</td>
<td>0.29</td>
<td>30</td>
<td>Furnace 932 F</td>
<td>Not recorded</td>
</tr>
<tr>
<td>761</td>
<td>7/11/2011</td>
<td>Same as 750</td>
<td>13.33</td>
<td>2.0</td>
<td>10</td>
<td>14.5</td>
<td>0.28</td>
<td>30</td>
<td>Furnace 932 F</td>
<td>Weld cycle terminated</td>
</tr>
<tr>
<td>762</td>
<td>7/8/2011</td>
<td>Same as 750</td>
<td>13.33</td>
<td>2.0</td>
<td>10</td>
<td>14.5</td>
<td>0.28</td>
<td>30</td>
<td>Furnace 932 F</td>
<td>Weld cycle terminated 85% of full interface, 8x1WI</td>
</tr>
<tr>
<td>763</td>
<td>7/18/2011</td>
<td>Reduced area</td>
<td>1.80</td>
<td>7.0</td>
<td>3</td>
<td>14.5</td>
<td>0.24</td>
<td>30</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>783</td>
<td>7/19/2011</td>
<td>Same as 750</td>
<td>13.33</td>
<td>2.3</td>
<td>10</td>
<td>14.5</td>
<td>0.24</td>
<td>30</td>
<td>Furnace 932 F</td>
<td>90% of full interface, see met at 5WI</td>
</tr>
<tr>
<td>848</td>
<td>11/15/2011</td>
<td>After testing of 782 at EWI more trials with longer times to get full interface</td>
<td>12.33</td>
<td>1.0 to 1.0</td>
<td>60 - 20</td>
<td>11.5</td>
<td>0.20</td>
<td>30</td>
<td>None</td>
<td>Cycle stopped no forge, up to 232</td>
</tr>
<tr>
<td>849</td>
<td>12/13/2011</td>
<td>After testing of 782 at EWI more trials with longer times to get full interface</td>
<td>13.33</td>
<td>1.0</td>
<td>80</td>
<td>11.5</td>
<td>0.28</td>
<td>30</td>
<td>None</td>
<td>Cycle stopped, 8x1WI, see met 8 mech. at 5WI</td>
</tr>
<tr>
<td>850</td>
<td>12/16/2011</td>
<td>Center area relieved 0.020 in</td>
<td>13.33</td>
<td>1.0</td>
<td>70</td>
<td>11.5</td>
<td>0.28</td>
<td>30</td>
<td>None</td>
<td>Cycle stopped, no forge, stress relieved on bottom</td>
</tr>
<tr>
<td>851</td>
<td>12/20/2011</td>
<td>Center area relieved 0.030 in</td>
<td>13.33</td>
<td>1.0</td>
<td>70</td>
<td>11.5</td>
<td>0.28</td>
<td>30</td>
<td>None</td>
<td>Cycle stopped, no forge, stress relieved on bottom</td>
</tr>
<tr>
<td>852</td>
<td>12/21/2011</td>
<td>Center area relieved 0.040 in</td>
<td>13.33</td>
<td>1.0</td>
<td>70</td>
<td>11.5</td>
<td>0.28</td>
<td>30</td>
<td>None</td>
<td>Cycle stopped, no weld, dieter broke</td>
</tr>
<tr>
<td>854</td>
<td>12/21/2011</td>
<td>Center area relieved 0.025 in</td>
<td>13.33</td>
<td>1.0</td>
<td>70</td>
<td>11.5</td>
<td>0.28</td>
<td>30</td>
<td>None</td>
<td>Cycle stopped, no forge, up to 3.4 mm</td>
</tr>
<tr>
<td>919</td>
<td>1/10/2012</td>
<td>Repeating process of 88, weld cycle held until reach burnoff distance 0.15 in.</td>
<td>13.33</td>
<td>1.0</td>
<td>8.6-mm dist</td>
<td>11.5</td>
<td>0.28</td>
<td>30</td>
<td>Torque 1000 F</td>
<td>Full interface, spec 0.5 in, forge hold 10 sec, 8x1WI, see met &amp; mech damaged welder</td>
</tr>
<tr>
<td>944</td>
<td>1/21/2012</td>
<td>One addition of weld, weld cycle held until reach burnoff distance 0.06 in.</td>
<td>13.33</td>
<td>1.0</td>
<td>4.5-mm dist</td>
<td>11.0</td>
<td>0.28</td>
<td>30</td>
<td>Torque 1000 F</td>
<td>Upset 0.35, full interface, forge hold 10 sec, 8x1WI, see met &amp; mech damaged welder</td>
</tr>
</tbody>
</table>

*Weld and Forge Pressure are the compressive stress for the weld interface applied by hydraulic force normal to weld plane.*
Final Weld Trial Set

• Trials 848 through 944
• Improved heating and flash formation
• Welds at low weld stress for longer time
  – 1 ksi weld stress
  – 70 to 80 seconds
  – Burn-off distance 0.15 inch
• Some incomplete with overload of oscillator
• Three completed cycle through forge
Weld Sample 944

Improvement in flash and weld development in base
## Strength Test Results

### Sample Removal Locations

![Sample Removal Locations Diagram]

### Tensile Tests from 849

![Tensile Test Samples]

### Destructive Test Results

#### Weld Samples with Base Metal

<table>
<thead>
<tr>
<th>Weld Number &amp; Rail Section</th>
<th>Tensile 0.2% Yield</th>
<th>Ultimate Strength Mode &amp; Stress</th>
<th>Bend Test Set 15% Elongation</th>
<th>Bend Test Set 10% Elongation</th>
<th>Met Section</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>849</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head</td>
<td>78</td>
<td>Softened Zone 140</td>
<td>Parent 28° &lt;</td>
<td>na</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Web</td>
<td>90</td>
<td>Softened Zone 146</td>
<td>Parent 28° &lt;</td>
<td>na</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Base</td>
<td>88</td>
<td>Near BL 128</td>
<td>Weld 60°</td>
<td>na</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>919</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head</td>
<td>110</td>
<td>Near BL 137</td>
<td>na</td>
<td>Parent 25° &lt;</td>
<td></td>
<td>1</td>
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<tr>
<td>Web</td>
<td>103</td>
<td>Softened Zone 163</td>
<td>na</td>
<td>Weld 80°</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Base</td>
<td>110</td>
<td>Near BL 119</td>
<td>na</td>
<td>Weld 80°</td>
<td></td>
<td>1</td>
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<td><strong>944</strong></td>
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<tr>
<td>Head</td>
<td>107</td>
<td>Near BL 148</td>
<td>na</td>
<td>Weld 80°</td>
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<td>1</td>
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<tr>
<td>Web</td>
<td>96</td>
<td>Softened Zone 154</td>
<td>na</td>
<td>Weld 80°</td>
<td></td>
<td>1</td>
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<tr>
<td>Base</td>
<td>107</td>
<td>Near BL 144</td>
<td>na</td>
<td>Weld 80°</td>
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<td><strong>Base Metal</strong></td>
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<td>102</td>
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</tbody>
</table>
Stress Strain Curves for Welds

Yield same as base metal
Web elongates in softened zone
Base and head fail at bond line

Yield lower than base metal about 85.6 ksi
Web and head elongate in softened zone
Base fails at bond line

Yield same as base metal
Web elongates in softened zone
Base and head fail at bond line
Weld Trials & Strength Testing

- Heating began in web then moved to head and base.
- Longer time heating and more plastic strain in the web.
- Ultimate tensile strengths were highest in the web.
- Tensile test specimens failed 0.39 to 0.47-inch from the bond line.
- Base and head specimen failed at bond line at lower strengths.
- High residual stress caused some samples to fracture before or during sectioning.
Sections Removed - Part 944

FROM HEAD
FROM WEB
FROM BASE
Flash Comparison

- HAZ in the base is about 0.35
- Flash not symmetric for 919
- Flash near symmetric for 944

See Flash Top of Head 849
Sections for 919 Base

- Upper left is noted ferrite-sulfide stringers at bond line
- Lower left base metal shows unrefined larger grains with structure of the parent
- Lower right small region in the fine grain HAZ identified as the softened zone
Sections for 944 Web

- The web section bond line was clean and without anomalies
- It reveals dynamic recrystallization typical for friction welded steel
- Characterized by the apparent grain refinement along the narrow region of the bond line
Sections for 944 Head

- Bond line with apparent decarburized regions
- Fine grain of HAZ has similar appearance as other sections
- Base metal also has same appearance as the base metal of all other samples
Hardness Traverse for Weld 849

- Parent base metal range is 300 - 320
- HAZ hardness drops between 300 - 270
- HAZ hardness raises to between 350 and 400 up to the bond line
- Hardness values are generally symmetric about the bond line
- Lower hardness in the HAZ
Project Summary

- Project resulted in full-area welds for 136RE rail
- Heating began in the web then moved to the head and base
- Ultimate strengths highest in the web; tensile specimens failed in HAZ
- Base and head specimen fractured at bond line at lower strengths
- Failure mode change related to variations in heating and forging
  - Best welds used compressive stresses of less than 1-ksi for long heating times
  - Residual stress level depends on rates of heating in the different sections
  - Longer heating times tended toward temperature balance
  - Shorter weld times usually fractured during aging or on initial sectioning
  - Necessary to reduce the heating difference between the rail sections
- A 100-ton welder was used in this study
  - 100-ton axial force over the 13.33-in^2 can generate a contact stress of 15 ksi
  - TFW oscillator ceased at axial welding loads making only about 1 ksi contact stress
  - The TFW system used a 75-hp motor for oscillation to deliver 12.4-kip of force
  - TFW 136RE section welds will require at least 5 ksi contact stress
  - An oscillator drive must deliver loads on the order of 65-kip - translates to 400 hp
Conclusions

• TFW joints of full rail sections conducted
  – With compact equipment facilitating portable rail welding systems reducing implicit system costs

• Inconsistent heating and forging observed across the section
  – Heating of the rail started in the web
  – Longer times improved heating uniformity

• Weld stress must be greater than 1 ksi more typically 5 ksi
  – At 1 ksi, oscillator stalled at 13500 lbs force
  – At 5 ksi the force would be about 65000 lbs force equals about 400 hp

• Develop a hybrid stored energy drive
  – Flywheel energy storage to overcome the high effective friction loads
  – With variable cam to transition the oscillation amplitude