

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

## Key Findings:

- Testing at FAST shows about 88 percent of the rail breaks are thermite weld breaks. About 95 percent of the thermite rail break occurs in the web, web-base fillet, and base regions.
- Full volumetric inspection of rail thermite welds will require several transducers to be placed on both sides of the rail simultaneously for complete coverage.
- A smaller pitch (0.5 mm) with a larger aperture PAUT (32-element) probe provided better results compared to other probes explored during this study.
- A favorable signal-to-noise ratio is especially challenging to maintain in the weld collar line.

# Phased Array Ultrasonic Beam Modeling for Rail Thermite Welds

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[TTCI](#) is researching new rail weld inspection techniques and approaches to detect and characterize rail weld defects. The intent of this work, funded by the Association of American Railroads (AAR) Strategic Research Initiatives Program, is to assist solution providers with the development of a portable full rail weld inspection approach or system by bringing forward promising technologies for eventual deployment by the railroads.

This *Technology Digest* details TTCI's efforts using Phased Array Ultrasonic Testing (PAUT) technology for a thermite weld inspection at the Facility for Accelerated Service Testing (FAST) in Pueblo, CO. The project explored theoretical ultrasonic testing (UT) beam modeling and propagation simulation approaches using the CIVA UT software platform from NDT simulation company EXTENDE.

It was determined that a full volumetric inspection of rail thermite welds will require several ultrasonic transducers to be placed on both sides of the rail simultaneously to ensure complete coverage. The following PAUT approach for each location is recommended:

- Inspection of base: Sectorial shear wave scan; variation of reflector angle in the plane perpendicular to the weld; and motion along the weld profile.
- Inspection of web base and head-web fillets in the heat affected zone: fixed PAUT probe at 45-degree shear wave.
- Inspection of web: Sectorial shear wave scan for web; motion along the rail rolling surface.
- Inspection of head: Sectorial longitudinal wave scan; motion in the plane perpendicular to the rail longitudinal direction.

## BACKGROUND

Thermite welding is a form of casting that involves melting a thermite mixture (molten metal) to fill a gap (1 to 1.5 inches) between the ends of the unjoined rails. Defects in thermite rail welds are caused by foreign objects (slag), improper mating between the weld mold and the rail surface, or thermal conditions that occur during the welding process. Defects associated with thermite welds can include dispersed porosity, microvoids, cold lap, shrinkage cavitation, and centerline defects in the weld cast microstructure.<sup>1</sup> Figure 1 shows the typical locations of potential defects in thermite welds, and Table 1 lists the possible weld defects found in those locations and their possible causes.

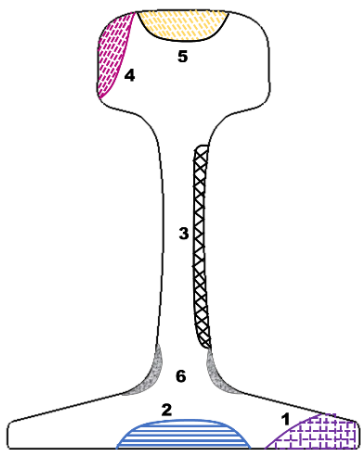


Figure 1. Typical thermite weld defect/failure areas

Table 1. Possible causes of thermite weld defects

Defect Location	Defect Type	Possible Causes
1	Lack of fusion	Attributed to welding process
2-3	Centerline defects and micro-shrinkage; Slag (cold laps)	Attributed to thermal expansion, phase transformations and the change in weld metal volume during weld formation and cooling
3	Shrinkage	
4	Gage corner cracking	Wear failures or result of internal stress concentrations at inclusions or pores
5	Rolling contact damage (RCD)	Attributed to plastic flow and subsequent crack growth
6	Slag or inclusion	Slag ("cold-laps") or inclusion entrapment during the welding process

Testing at FAST showed that approximately 88 percent of the rail breaks were thermite weld breaks, a result that aligns well with other published literature.<sup>2</sup> Figure 2 provides a six-year summary of thermite weld break distribution in the rail at FAST from spring 2014 to spring 2020.

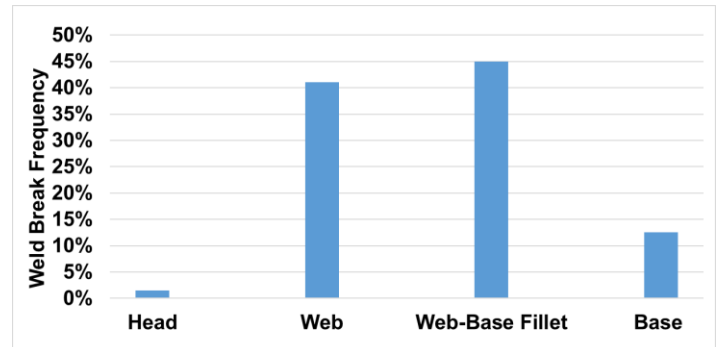


Figure 2. Thermite weld break distribution in the rail during testing at FAST from spring 2014 to spring 2020

Existing practices for flaw detection and characterization in thermite rail welds after installation are limited to visual inspection, which does not reveal purely internal defects. Successful development of nondestructive evaluation (NDE) technologies that include complete volumetric inspection of rail welds could present benefits to the industry. Such technology would provide an effective way to monitor field welds for internal defects, especially if the monitoring process could locate the defect at any location in the weld.

## ULTRASONIC BEAM MODELING AND SIMULATION

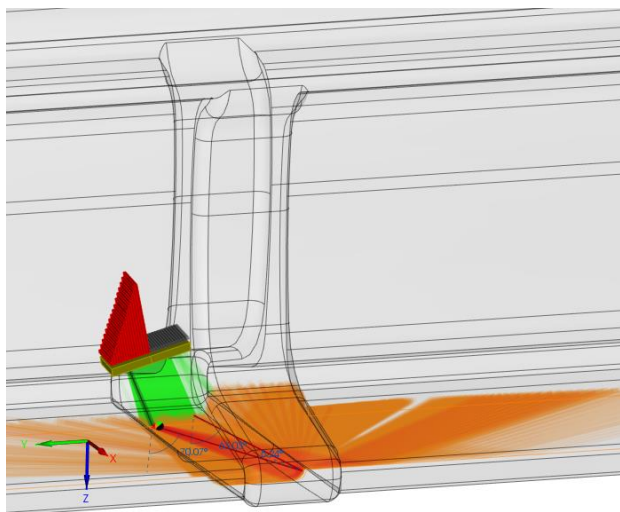
Beam coverage in thermite rail welds was studied to determine if ultrasonic inspection beams could reach difficult areas (i.e., web base fillets and base flanges). Several configurations of PAUT probes were modeled and explored for use in the inspection of the thermite welds at the base, web, and head of the rails. Based on the beam modeling and simulation conducted, the probe configurations in Table 2 are recommended.

Figure 3 shows the ultrasonic beam coverage for the thermite weld at the base region of the rail. During the modeling and simulation process, it was demonstrated that full coverage of the base could not be achieved without using a "full skip." Used in ultrasonic angle beam testing, a full skip is the path traveled by an ultrasonic beam from the point of entry on the front surface to the back surface where it reflects to the front surface. However, this technique is feasible using

only the rail and not the weld as a reflector due to the uneven underside of the welded area. Angles between 45 and 70 degrees are sufficient to obtain full coverage.

**Table 2. PAUT probe configurations for thermite weld inspection**

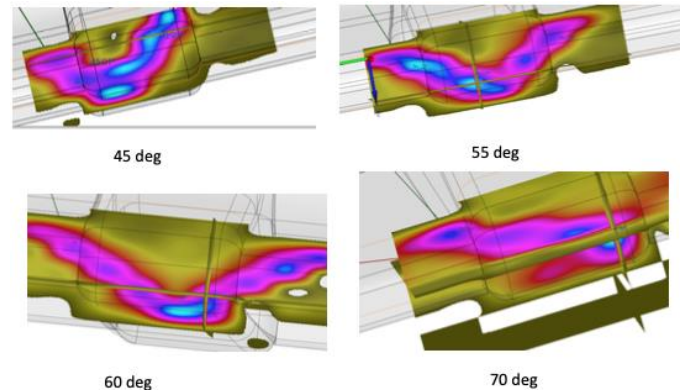
PAUT Parameters	Base/Web	Head	Web/Base and Head/Web Fillet
Frequency	5 MHz	5 MHz	5 MHz
No. of elements	32	32	16
Pitch	0.5 mm	1 mm	1 mm
Elements interspacing	0.08 mm	0.08 mm	0.08 mm
Elevation	12 mm	12 mm	12 mm
Probe positioning (from weld center)	40 mm/ 125 mm	Centerline of the head (transverse direction)	Perpendicular to weld
Refracted shear wave	45° to 70°/ 30° to 70°	-45° to +45°	45°



**Figure 3. Thermite weld base ultrasonic beam coverage (45-70 degrees)**

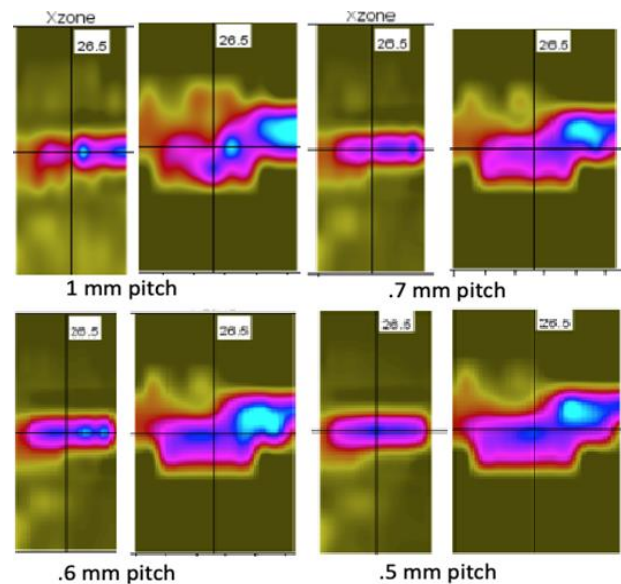
Similarly, web inspection can be achieved from the top of the rail head and also uses several angles. However, during this process, probes must be placed further away from the weld, and a larger angle range (30-70 degrees) is required to cover the full web area. Beam coverage on the head can be achieved by rotating the probe 90 degrees (along transverse direction) and performing a sectorial scan in the  $\pm 45$ -degree directions. An uncovered area can be inspected by moving the probes in the direction perpendicular to the rolling direction or by using larger element probes. Figure 4 shows the beam simulation results for the thermite weld base. The light blue color indicates areas with the highest energy. The

intent of the beam field coverage is to obtain a smooth (constant) beam profile with sufficient energy over the full beam travel path. Using a 25 mm water column, the near field is estimated at 97 mm for a 5 MHz transducer (45-degree beam). The longer length of the near field of the 5 MHz transducer helps to improve this probe response. Subsequent simulations on the rail samples also did not lead to unacceptable noise at 5 MHz.



**Figure 4. 5 MHz ultrasonic beam field in the thermite weld base region**

The team also investigated the effects of element pitch—the distance (mm) between the centers of two adjacent elements of a phased array probe. Figure 5 shows the results obtained for web/base fillet region with varying element pitch for a 32-element, 5-MHz probe. It was demonstrated that a smaller pitch with a larger aperture, in this case, leads to better results.



**Figure 5. Ultrasonic beam field in the thermite weld web/base fillet region with varying element pitch**

Figure 6 shows the beam simulation results for the thermite weld web. The ultrasonic beam field is smooth (constant) with sufficient energy over the full beam travel path and provides good coverage in the base section. In addition, a smooth beam field is also observed in the thermite weld head (not shown) that provides good coverage in the full beam travel path.

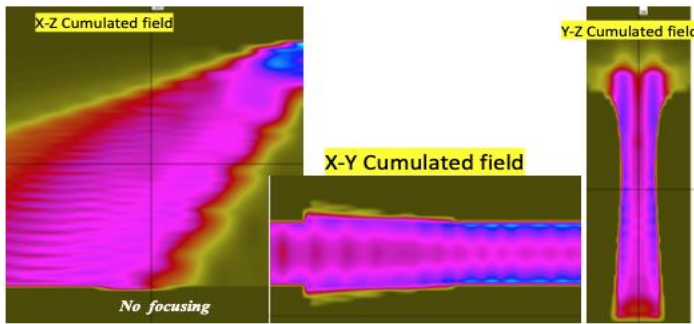


Figure 6. Cumulative ultrasonic beam field in the thermite weld web region

## RECOMMENDATIONS

Full volumetric inspection of thermite rail welds will require the placement of several transducers on both sides of the rail simultaneously. Thermite rail geometry is very complex and uneven, restricting access to some critical areas, especially the fillet areas. In such cases, the PAUT probe needs to be moved further back, re-oriented, and deployed using a full skip approach. Thermite welds have a variable geometry which generates indications that could be misinterpreted as defects. Therefore, extra considerations should be taken to discriminate noise from the actual indications. Based on the modeling and simulation results, the following probe configurations are recommended for a portable manual scanner for thermite weld inspection:

- Base and web: Four PAUT probes of 32 elements.
- Head and web: Two PAUT probes of 32 elements.

- Head/web and web/base fillets: Four PAUT probes of 16 elements.
- Total number of elements: 256.
- Maximum number of phased array pulsers: 32.

## CONCLUSIONS

The project explored theoretical PAUT beam modeling and propagation simulation approaches using the CIVA UT software for the thermite rail welds. The objective of using this simulation study was to determine if ultrasonic inspection beams could reach the difficult areas of a weld geometry (i.e., web base fillets and base flange). Several configurations of PAUT probes were modeled and explored for inspecting the base, web, fillets, and head of the thermite rail welds. Based on the modeling results, full volumetric inspection of thermite rail welds is possible, but would require multiple probe configurations.

## References

1. Chen, Y., F.V. Lawrence, C. Barkan, and J.A. Dantzig. 2006. Weld Defect Formation in Rail Thermite Welds. *Proc. IMechE, Part F: Journal of Rail and Rapid Transit*, 220(4), 373–384.
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