M. NDE Tools for the Evaluation of Laser-Welded Metals

Principal Investigator: William Charron
Ford Motor Company
17000 Oakwood
Room B154
Allan Park, MI 48101
(313) 390-3792; fax: (313) 594-1898; e-mail: wcharron@ford.com

Project Administrator: Constance J. S. Philips
National Center for Manufacturing Sciences
3025 Boardwalk
Ann Arbor, MI 48108-3266
(734) 995-7051; fax: (734) 995-1150; e-mail: conniep@ncms.org

Technology Area Development Manager: Joseph A. Carpenter
(202) 586-1022; fax: (202) 586-1600; e-mail: joseph.carpenter@ee.doe.gov
Field Technical Manager: Philip S. Sklad
(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

---

Contractor: U.S. Automotive Materials Partnership
Contract No.: FC26-02OR22910

Objective

- Develop fast, accurate, robust, noncontact Nondestructive Evaluation (NDE) tools and methodologies to replace current manual destructive testing of laser-welded sheet and structures in zinc-coated and uncoated steel and aluminum.
- Demonstrate accuracy and repeatability of the technologies developed or applied.
- Supplant the need for highly trained/experienced NDE operator.

Approach

- Evaluate and develop NDE tools for laser-welded steel.
- Evaluate and develop NDE tools for laser-welded aluminum.
  - Phase 1—the comprehensive assessment of existing and emerging NDE technologies for steel and aluminum, down-selection, performance testing using fabricated welded coupons in steel, correlation of NDE test results with validation test results, and NDE technology selection for Phase 2.
  - Phase 2—the specification and build of a prototype from the selected NDE methodology(ies) for
    - Steel—Conduct controlled evaluations of NDE capabilities using fabricated weld coupons and ultimately coupons made from laser-welded production parts and correlation of NDE test results with validation test results. Finally, comparison of NDE test results will be made to destructive test results obtained on production part coupons.
    - Aluminum—Conduct controlled evaluation of NDE capabilities using fabricated weld coupons and correlation of NDE test results with validation test results. Finally, comparison of NDE test results will be made to destructive test results obtained on aluminum coupons.
    - Demonstrate the selected technology with a bench prototype system in a production plant setting.

Accomplishments

- Conducted original equipment manufacturer (OEM) weld flaw characterization, selection of target laser weld application, definition of NDE system functional specifications, and assessment of NDE state-of-the-art technologies.
- Performed controlled testing of four selected NDE technologies using Coupon Set One and analyses of vendor test results.
- Defined NDE system functional specifications based on roof ditch rail application and production plant input.
- Selected of ultrasonic through-transmission technology for further testing and development.
- Evaluated ultrasonic through-transmission sensor using steel roof ditch samples fabricated on laser weld production-equal equipment, aluminum lap-weld samples fabricated on laser weld production-equal equipment, and steel roof ditch production part coupons.
- Analyzed test results for steel roof ditch samples, aluminum lap-weld samples, and steel production part coupons.
- Initiated prototype optimization based on initial plant trial performance results for roof ditch rail application.
- Redesigned aluminum coupon weld construction for NDE testing (Coupon Set Five).
- Defined plant test plan and prototype in-plant trials.

Future Direction

- Analyze the test results on (1) redesigned aluminum lap weld coupons (Coupon Set 5) and (2) additional in-plant trials using the prototype modified for the production part in steel.
- Correlate all test results from coupon and production part coupon tear-down results with the ultrasonic through-transmission signatures, C-scans, and radiographic X-ray images.

Introduction

Approved for incorporation into the United States Automotive Materials Partnership (USAMP) project portfolio in January 2001 and launched in May 2001, this project has two primary investigative missions: (1) evaluate and develop nondestructive evaluation (NDE) tools for laser-welded steel and (2) evaluate and develop NDE tools for laser-welded aluminum. The investigative approach is divided into two phases:

- Phase 1—the comprehensive assessment of existing and emerging NDE technologies for steel and aluminum, down-selection, performance testing using fabricated welded coupons in steel, correlation of NDE test results with validation test results, and NDE technology selection for Phase 2.
- Phase 2—the specification and build of a prototype from the selected NDE methodology(ies) for
  - Steel—Conduct controlled evaluations of NDE capabilities using fabricated weld coupons and, ultimately, coupons made from laser-welded production parts and correlation of NDE test results with validation test results and comparison of NDE test results to destructive test results obtained on production parts.
  - Aluminum—Conduct controlled evaluation of NDE capabilities using fabricated weld coupons and correlation of NDE test results with validation test results. Finally, comparison of NDE test results will be made to destructive test results obtained on selected aluminum coupons.

While laser welding is accepted by the automotive industry for many applications, cost factors are an issue, particularly with respect to weld discontinuities in body applications. With the high speed and high volume of laser welding coupled with the flaw sizes of interest, finding these discontinuities can be difficult, time-consuming, and hence, expensive. If not detected before subsequent processing and/or assembly, they could cause failures during processing down line or while in use. For example, porosity in a laser-welded tailor blank can cause failure during a stamping operation, which in turn can damage dies and cause downtime for the press. To forestall this, laser welding must be accomplished with no detrimental weld discontinuities, and the process and product output must be monitored with a high degree of reliability.

A number of systems have been developed to monitor laser welding systems in real time. Generally, these systems examine the byproducts of the laser-to-metal interaction to infer the quality of the weld itself. These process monitoring methods may include examination of the frequency and intensity of the light that is given off, for example, and compare it to those parameters known to have produced an “acceptable” weld. Most of these monitoring systems use this “training” method as a basis for determining if acceptable welds or unacceptable welds were created by the laser weld process. As of this writing, such systems are being applied in the production environment to gage the process, not as a substitute for weld quality inspection or destructive testing.

Because laser welding will facilitate the use of lightweighting materials and designs, the development of NDE tools is viewed as an enabling technology for the reduction of vehicle mass through increased use of laser welding in automotive plants. Thus, this project focused on developing and using NDE for laser-welded body structures, specifically for laser stitch welds in a roof ditch rail in steel and aluminum. Demonstrations of accuracy and repeatability of the NDE system on steel and aluminum weld samples and on steel production part coupons are essential for obtaining plant acceptance and eventual implementation.

Details of Phases 1 and 2

Phase 1

AMD 303 is exploring NDE tools for use on the weld itself after creation of the weld. Of interest was the identification of progressive and emerging technologies in NDE, an assessment of the state of the art. As part of its Phase 1 effort, the AMD 303 project performed phased assessments of NDE technologies, progressively narrowing down the technologies best suited to the production application. From these assessments, specific NDE technology recommendations were reviewed and a technology chosen with the goal to have a NDE prototype ready for evaluation in a factory setting by the end of the project.

The NDE techniques included in the state-of-the-art assessment are identified in Figure 1. Commercial off-the-shelf systems were included along with emerging NDE technologies. Based on this initial assessment, four technologies were then selected for detailed evaluation using a scientifically designed and statistically controlled study. These four technologies were: ultrasonic through-transmission, ultrasonic EMAT, visual inspection—laser mapping, and resistivity. NDE performance capabilities of these four were evaluated using laboratory-fabricated weld samples simulating laser-welded roof ditch welds (Coupon Set One). See Figure 2 for an illustration of the roof ditch coupon.

To down-select further, it was determined which NDE technology offered the best array of detection capabilities and potential for conforming to the roof ditch rail geometry. All four NDE systems were found to have varying deficiencies, including false calls (reacting to a good weld as if it were flawed)

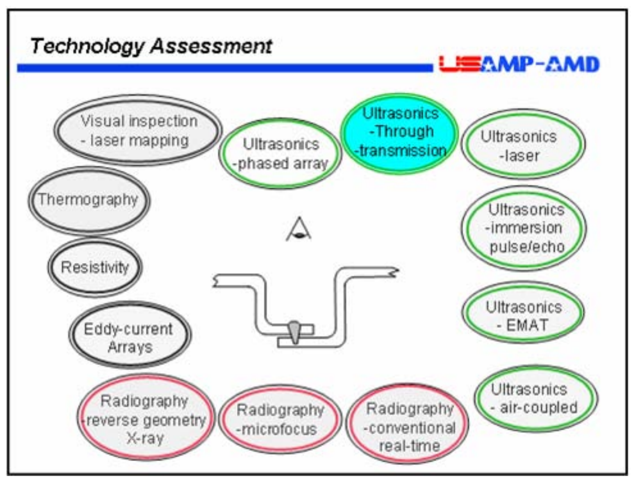

Figure 1. Phase 1 technology assessment examined the capabilities of thirteen technologies/techniques for their suitability to inspect the target weld configuration and the weld discontinuities of interest. Initial analyses identified four techniques, highlighted here in color, for detailed evaluation.

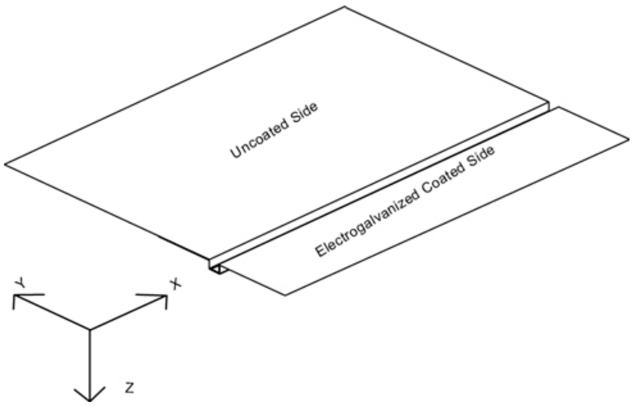

Figure 2. Overall dimensions of roof ditch weld sample: X = 400 mm; Y1 = 202 mm; Y2 = 89 mm; overall Y after bending = 287 mm; Z = 12 mm.

and missed discontinuities (not reacting to flaws known to be present), including the discontinuity of highest interest, lack of fusion. Additionally, all four tended to undersize defects.

Ultimately, two technologies were selected for their capabilities for detecting weld discontinuities judged critical by the AMD 303 Committee. The two NDE systems, one based on ultrasonic EMAT and one based on ultrasonic through-transmission, performed comparably well (albeit on some differing discontinuities). The evaluations indicated both systems required additional development and reconfiguration to perform acceptably well in the OEM production environment and on the roof ditch rail application. Finally, due primarily to cost advantages, the through-transmission ultrasonic sensor technology was selected for Phase 2 in-depth evaluation, reconfiguration, and build for the roof ditch weld application. Figure 3 illustrates a roof ditch rail in detail and the required sensor orientation to the part.

Phase 2

Specific discontinuities of interest were identified in meetings and interviews with OEM assembly plant personnel. Two high-priority detection needs were "Lack of Fusion" and "Missing Welds and Skips." Other discontinuities were rated as being of lower priority, and some were unrated, because they could be controlled with process controls or are detectable by visual means. Table 1 lists the discontinuities of interest, shows their priority classification by plant personnel, and if the discrepancy can be detected by ultrasonic through-transmission and/or ultrasonics additionally having pitch/catch capability.

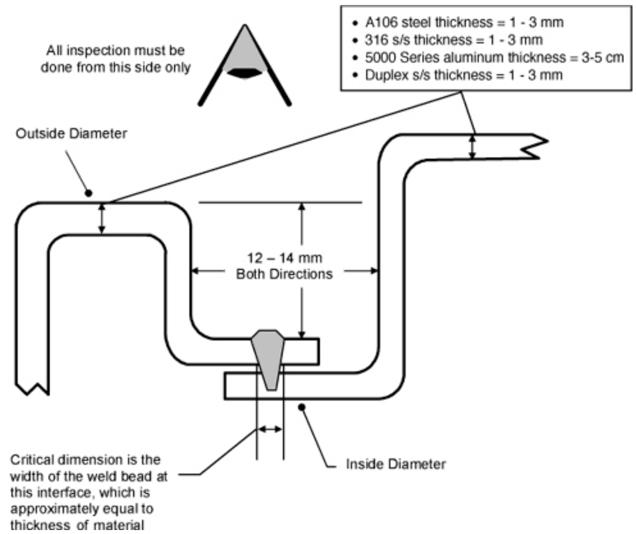

Figure 3. Laser-welded roof ditch joint details showing the sensor's field of view.

Table 1. Discrepancy detection requirements at the plant level

Discontinuity type defined in NDE-001	Plant priority	Detection table	
		Ultrasonics through-transmission	Ultrasonics with pitch/catch
Lack of fusion	High	√	√
Undersize welds	Medium	√	√
Underbead cracks	Low		√
Crater cracks	Low		√
Longitudinal cracks	Low		√
Transverse cracks	Low		
Missing welds skips	High	√	√
Pore, porosity	Medium	√	√
Inclusions			√
Burn-through and holes	Medium	√	√
Top sheet through-cut			√
Undercut of underfill			√

Laser-Welded Coupons

The project has created four groups of laser-welded coupons for testing and evaluation purposes, and a fifth was designed but not yet fabricated as of this report.

Coupon Set One: EWI Roof Ditch Coupons— During Phase 1, 36 laser-welded coupons were fabricated by Edison Welding Institute in welding laboratory conditions and used in Phase 1 vendor technology evaluations. These 36 coupons form Coupon Set One.

Coupon Set Two: Roof Ditch Weld Coupons in Steel—Subsequent to the selection of the ultrasonic through-transmission technology for Phase 2, additional coupons were fabricated using production-intent welding cells built by Kuka Flexible Production Systems having a 4-kW Nd:YAG laser with robot.

Ford Motor Company, in cooperation with Kuka, laser welded 13 roof ditch weld coupons in steel. Eleven of these coupons contained lack of fusion with lengths ranging from 2.0 mm to 43.8 mm. Two coupons contained no known discrepancies.

Coupon Set Three: Lap Weld Coupons in Aluminum—Ford, in conjunction with Kuka, laser welded eight aluminum sheet coupons with a continuous lap weld. The coupons contained lack of fusion, burn through, and porosity among other discontinuities. These laser-welded coupons had distortion and configuration variances among the coupons, such as varying amounts of metal overlap, that posed additional challenges for the NDE testing. (See Figures 4 and 5.)

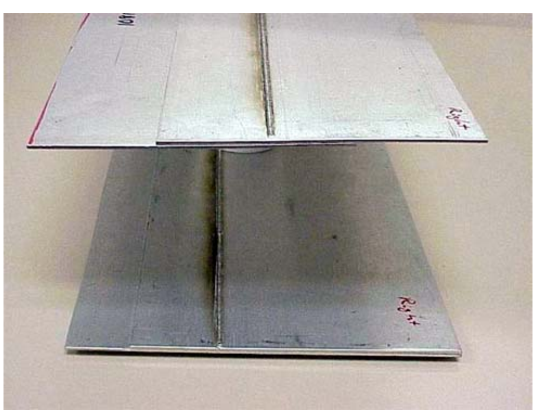

Figure 4. Lap-welded aluminum coupons using 4-kW Nd:YAG laser. The coupons illustrate the varying sizes and overlap configurations.

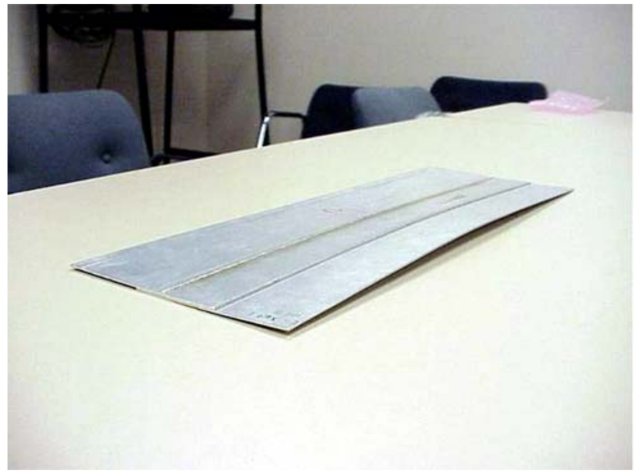

Figure 5. Aluminum coupon with distortion in the sheet caused by the laser welding process.

Coupon Set Four: Production Roof Ditch Welds in Steel—Eight production part coupons were sectioned and cut from an assembled vehicle roof produced in a production laser welding cell being readied for new model production at an OEM plant. The production parts were fabricated in steel. They exemplify the issues posed by complex part geometries in mating part contours of the roof and body sides.

Coupon Set Five: Controlled Aluminum Lap Weld Coupons—In FY 2005 General Motors Corporation (GM) will fabricate an additional set of aluminum lap weld coupons using a production equal laser welding cell at GM. This set will control the width of overlap, stitch weld length, gaps between welds, and welding parameters to control distortion.

NDE Tool: Ultrasonic Through-transmission

Ultrasonic through-transmission was found to have the following attributes:

- Through-transmission is accomplished by use of two separate transducers, which transmit and receive a 4-MHz ultrasonic wave.
- Transducers are encapsulated in dry couplant rollers that travel along in contact with the two welded sheets on both sides of the weld seam.
- Lack of fusion is indicated by drops in signal amplitude.
- “Good weld” coupons are required to calibrate and set the system gain (signal threshold).
- Encoder tracks its location along the weld as the signal is generated.

- Inspection speed determines spatial resolution.

The ultrasonic through-transmission device is capable of detecting most lack-of-fusion regions in the above test coupons, except Coupon Set Three. System noise from nonwelded contact generated by fused wax between the plates obfuscated testing. To better test the device on aluminum sheet with stitch welds, a new aluminum coupon set will be fabricated (Coupon Set Five) and the tests repeated in FY 2005. The ultrasonic through-transmission device and user interface proved to be user friendly and did not require extensive user training. The device, configured for testing of roof ditch coupons as in Coupon Set Two, is shown in Figure 6.

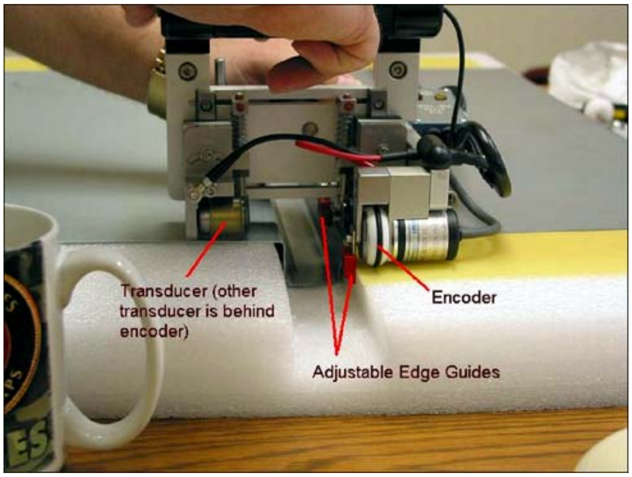

Figure 6. Ultrasonic through-transmission device shown at testing start on a steel coupon from Coupon Set Two.

NDE Test Plan

A standard test matrix was defined consisting of the following measurements:

- RMS variations,
- baseline noise,
- gage repeatability and reproducibility, and
- surface roughness.

The test plan was applied to Coupon Sets One through Four. Figure 7 shows a scan being made, and the user interface providing real-time graphic feedback to the operator representing the signature amplitude of the ultrasonic wave in response to the subject weld.

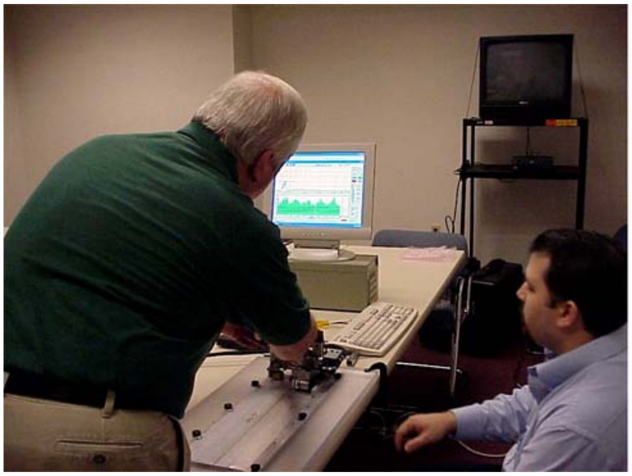

Figure 7. Ultrasonic through-transmission device testing an aluminum coupon from Coupon Set Three with the user interface displaying the signature of the ultrasonic wave in response to the weld sample.

Analyses of Test Results

Analyses of the testing results from Coupon Sets One and Two yielded the following findings:

- electronics-induced variance: 1.3% of full scale (FS)
- repeatability/scanning variance: 7.6% of FS
- total variance: 7.9% of FS
- reproducibility/operator-induced variance: 2.0% of FS

Further examination of the repeatability/scanning variance seen in these tests results focused on the rollers that encapsulate the transducers. The wheels were found to compress as the force was increased, and this had a dominant effect on the repeatability variance.

Additional analyses were conducted to determine the resolution of the scanner. Resolution is reflected in the probability of detecting a particular size gap and is dependent upon the threshold setting and the noise of the system. Using the derivative of the signal to define the beam shape, it was determined to be triangular, with a 6-db beam width of 6.5 mm. Examining the drops in amplitude of the dips between signals (equating to gaps between the stitch welds or lack of fusion) allows one to measure the magnitude of the dip along with the variance and to calculate the probability of detection. The data analysis indicated that gaps from 2 to 6 mm in length are not able to be detected. Based on a probability plot curve, the probability of detecting gaps more than 6 mm increases until >99% probability is reached at 8 mm and larger. (See Figure 8.)

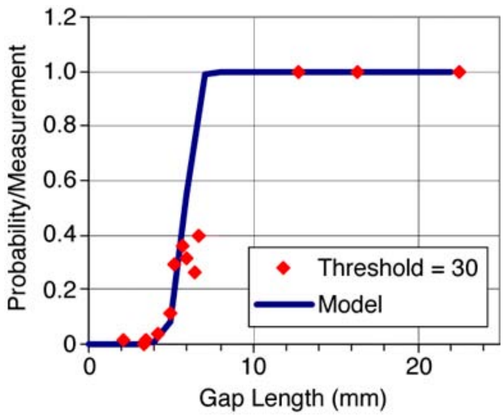

Figure 8. Graph of gap detection probability indicates the probability significantly increases for gaps exceeding 6 mm in length at a threshold setting of 30, reaching >99% probability for gaps of 8 mm or larger.

Data analyses and reporting of the test results for Coupon Set Four (production part coupons) are under way at this writing. General observations reported following the testing of Coupon Set Four using the unmodified prototype included the following:

- Maintaining dual roller contact with the geometry of the part was difficult for the operator. The part profile is a complex geometry owing to the downward slope of the body side member away from the weld location in the roof ditch.
- The time needed for data collection was adversely affected by one inexperienced operator having to back up and repeat the scan more frequently than normal.
- Electrical interference from within the plant was seen to affect the ultrasonic signal and will be reflected in the data.
- Data displayed on the prototype screen is limited to 1000 points. This number does not register sufficient data to cover a scan along the full length of the ditch rail. Thus, the part had to be marked off in sections, scanned in sections, and data collected by section. (See Figure 9.)
- Testing was done on two vehicles. Tests were performed using three operators, who switched right-hand (RH) and left-hand (LH) body sides by scanning RH from front to rear and LH by scanning from rear to front. Figure 9 illustrates the sectioning and direction of scanning by the operators.
- Eight sections cut from one vehicle (Coupon Set Four) were validated by C scan by GM and radiographic X-ray by DaimlerChrysler.
- Four welds had shims inserted in an attempt to create lack of fusion; some welds partially penetrated through the shims.

Coupon Validation

Validation tests of Coupon Set Two using radiographic X-ray and ultrasonic pulse/echo "C-scans" of the midplane in an immersion tank were completed. C-scan results were recorded for

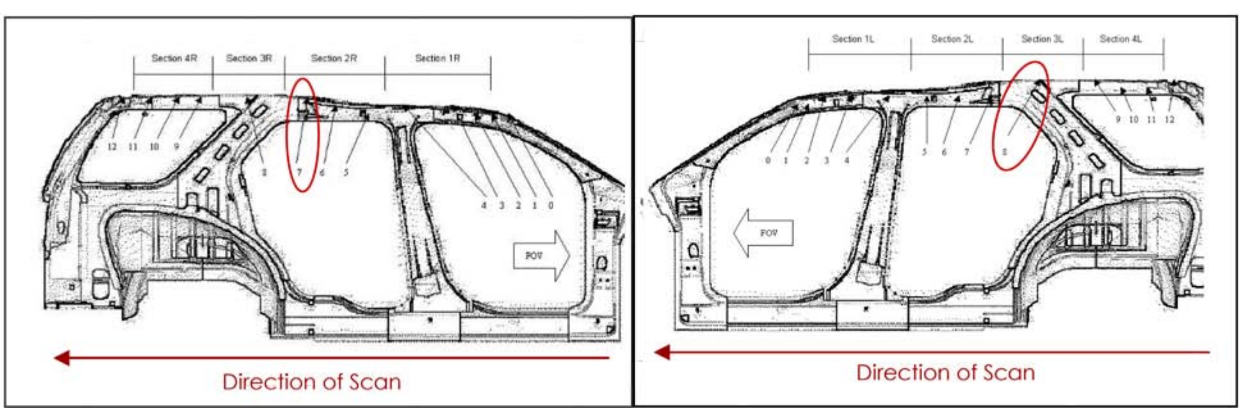

Figure 9. Illustration of scanning direction and sectioning of vehicle roof ditch for data collection purposes.

each coupon and analyzed against the ultrasonic through-transmission sensor's amplitude output data (signature) by coupon. Figure 10 is a graphic depiction of such a correlation between C-scan data and the ultrasonic through-transmission signature for Steel Coupon No. 45 from Coupon Set One. The weld is clearly visible in both the signature and the C-scan image and correlates with one another in size and position.

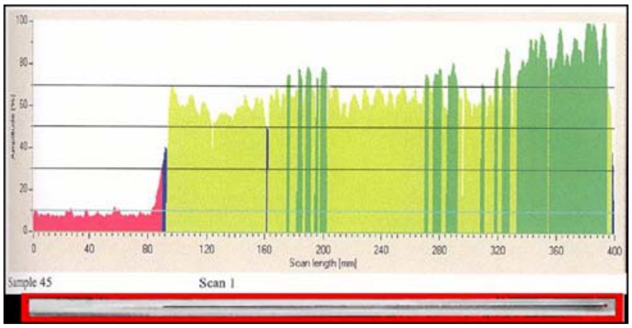

Figure 10. Ultrasonic C-scan data (bottom) and ultrasonic through-transmission signature of steel sample No. 45 from Coupon Set One.

Validation of Coupon Sets Two through Four using ultrasonic C-scans and radiographic X-ray are also complete. Production part coupons from Coupon Set Four posed particular difficulties for C-scanning as the parts were badly distorted when they were cut into sections. Weld validation data of the type shown in Figure 10 have been analyzed and will be compiled and reported in FY 2005.

A test plan for tear-down of the production part coupons is currently being implemented for Coupon Set Four, and the results will be correlated with the ultrasonic through-transmission, C-scans, and radiographic X-ray images for selected coupons. These results will be available for inclusion in the FY 2005 report. Figures 11 and 12 contain photographs of one stitch weld from Coupon Set Four, before and after tear-down. Such images will also be incorporated with the above data in the FY 2005 report.

Additional Technology Explored

Technological advancements since the beginning of this project in the areas of infrared cameras, hyper spectral imaging (3–5 μm), spectrometer

Figure 11. Photograph of production-part single stitch weld from Coupon Set Four. (Section 2R—Stitch No. 7 in Fig. 8) before tear-down.

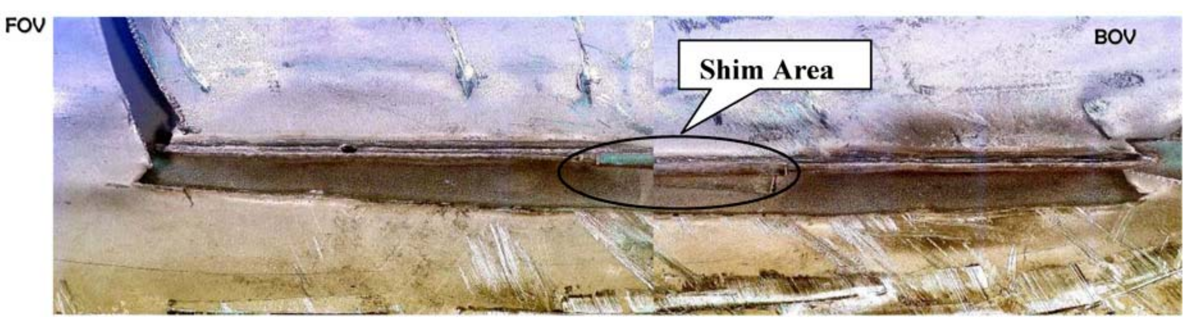

Figure 12. Picture of production-part stitch weld in Figure 11 after tear-down. (Section 2R—Stitch 7 in Fig. 8.)

capability in the ultraviolet-infrared range, high-speed capability (346 to 38,000 frames/s), high-sensitivity, and spatial resolution from 5-µm/pixel have resulted in one technology being brought back to our attention in recent months. Infrared thermography research at Oak Ridge National Laboratory by Drs. Zhili Feng and Hsin Wang has shown promise as a NDE technology now capable of detecting weld flaws without having to paint a metal part black. This possibility, which, along with the advancements cited above, could make this technology feasible for use in a production plant and was believed worthy of further investigation. Various coupons from Coupon Set One and Coupon Set Four were provided for initial feasibility experiments at ORNL. Results of these experiments will be available for inclusion in the FY 2005 report.

Conclusions

- Sufficient performance information was gained in the coupon testing conducted to date to allow performance and design guidance to be provided for prototype improvement and configuration to the ultrasonic through-transmission vendor for further production part testing in an OEM production plant.
- Additional in-plant trials are scheduled in FY 2005 to apply the prototype device modified for the roof ditch production part.
- Physical tear-down results can be correlated with the ultrasonic through-transmission signatures, C-scans, and radiographic X-ray images for selected coupons.
- Aluminum coupon testing must be repeated using coupons fabricated using thoroughly cleaned sheet stock. Results from this testing and implications for ultrasonic through-transmission inspection of aluminum laser welds will be reported in FY 2005.