B. NDE Inspection of Resistance Spot-Welds in Automotive Structures Using an Ultrasonic Phased Array

Principal Investigator: Deborah Hopkins, Ph.D.
Lawrence Berkeley National Laboratory
1 Cyclotron Road, MS 46A-1123, Berkeley, CA 94720
(510) 486-4922; fax: (510) 486-4711; e-mail: dlhopkins@lbl.gov

Technology Area Development Manager: Joseph 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

Participants:
U.S. Automotive Materials Partnership Ultrasonic Phased-Array System for RSW Inspection Project (AMD409) Team
Frédéric Reverdy, Ph.D., Lawrence Berkeley National Laboratory
Daniel Türler, M.S., Lawrence Berkeley National Laboratory
William B. Davis, M.S., Lawrence Berkeley National Laboratory
William Charron, Ford Motor Company
George Harmon, DaimlerChrysler Corporation
Cameron Dasch, General Motors Corporation

Contractor: Lawrence Berkeley National Laboratory
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Objective

- Develop a cost-effective ultrasonic phased-array system that is sufficiently fast, accurate, and robust in manufacturing environments to be suitable for inspection of spot welds in automotive structures.

Approach

- Develop a spot-weld inspection system that can be used by operators with minimal training by using state-of-the-art ultrasonic phased-array technology. The multi-element probe allows the ultrasonic energy to be focused at the interface between the welded sheets and electronically scanned through the weld.
- Design and fabricate a miniature mechanical scanner that will allow scanning in the direction perpendicular to the electronic scan to produce two-dimensional images of the weld. The portable system allows more than 3000 signals to be acquired in less than 4 seconds.
- Develop signal-processing and image-analysis software to distinguish satisfactory, undersized, and defective welds and provide dimensional analysis of the weld in a few seconds.
- Minimize the footprint of the probe assembly to ensure access to welds on complex components.
- Design and fabricate a probe housing that meets the size constraints while allowing mechanical scanning over a travel distance of 14+ mm. The housing must also maintain the probe in water and include an outer membrane that confines the water column and provides acoustic coupling to the part under inspection.
- Conduct trials on individual samples made under controlled conditions and on production parts to determine the resolution, repeatability, and accuracy of the prototype system.
- Conduct plant trials to demonstrate the system's ability to characterize welds with sufficient accuracy and repeatability in practice and to demonstrate that the integrated probe housing can be used successfully in a production environment by a skilled and trained operator.

Accomplishments

- Evaluated the performance and limitations of existing ultrasonic phased-array systems.
- Conducted a series of laboratory experiments to evaluate the performance of 5-, 10-, and 17-MHz phased-array probes for characterization of spot-welds in galvanized steel.
- Developed signal-processing algorithms to distinguish between satisfactory, undersized, and defective welds.
- Developed image-processing algorithms that allow three-dimensional analysis of welds.
- Demonstrated the ability to acquire more than 3000 signals per weld and analyze the resulting data in a few seconds to render an estimate of weld quality.
- Developed a difference-equation model that enables simulation as well as signal processing to recover reflectivity estimates, and to detect poor coupling and malfunctioning probe elements. Pre-processing algorithms are used to measure changes in thickness and to detect misalignment of the probe.
- Demonstrated good correlation between ultrasonic measurements, measurements of weld buttons on peeled samples, and metallographic images of cross-sections through welds.
- Designed and fabricated a probe housing that maintains the probe in water, contains a miniature mechanical system that allows linear translation of the probe, and provides an outer membrane that confines the water column while also providing acoustic coupling to the part under inspection. Identified and tested coupling materials that allow satisfactory signals to be obtained outside of a water tank.

Future Direction

- Conduct laboratory experiments on samples prepared under carefully controlled conditions, make measurements on production parts, and conduct plant trials to demonstrate the ability of phased-array systems to inspect spot welds with sufficient accuracy and repeatability for the full range of materials and joint configurations used in production.
- Conduct laboratory experiments to determine the concept feasibility of using ultrasonic phased arrays to inspect welds in aluminum and advanced high-strength steels (AHSS).
- Develop automated classifiers to determine weld dimensions and identify defective welds including cold welds.
- Develop a user interface in conjunction with end users to ensure ease of use and reporting of data in the most useful format for inspectors, welding engineers, and plant managers.
- Develop a fully integrated prototype system suitable for deployment and testing in a manufacturing plant.
- Perform large-scale testing and measurement system analysis.

Introduction

Development of nondestructive evaluation (NDE) techniques is an enabling technology for greater use of lightweight materials in the automotive industry where NDE methods to assure product quality are essential for industry and consumer acceptance of new materials and manufacturing methods. Recent studies have demonstrated cost savings associated with implementing NDE that derive from finding defects early in the production process and reducing waste compared to destructive testing. One of the critical technical challenges in introducing lightweight materials is developing joining technologies and inspection strategies suitable for mass production. At present, the most common methods for inspecting spot-welds in automotive manufacturing are pry checks and physical teardown, during which spot-welded joints are pried apart and the resulting weld buttons are visually inspected or measured with calipers. Although these methods have been used successfully for decades, destructive weld testing has several drawbacks including high costs associated with scrapped material, ergonomic injuries, and the time-lag between the onset and identification of problems. In addition, pry tests and teardowns do not allow plant managers and engineers to easily collect inspection data that would allow them to identify trends and potential problems. Furthermore, these inspection techniques are not viable options for lightweight and high-strength materials. Composite structures with adhesive-bonded joints cannot be pry checked and aluminum is relatively expensive and more difficult to rework than steel, making pry checks and teardown cost prohibitive. Welds in high-strength steel are often too strong to be pry-checked or torn down and satisfactory welds sometimes fail interfacially rather than by pulling a weld button, making it difficult for inspectors to distinguish between satisfactory and defective welds.

Advances in sensors, computing, communication, and engineering technologies have all played a role in advancing the development of NDE methods with promising automotive applications. For example, ultrasonic phased-array systems have been available since the mid-1970s, but they were prohibitively expensive. In the past decade, prices have dropped dramatically, and increased competition promises additional price reductions in the future. A recent breakthrough is the availability of portable systems that are particularly attractive for use in production environments.

Lawrence Berkely National Laboratory (LBNL) previously evaluated the adequacy of conventional, commercially-available ultrasonic systems for the inspection of spot-welds. These systems are relatively inexpensive and are widely used in European automotive plants, but have not gained widespread acceptance in the United States for reasons that include their dependence on trained operators to set system variables and the need to change probes frequently because of the wide range of materials and sheet thicknesses used in production vehicles. An important goal of the current project is to develop a system that is easier to use. Plant managers also emphasize the need for intuitive user interfaces and summary reports that can be customized for welding engineers and other plant personnel.

To best advance the adoption of lightweight materials while also serving the needs of the auto industry, the current project team has adopted a strategy that strives to develop platforms that add value immediately, minimize barriers to incorporating emerging technologies at a later date, and that are as modular as possible so that they can be easily modified or adapted for new applications. Consistent with that model, the current work is focused on development of a prototype spot-weld inspection platform that integrates the best available ultrasonic phased-array technology with custom-designed signal processing and analysis software, and hardware that will allow the system to be tested and implemented in manufacturing plants as a portable, stand-alone unit.

Ultrasonic Phased-Array Technology

Most commercially-available spot-weld inspection systems use conventional high-frequency, single-crystal ultrasonic probes working in pulse-echo mode. The output from these mono-probes is a single signal that is an integrated response over an area that depends on the diameter of the probe. Different probes must be used for different-sized welds. In contrast, a phased array is composed of many piezoelectric elements that are individually excited by electronic pulses at programmed delay times. As a result, phased arrays have several advantages over conventional ultrasonic probes that derive from the ability to dynamically control the acoustic beam transmitted into the structure under examination. An electronic delay can be applied separately to each electronic channel when emitting and receiving the signal. These delay laws permit constructive and destructive interference of the acoustic wavefront transmitted into the structure, allowing predefined ultrasonic beams to be formed. The acoustic energy can be focused, and delay laws can be used to steer the acoustic beam. Electronic scanning is accomplished by firing successive groups of elements in the array.

Instead of assessing weld quality based on a single signal, as is the case with mono-probes, phased arrays allow thousands of signals to be obtained for individual welds in a few seconds. The ability to perform complex scanning of the acoustic beam through the weld allows greater accuracy in sizing weld nuggets, while also improving the flaw characterization capability. These attributes of phased-array probes allow us to measure the weld-nugget diameter, locate defects, and identify misshapen and burnt welds. In addition, the same probe can be used to inspect different-sized welds and welds in sheets with different thicknesses. It is also possible to electronically compensate for misalignment of the probe with respect to the sample.

To demonstrate concept feasibility, initial experiments were conducted in a water tank or using a confined water column with coupling gel between the probe and the sample. As described below, to allow measurements to be made in a production environment, a self-contained probe housing has been designed and fabricated that maintains the probe in water while also providing acoustic coupling to the part under inspection.

Probe Housing

Although the phased-array probe allows electronic scanning in one direction, mechanical scanning in the perpendicular direction is required to obtain two-dimensional images of the weld. Thus, a plant-deployable unit requires a housing for the ultrasonic probe that maintains the probe in water and contains a miniature mechanical system for linear translation of the probe. The mechanical system designed and encapsulated into the probe housing allows the probe to travel a distance of 14.7 mm. A mechanical drawing of the scanning system is shown in Figure 1a. The small motor used to drive the system has a nominal speed of 4800 RPM and is coupled to a 1:16 gearbox. The drive assembly is separated from the water column containing the probe by two slider plates and O-rings that form a watertight seal. A picture of the integrated probe housing is also displayed in Figure 1b, where the probe assembly is shown on a production part, and in Figure 1c, where the bottom of the housing is visible. The bottom plate was designed with a circular lip to help the outer membrane conform to the surface indentations caused by the welding electrodes.

One of the engineering challenges in designing the housing is minimizing the footprint of the probe assembly, which is essential to ensure access to welds on complex components. The overall footprint of the first prototype, shown in Figures 1b and 1c, is 26 by 44 mm. This design works well on relatively flat components where there is easy access to the welds. In the next several iterations of the probe design, also shown in Figure 1, the bottom section of the housing was tapered to allow improved access to welds on production parts. As shown in Figure 1d, the bottom half of the housing in the latest designs is a cylinder. The probe housing pictured has a circular footprint with a diameter of approximately 2 cm.

Several different designs of the end cap on the probe housing have also been tried, with two objectives: maximizing the ease of changing the membrane that confines the water column, and determining which design provides the best coupling between the membrane and the parts under inspection. Figure 1e shows the end of the probe assembly after being filled with water, and Figure 1d shows one of the membranes used and the bulge in the membrane induced to provide good coupling to welds with deep surface indentations. Experiments are ongoing to determine the best design for inducing and maintaining the bulge in the membrane.

The optimal material for the outer membrane is also under investigation. The material must provide acoustic coupling to the part, which requires that it conform exactly to the surface. Since many welds on production parts are associated with deep surface indentations caused by the welding electrodes, the membrane must be highly pliable, while also being durable enough to withstand thousands of measurements made on rough surfaces with deep indentations. Another important consideration in choosing a material is that it be relatively inexpensive and available off the shelf. Toward that end, experiments have been performed with readily-available materials including finger cots and latex products.

With regard to its acoustic properties, the ideal membrane has an acoustic impedance very close to that of water, and does not attenuate the acoustic signals. Any impedance mismatch between water and the membrane will result in reflection of some of the acoustic energy at the membrane, reducing the energy transmitted into the part, and making it more difficult to analyze the acoustic signals. A recent series of experiments were performed using a newly-available elastomer material specifically designed for ultrasonic inspection. The advantage of Aqualene™ is that it has an acoustic impedance very close to that of water and a very low attenuation coefficient. Initial experiments indicate that the material is also very durable.

Aqualene™ is available in a variety of thicknesses and experiments were conducted to determine the optimal thickness for spot-weld inspection. The

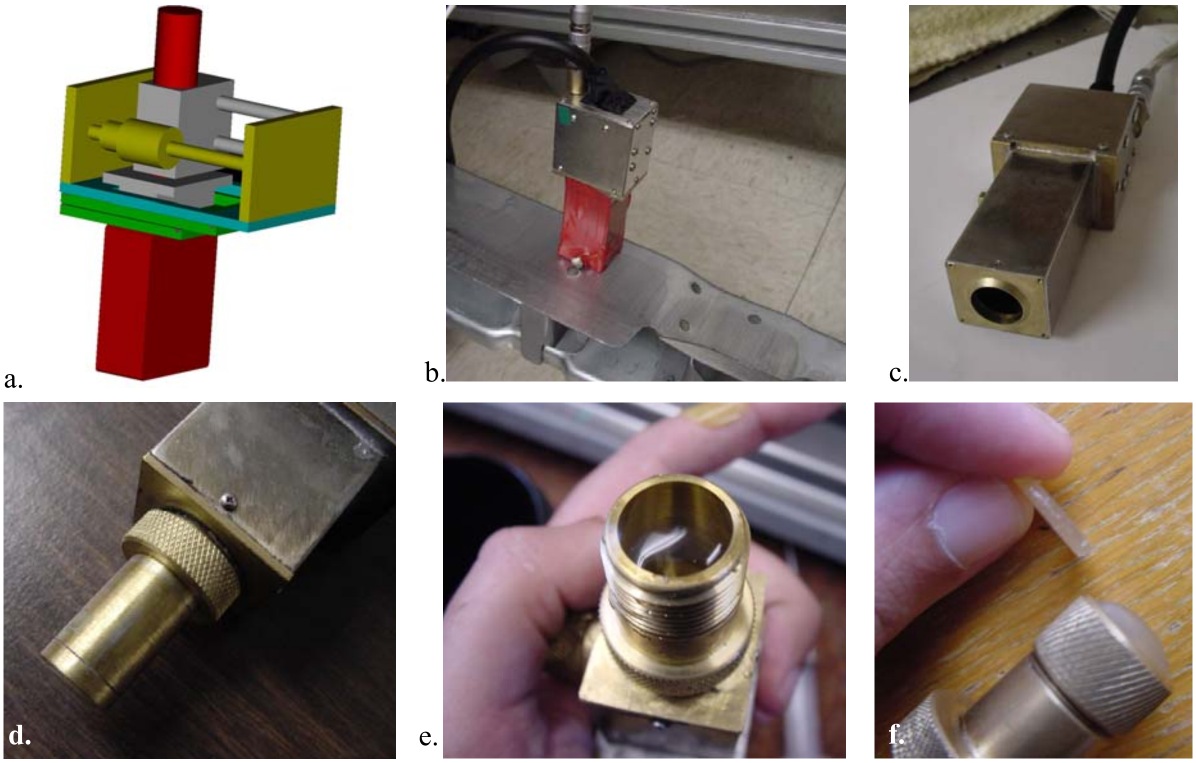

Figure 1. Mechanical drawing of the miniature scanning system (Figure 1a) encapsulated into the prototype probe housing (Figure 1b). The bottom plate of the prototype in Figure 1c has a circular lip to improve coupling between the housing and parts under inspection. In later prototypes, the lower section of the housing was redesigned to be much smaller, for better accessibility to welds on production parts (Figure 1d). After filling the housing with water (Figure 1e), an endcap containing a thin membrane is placed over the tip of the housing assembly (Figure 1f). A bulge is induced in the membrane to improve coupling to parts with deep surface indentations.

tradeoff is between durability and acoustic coupling: the thicker the material, the more durable it is, but the more difficult it is to get good coupling with the part. To evaluate the acoustic coupling, signals obtained using Aqualene™ were compared to signals obtained for the same welds inspected in a water tank. For measurements in the water tank, the outer membrane is removed from the probe assembly, and the sample and probe are submerged. These experiments demonstrated that acceptable results are achieved using an Aqualene™ membrane. Acceptable results are also obtained using finger cots and other off-the-shelf acoustic membranes, which have the advantage of being thinner than the thinnest Aqualene™ currently available (0.5 mm). For welds on production parts with deep surface indentations, membranes thinner than 0.5 mm have been necessary to achieve good coupling with the part. Tradeoffs between price, durability, and coupling will determine the best membrane option for any particular application.

Phased-Array Inspection Strategy

For all experiments performed to date, electronic scanning and focusing laws were combined to inspect the spot welds. The acoustic energy is focused at the interface between the two sheets by applying symmetrical delay laws to the elements of the phased-array probe (see Figure 2). The results presented here were obtained using a new, 17-MHz focused probe. In contrast to the probes used for initial experiments that had flat elements, the 17-MHz probe has curved elements that focus the energy with a natural focal length of 37 mm. When used in conjunction with the delay laws described above that focus the energy from multiple elements, the acoustic beam at the interface between the welded sheets is a circular spot that is scanned across the weld. Using a portable phased-array controller, more than 3000 signals are recorded for each weld in approximately 5 seconds.

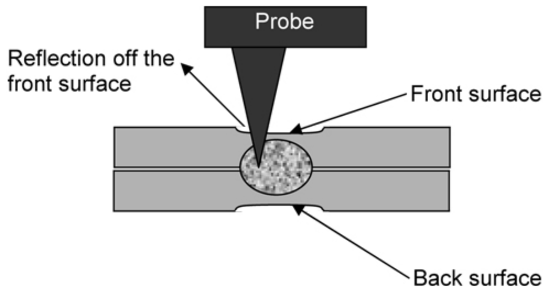

Figure 2. Schematic drawing illustrating focusing of the ultrasonic energy from several phased-array elements at the interface between two spot-welded sheets.

As part of the work underway, experiments are being performed to determine the optimal number of elements to use in the probe. The advantage of using more elements is that more energy is transmitted into the part, and a larger area can be imaged. Disadvantages of using more elements are increased cost; increasing the width of the acoustic beam making it more susceptible to diffraction caused by the indentation at the surface made by the welding electrodes; and requiring the probe housing to be larger to accommodate the larger probe and the wider acoustic beam.

Scanning in one direction is performed by electronically translating the ultrasonic beam across the sample by firing a specified number of elements in sequence. For example, when eight elements are used at a time, the beam is electronically scanned across the weld in steps of one element; that is, elements one through eight are excited to generate the first signal, elements two through nine are excited to generate the second signal, and so forth. To obtain two-dimensional (2-D) images of the weld, the probe is mechanically translated across the weld in the direction perpendicular to the electronic scan.

As described above and illustrated in Figure 2, the acoustic energy generated by several adjacent elements in the probe is focused and transmitted into the test specimen. Some of the energy is reflected off the front surface as indicated in the diagram. In the welded region, the signals pass through both sheets and are reflected off the back surface of the lower sheet. It is interesting to note that the metallurgical changes in the welded area do not cause a change in acoustic impedance large enough to create a noticeable reflection at the boundary of the weld nugget. Outside the welded region, the signals are confined to the top sheet, that is, the acoustic waves are reflected back and forth in the upper sheet and no energy is transferred into the lower sheet.

Signal Processing

The signals recorded while scanning through the weld are currently analyzed in the frequency and time domains with the goal of developing fast and accurate algorithms that work for the wide range of welds found on production parts. For a satisfactory weld, ultrasonic waves are transmitted through the weld nugget and reflected off the back surface of the lower sheet (see Figure 2). In contrast, for a defective weld, incomplete fusion at the interface between the two sheets results in partial reflection of the ultrasonic energy at the interface. This affects the periodicity of the train of echoes, that is, signals that are reflected at the interface have a shorter travel path than signals that propagate through the weld, resulting in echoes in the time domain that are closer together than echoes off the back surface.

Fourier peak ratio and image processing

In the frequency domain, the power spectrum captures the periodicity of the ultrasonic echoes. The relative magnitude of the peaks in the spectra is indicative of the amount of energy reflected at the interface between the welded sheets. For a satisfactory weld, the ultrasonic wave propagates through the weld and reflects back and forth between the front and back surfaces resulting in a peak that corresponds to the travel path through both sheets. For defective welds, where most of the energy is reflected at the interface between the two sheets, there is a peak in the spectrum that corresponds to a travel path equal to twice the thickness of the upper sheet. For each of the 3000 signals that comprise each weld image, the ratio of the peaks in the power spectrum is calculated and then compared to a threshold that is used to create binary images.

The peak-ratio images allow satisfactory and undersized welds to be distinguished according to the size of the area where there is significant transmission of energy into the lower sheet. Although defective welds such as cold welds can result in a large area of ultrasonic transmission into the second sheet, the Fourier peak ratio indicates that the areas of high transmission are relatively sparse and dispersed compared to the well-defined and concentrated areas for the satisfactory and undersized welds. At present, the quality of the weld is assumed to be associated with the largest contiguous area of transmission. As described below, image-processing techniques are used to identify this area and separate it from the smaller transmission zones. These techniques were developed last year [2], and are only briefly described here.

The first step in processing the peak-ratio images is to extract the largest group of contiguous pixels with high ultrasonic transmission across the interface between sheets, which we assume corresponds to the welded zone. The algorithm used to determine whether individual pixels should be considered connected to or separate from the zone of interest is based on the operation of connected-component extraction. We then apply morphological filters that are commonly used for image processing. The operations applied to the binary peak-ratio images are erosion and dilation, which are used to smooth the boundary of the image and to remove small, isolated holes in the image that result from small defects or a poor signal-to-noise ratio. A processed image is shown in Figure 6c.

As discussed previously, during physical teardown of automotive components, spot-welded joints are pried apart and the resulting weld buttons are visually inspected or measured with calipers. To allow the results of the acoustic measurements to be compared to the size of the weld buttons, it is necessary to estimate weld dimensions from the peak-ratio images. Once the largest contiguous area of high acoustic transmission is identified and extracted, either an ellipse is fit to the area or the total area is calculated as a means of estimating the size of the weld button.

Surface Indentation Measurements

A recent addition to the signal processing software is an algorithm to measure and display the surface indentation caused by the welding electrode for the inspection surface. For our purposes, knowing the depth and location of the top-surface indentation is advantageous for signal processing, and is also important in analyzing the quality of the weld. The criteria used in the automotive industry for assessing weld quality includes specifications for allowable indentation and loss of material. For signal processing, the location of the indentation is being used to locate the weld within the scan region. The estimated location of the weld is used to reduce the number of signals that are processed and analyzed, thus minimizing the total inspection time. As described above, the indentation data are also being analyzed to provide information on weld quality. Excessive indentation and loss of material are indicative of a burnt weld. Although the relationship does not always hold, the depth of the indentation and the size of the weld nugget are often related; thus, the indentation depth may be of some value as a secondary criterion in evaluating quality for those welds that prove difficult to analyze. In addition to indentation depth and size, it is also possible to determine the shape and gradient of the indentation, which provides useful information on the state of the electrodes and may indicate problems in the fit between parts.

Weld Reflectivity

In addition to the signal processing based on Fourier peak ratios, a difference-equation model has been developed that describes the amplitude of the ultrasonic echoes in the time domain as a function of the *reflectivity* of the weld. At each measurement point, the reflectivity measures the share of acoustic energy incident on the interface between the sheets that is reflected. To create images of the welds, the signal obtained at each location during scanning is reduced to a single bounded value (reflectivity), and these values are plotted to create a reflectivity map of the weld. Figure 3 shows reflectivity maps for an undersized, a satisfactory, and a burnt weld.

The peak-ratio method and difference-equation models have different advantages and disadvantages, making it valuable to have two approaches to signal processing. For example, the peak-ratio method is very fast, whereas the difference-equation model enables simulations. Features of the reflectivity model also include the ability to detect and correct for weak signals. Even in a laboratory setting, some weak signals are almost always unavoidably present because the edge of the surface indentation tends to

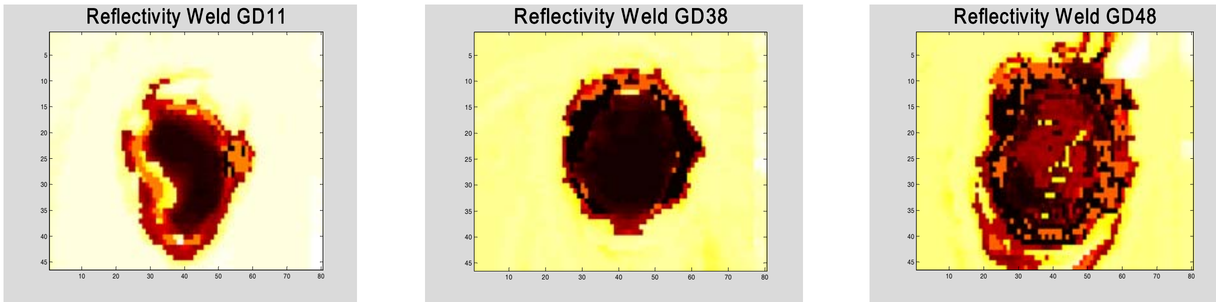

Figure 3. Reflectivity maps obtained for an undersized, a satisfactory and a burnt weld, respectively (left to right). The darkest regions correspond to high transmission of acoustic energy across the interface between sheets, indicative of fusion.

"scatter" the ultrasonic signals. Weak signals may also be present because of poor coupling or because of malfunction of one or more elements in the probe. The software identifies and, as far as possible, corrects for these cases as well.

Metallography

In previous work, metallographic methods were employed to help understand the relationships between ultrasonic signals, the size of the weld nugget, and the dimension of the weld button obtained by peeling the joint. While there is generally a relationship between the size of the weld button obtained from peel tests and the size of the actual weld nugget determined from metallograhy, their dimensions are not exactly the same.

To better understand changes in structure in the welded zone and how these changes are manifested in the ultrasonic signals, as well as to validate LBNL's signal-processing algorithms, a new study was undertaken in collaboration with the Ford Motor Company [3]. For the initial study, Ford created spot-welded test specimens using two sheets of 1.4-mm-thick hot-dipped-galvanized steel. Welds of varying quality were created by varying the number of cycles during welding, while keeping the force and current constant. After LBNL made ultrasonic images of the welds, Ford analyzed a series of vertical cross-sections through each weld. This painstaking process consisted of carefully cutting the weld and the surrounding area out of the test coupons and mounting it in epoxy, and then grinding down the specimen to expose cross sections every few hundred microns through the weld perpendicular to the plane of the interface. Care was taken to ensure that the cross-sections were parallel to one another and to accurately measure the location of each section.

As described above, the samples were created from hot-dipped-galvanized steel, meaning that the surfaces of the sheet metal are coated with a thin layer of zinc. During welding, much of the zinc coating melts and is expelled out of the welded zone. The expelled zinc can form a brazed corona around the weld, and one of the objectives of the study was to determine whether the ultrasonic signals could distinguish between this weak brazed zone and the fused area. To answer this question, the cross sections were polished with a 1-µm grit polish, and optical micrographs of the polished surface were digitally recorded. A metallurgical technique was used to identify and map the location of zinc. The polished surfaces were then treated with a metallographic etch that removed the zinc and revealed the steel grain structure. Optical micrographs of the etched surfaces were carefully studied to identify the fused area at the interface between the two sheets.

Figure 4a shows a cross-section from an undersized weld after etching (Figure 4a). The individual cross-sections were combined to create two-dimensional maps of the welds, as illustrated in Figure 4b, where three zones are identified. The central region marked with heavy dark lines indicates the zone of fully-fused steel. Outside of this area, thin and thick gray lines indicate the regions where zinc is present. Figure 4c shows the estimated weld nugget from the ultrasonic Fourier peak-ratio map superposed on the metallurgical map, showing good agreement between the estimated weld nugget and the fused zone identified in the micrograph.

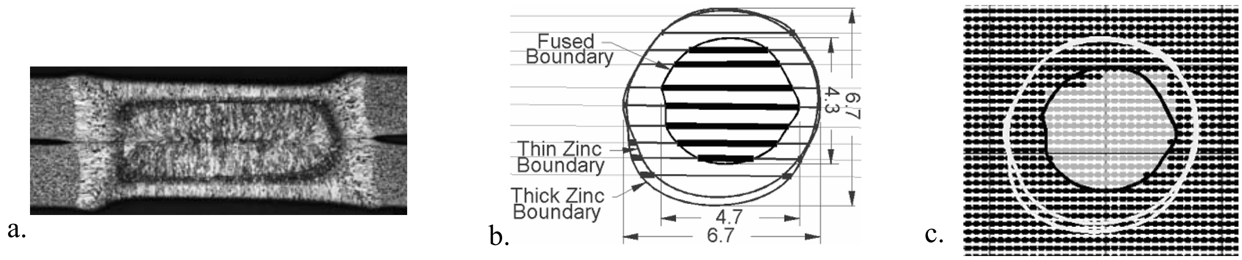

Figure 4. A micrograph of a polished and etched cross section through an undersized weld is shown in Figure 4a. The metallurgical map determined from the micrograph is shown in Figure 4b. The estimated weld nugget from the Fourier peak-ratio map is superposed on the metallurgical map in Figure 4c, showing good correspondence between the estimated weld area and the size determined from the metallurgical analysis. Figures 4b and 4c are reprinted with permission from T. Potter, B. Ghaffari, G. Mozurkewich, F. Reverdy and D. Hopkins, "Comparison of Metallurgical and Ultrasonic Inspections of Galvanized Steel Resistance Spot Welds," *32nd Annual Review of Progress in Quantitative Nondestructive Evaluation*, Copyright 2005, American Institute of Physics.

Although this initial study was promising in that LBNL's signal post processing resulted in images that correlated well with the weld nuggets, the sample size was very small and a larger and more fundamental study was required to establish a physical basis for choosing signal-processing parameters. Toward this end, more than 120 weld coupons were created by Ford, with a range of weld qualities from satisfactory to undersized, cold, and burnt. After LBNL made ultrasonic measurements of the welds using the prototype integrated probe shown in Figure 1b, Ford subjected the welds from each of 15 groups to strength testing, peel testing, or metallurgical analysis. Using a novel technique applied to two welds from each group, Ford created planar sections through the weld parallel to the interface between the sheets. What is particularly appealing about this technique is that it creates a metallographic map in the same plane as the image created from the ultrasonic measurements. In general, good agreement was found between the fused areas identified in the metallographic micrographs and the estimated areas determined from the processed ultrasonic peak-ratio images. Figure 5 is a plot of the weld-nugget areas determined from the metallographic image against the areas estimated from the ultrasonic peak-ratio images, along with the best-fit line from a linear regression. The regression yielded an R-square coefficient of 0.79 (a perfect linear fit would result in a coefficient of 1.0). The line is very close to the 45-degree line, as it should be if the peak-ratio area is a good proxy for the planar-section area.

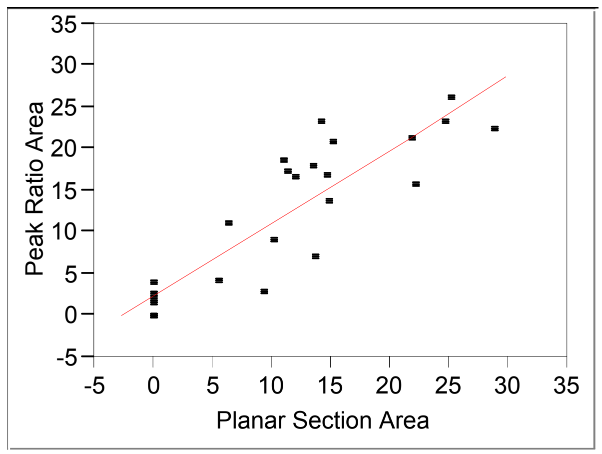

Figure 5. The plot shows the relationship between the weld areas determined from planar-sections and the ultrasonic peak-ratio maps, and the least-squares line fit to the data.

Measurements on Production Parts

To demonstrate technical feasibility of phased arrays for spot-weld inspection, the recently completed prototype probe housing is being used to make measurements on production parts. This was not possible earlier, because it was necessary to design and build the miniature scanning system and the housing that allows the ultrasonic probe to be used outside of a water tank.

To date, preliminary measurements have been made on package trays, apron assemblies, and a truck door. The weld pictured in Figure 6a is on a truck door, and is relatively easy to inspect with the prototype system. The relatively shallow and uniform indentation (Figure 6b) allows good coupling between the probe assembly and the surface, and the two sheets are reasonably parallel. The measured indentation of the inspection surface is shown in Figure 6b, and the processed peak-ratio image of the weld is shown in Figure 6c.

In general, the quality of the measurements depends in large part on the surface conditions of the parts including the shape and roughness of the surface indentations. For example, very deep spherical indentations make it difficult to get enough energy into the parts to provide a dimensional analysis of the welds, and deep indentations make it difficult to achieve good coupling with the probe. Another challenge arises when the welding electrodes are not aligned, creating non-parallel surfaces. In this case, some of the acoustic energy transmitted into the part is reflected away from the weld, and the reflected signals are not captured by the probe. Non-parallel surfaces and distortion of the parts during welding occurs most often in thin sheets. Surface roughness inside the weld indentation also creates a challenge, because it causes scattering of the acoustic waves. Many of these conditions are associated with burnt welds, in which case it is easy to identify the welds as defective based on excessive material loss and indentation, which is relatively easy to measure. Thus, the weld quality can be determined even though it is difficult to provide a dimensional analysis.

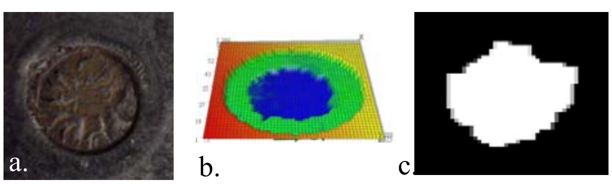

Figure 6. Picture of a spot weld on a truck door (Figure 6a), along with the measured indentation of the inspection surface (Figure 6b) and the processed peak-ratio image of the weld (Figure 6c).

Conclusions

There are substantial challenges in nondestructive testing of welds on automotive parts such as surface roughness, indentations on the surface caused by the welding electrodes, expulsion, and complex geometries that make it difficult to access welds. There is also variability between parts that arises from variations in materials and differences that are inherent in products produced in any large-scale manufacturing operation. Previous work demonstrated the concept feasibility of inspecting spot-welds in steel using ultrasonic phased-array technology. To demonstrate the technical feasibility of phased arrays for spot-weld inspection, a recently completed prototype probe assembly is being used to make measurements on coupons and production parts. This was not possible earlier, because it was necessary to design and build the miniature scanning system and the housing that allows the ultrasonic probe to be used outside of a water tank. Initial experiments were used to guide modifications made to the first prototype to improve accessibility to welds and coupling on production parts. Experiments are underway to validate the results obtained using the prototype probe assembly and LBNL's signal-processing algorithms. Work under way will also yield integrated, real-time diagnostic tools that operate at sufficient speed for assembly-line use. The remaining challenges include determination of resolution limits and the best diagnostic parameters for specific applications, as well as demonstration of robustness, accuracy, and cost-effectiveness under realistic operating conditions.

Presentations

1. F. Reverdy, Lawrence Berkeley National Laboratory, "Inspection of Spot Welds Using a Portable Ultrasonic Phased-Array System," 31st Annual Review of Progress in Quantitative Nondestructive Evaluation, July 25–30, 2004, Colorado School of Mines, Golden, Colorado.
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