Matrix Phased Array (MPA) Imaging Technology for Resistance Spot Welds

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Abstract. A three-dimensional MPA probe has been incorporated with a high speed phased array electronic board to visualize nugget images of resistance spot welds. The primary application area of this battery operated portable MPA ultrasonic imaging system is in the automotive industry which a conventional destructive testing process is commonly adopted to check the quality of resistance spot welds in auto bodies. Considering an average of five-thousand spot welds in a medium size passenger vehicle, the amount of time and effort given to popping the welds and measuring nugget size are immeasurable in addition to the millions of dollars' worth of scrap metals recycled per plant per year. This wasteful labor intensive destructive testing process has become less reliable as auto body sheet metal has transitioned from thick and heavy mild steels to thin and light high strength steels. Consequently, the necessity of developing a non-destructive inspection methodology has become inevitable. In this paper, the fundamental aspects of the current 3-D probe design, data acquisition algorithms, and weld nugget imaging process are discussed.

Keywords: Matrix Phased Array (MPA), Resistance Spot Weld (RSW), Three-Dimensional MPA
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INTRODUCTION

Advanced high-strength steels (AHSS) have continued to gain momentum in popularity in the automotive industry as a result of initiatives to increase body rigidity (driving performance), improve crash ratings, and improve fuel economy (reduce weight to meet CAFÉ legislation requirements). These steels have challenged manufacturing practices in a variety of ways, from forming to joining to inspecting. A major issue with these higher-strength, thinner gauge materials is integrity of resistance spot welds.

There are typically somewhere between 4,000 and 7,000 resistance spot welds on U.S. manufactured automobiles, and the reliability of the structure and safety of passengers relies heavily upon sound welds. It has been found that the stress state at the weld, fracture toughness of the weldment, and presence of pores, cracks, and embrittled regions in AHSS are driving factors that result in differing failure modes from conventional steels – especially interface type failures [1]. It has been recognized that traditional RSW destructive test methods (pry-bar or chisel check and peel test) are costly and inaccurate when applied to AHSS. The automotive industry needs a replacement for current destructive testing in order to ensure safe implementation of AHSS steels. In addition, a more reliable method for detection and classification of stuck (stick, cold) welds in low strength steels is needed.

Some advanced nondestructive inspection (NDI) techniques that can provide solutions to automotive market already exist on other markets. Unfortunately, a rapid technology transfer of NDI techniques, already used in aerospace and power generation markets, to the automotive industry is limited because of fundamental differences between these markets [2]. There is still a gap to validate and correlate NDI techniques findings. The desired status is to reduce the time for validation and increase the confidence in correlation methodology with less engineering and laboratory time. To reduce the repeatability gap, the automotive industry desires improved robustness of NDI techniques and little or no operator dependence [2]. These problems have been addressed by using ultrasonic matrix phased array (MPA) technology as an alternative to destructive testing of AHSS [3].

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THREE-DIMENSIONAL MATRIX PHASED ARRAY PROBE

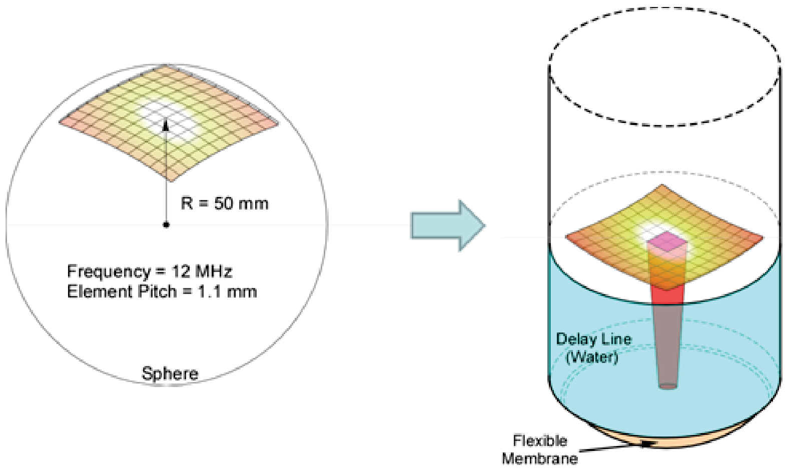
Three-Dimensional Array Design

The geometry of the curved three-dimensional probe element as well as various firing sequences for the sub-element groups are illustrated in Fig. 1. The ultrasonic probe illustrated in Figure 1(b) includes a plurality of piezoelectric elements arranged in a three-dimensional array and having a flexible membrane to conform to the contoured surface of a spot weld while enabling the sound energy to be transferred directly into the spot weld under test. The current matrix phased array has a radius of 50 mm. The distance of water path from the array to the center of the membrane is approximately 200 mm.

An excitation is coupled to the array and a subset group of transducer elements are combined to send an ultrasonic beam toward a spot weld. Each transducer element in a subset group may be pulsed at different time intervals (phase delay) and their individual waves summed to produce a focusing effect of the beam as well as a steering effect if needed. Other three-dimensional arrangements are possible for optimizing the performance for specific applications. The total number of elements, overall dimension, and operating frequency determine the overall three-dimensional surface contour shape and its operating characteristics and parameters.

Operational Principle

A block diagram of the current spot weld inspection system is shown in Fig. 2. The weld nugget forms at the interface between upper sheet and lower sheet having thickness of about 0.6 mm to 3 mm. It is typical to have an air gap of about 0.1 mm to about 0.5 mm may be present between upper sheet and lower sheet.



(a) 3-D MPA elements (b) 3-D array element in probe

FIGURE 1. Illustrations of the shape of the 3-D curved MPA probe element as well as firing sequences for the sub-element groups.

Upon inspection, as the first step, a dap of water is applied on the surface of upper sheet before an MPA probe is placed on the weld depression of upper sheet that is located over the welded area. The flexible membrane allows the tip of the probe to conform to the contour of the welded area. The fluid filled chamber or solid sound delay material acts as a pathway for focusing and steering ultrasonic beams. A curved array of ultrasonic elements transmits ultrasonic beams into the welded area and to capture the associated reflections of those ultrasonic beams. A Phased array unit is in electrical communication with the ultrasonic elements through signal pathways. Phased array unit is also in electrical communication with computer, which processes incoming ultrasonic data and generates a visual representation of the fused area.

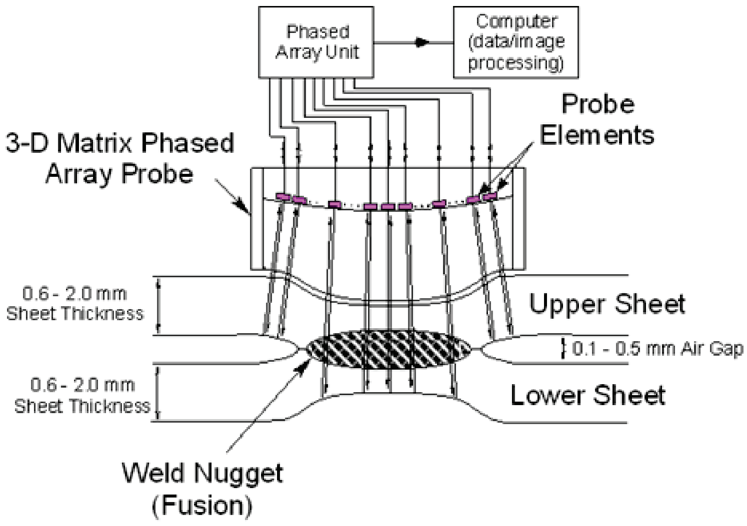


FIGURE 2. A block diagram showing the primary components of a three-dimensional matrix phased array spot weld inspection system.

ULTRASONIC SIGNAL PROCESSING METHODOLOGY

No Weld at Interface

Figure 3 provide illustrations of test results derived from analyzing a poor spot weld using the MPA system. In this figure, because no weld nugget exists, ultrasonic beams do not travel completely through interface, but rather reflect back to probe from interface.

Figure 4(a) illustrates diagrammatically the direction and relative strength of each sound wave as it reflects at interface. In this figure, a thinner line represents loss of elastic energy as the sound wave interacts with interface. The reflected signals designated as circled 1, 2, 3, 4, and 5 correspond to the peaks shown in the A-scan presented in Figure 4(b) wherein signal 1 represents the first reflection from the top surface of upper sheet, signal 2 represents the first reflection from interface, signal 3 represents the second reflection from interface, signal 4 represents the third reflection from interface, and signal 5 represents the fourth reflection from interface. The horizontal line drawn through signal 1 (Gate #1) represents the surface gate and the horizontal line drawn though signal 2 (Gate #2) represents the interface gate.

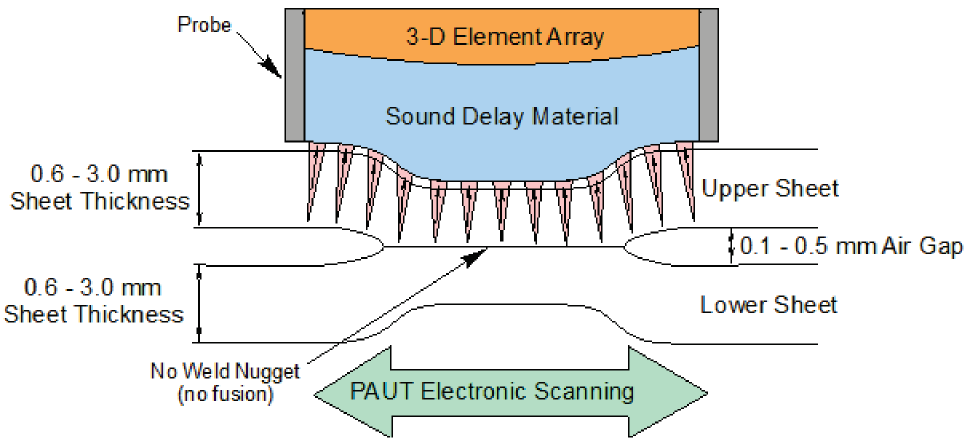
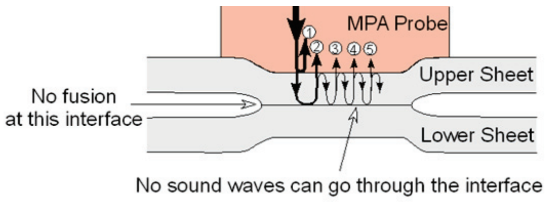
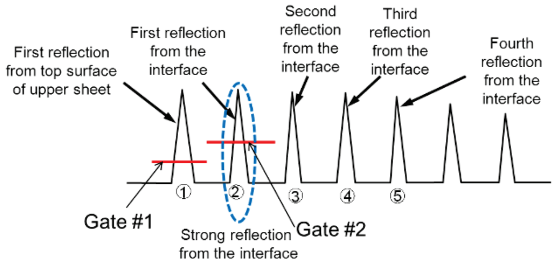


FIGURE 3. Ultrasonic beam launching from 3-D MPA probe through the interface with no weld.



(a) Reflections at interface



(b) A-scan representation of reflections

FIGURE 4. Multiple reflections of ultrasonic beam from the interface when no weld nugget is formed at the interface.

Weld at Interface

Figure 5 provide illustrations of test results derived from analyzing a good spot weld. In this figure, ultrasonic beams travel completely through weld nugget and interface and reflect back to probe from the backside of lower sheet.

Drawings in Fig. 6 illustrate diagrammatically the direction and relative strength of each sound wave as it transmits and reflects at interface. Again, a thinner line in Fig. 6(a) represents loss of acoustic energy as the sound wave interacts with interface. The reflected signals designated as circled 1, 2, and 3 correspond to the peaks shown in the A-scan presented in Fig. 6(b). The horizontal line drawn through signal 1 represents a surface gate and the horizontal line between signals 1 and 2 represents an interface gate.

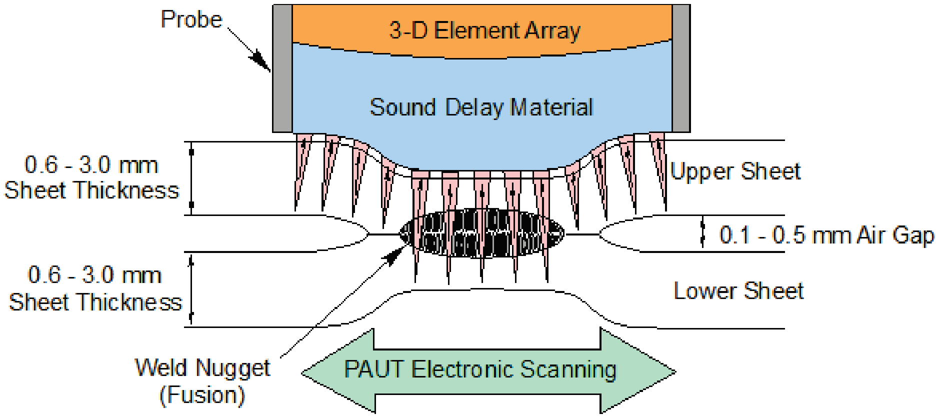
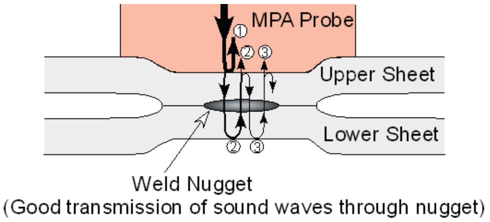
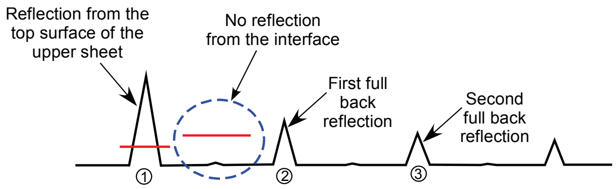


FIGURE 5. Ultrasonic beam launching from 3-D MPA probe through the interface with a well fused weld nugget at the interface.



(a) Reflections at interface

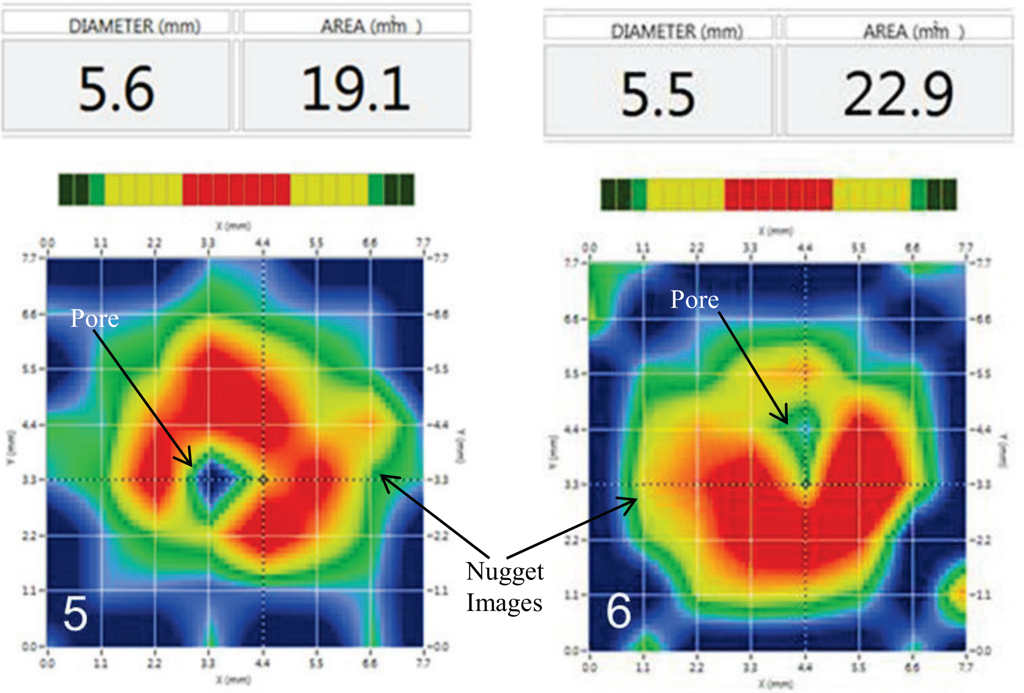


(b) A-scan representation of reflections

FIGURE 6. Multiple reflections of ultrasonic beam through the interface when well-fused weld nugget formed at the interface.

Ultrasonic Image Processing

Based on the ultrasonic energy transmission and reflection at weld interface and the back side of lower sheet, the system uses two adjustable electronic gates to filter out all unwanted reflected signals. The two signals that pass through the gates are either the reflected signal from the back side of the second sheet metal or the reflected signal from the interface of the two sheet metals. The first gate is called the "surface gate" and the second gate is called the "interface gate". This approach differs from the current commercially available systems that utilize an attenuation coefficient compensation method. The current MPA system measures the ration of signal amplitude between gate #1 and #2. Depending on the value of the ratio (Gate #2/Gate #1), four different colors, orange, yellow, green, and blue, are assigned to form a C-scan image. When the amplitude ratio is zero, orange color is assigned, while blue is assigned for the ratio value of ~ 0.8 or higher. Images in Fig. 7 show the color coded C-scan results of the resistance spot welded part shown in Fig. 8. The weld diameter was estimated to be 5.6 and 5.5 mm for weld #5 and weld #6, respectively.



(a) C-scan image of weld #5

(b) C-scan image of weld #6

FIGURE 7. Ultrasonic C-scan images of resistance spot welds with pores.

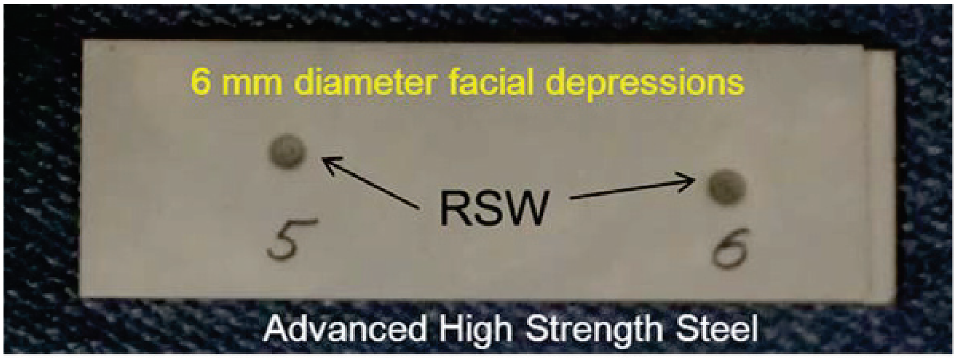


FIGURE 8. Photo of the resistance spot weld part used for the images in Fig. 7.

The same part used for ultrasonic imaging was cut across the width of the specimen to inspect the nugget size and porosity destructively. The results are shown in Fig. 9. Both welds #5 and #6 have about 5.6 mm of nugget diameter and the pore in weld #5 was estimated to be 0.85 mm, while the pore in weld #6 was estimated to be 0.7 mm. From comparison with these estimations with the images in Fig. 7, one can notice that the ultrasonic data for the diameter is very close to the destructive results. In addition to the accurate nugget diameter estimation, the relative sizes of pores can be estimated from the images as well. Qualitatively speaking, the pore in weld #5 is larger than the pore in weld #6 as measured from the macro images in Fig. 9.

FUNCTIONAL PROTOTYPE INSPECTION UNIT

A photo of production ready prototype MPA inspection unit is shown in Fig. 10. This unit operates on batteries and weighs approximately 5 pounds. The system was tested on a car body part obtained from an automotive manufacturing company to estimate the inspection time per spotweld. First, all the spot welds on the part were identified with numbers, 1 through 22, and the system was programed with the ID numbers in sequence. A round of inspection was performed on the part from spot weld #1 through #22 without stopping while the total inspection time was timed with a stopwatch. The average inspection time was estimated to be about 13 seconds per weld.

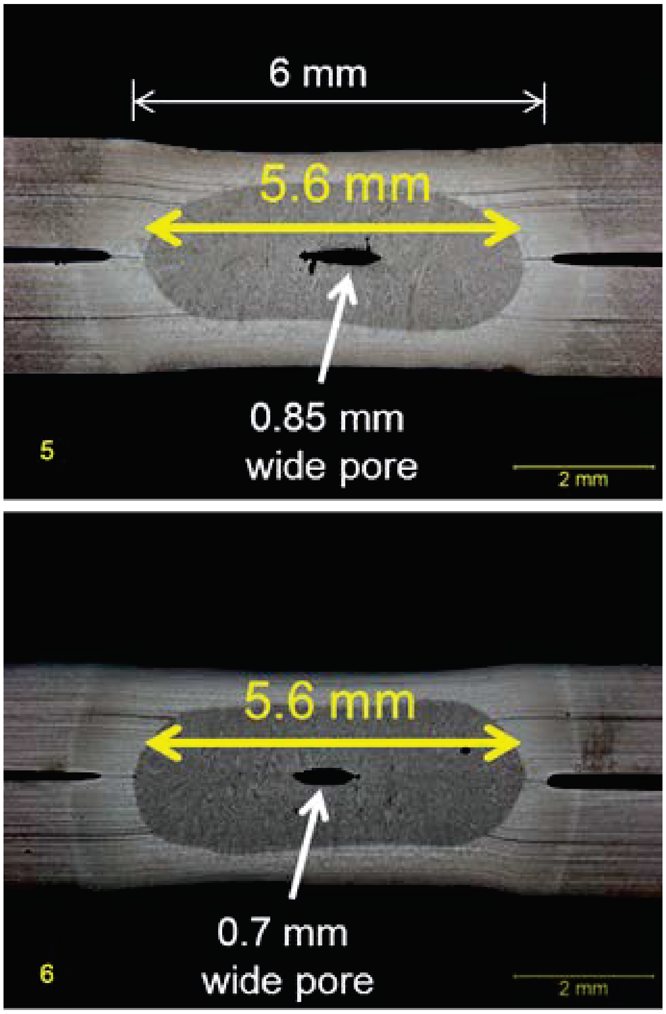


FIGURE 9. Cross-sectional macro images of pores in the spot welds used for the ultrasonic imaging in Fig. 7.

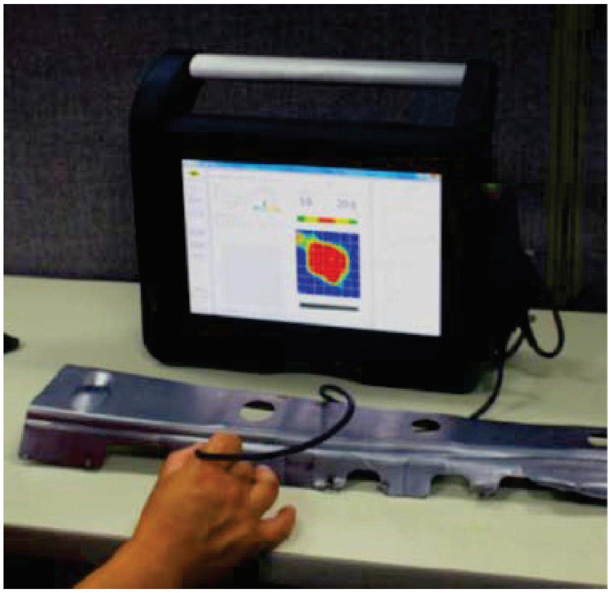


FIGURE 10. A portable battery operated MPA ultrasonic inspection unit shown in action.

SUMMARY AND FUTURE WORK

A functional prototype matrix phased array ultrasonic imaging system has been developed and tested. The dual gate concept works extremely well to detect and estimate the nugget diameters as well as the area of fusion. The ratio of the ultrasonic signal amplitudes measured through the two gates is represented with various colors to form a C-scan image for an easy interpretation. The average diameter of the nugget is estimated based on the C-scan image and the number is displayed on the screen. The area of fused nugget is also estimated based on the image. In this case, the number of pixels that form the image is counted and displayed on the screen.

The future work with the current inspection system is making it as an automated inspection process. It is envisioned that a robot places the probe on car body or parts in a production line. An automated inspection scheme is the ultimate goal for the today's high speed manufacturing processes.

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