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CONTENTS

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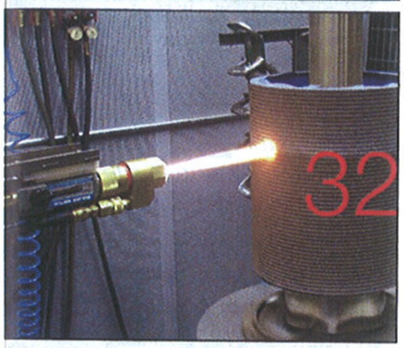
Features



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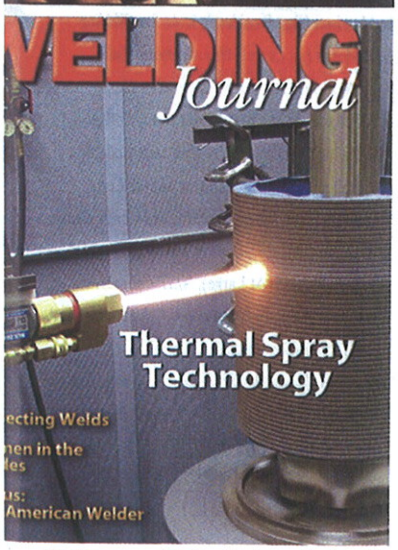

On the cover: High-velocity oxyfuel application of tungsten carbide to a lumber roll. (Photo courtesy of Sulzer Metco Coating Services.)

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Phased Array Testing of Resistance Spot Welds

An ultrasonic, 3-D matrix phased array probe has been designed and tested for performing nondestructive examination of resistance spot welds on automotive chassis

BY JEONG K. NA

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To reduce vehicle weight and improve fuel efficiency, advanced high-strength steels (AHSS) have been introduced to the automotive industry. Advanced high-strength steels continue to gain momentum in the 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 materials is integrity of spot welds. Typically, there are between 4000 and 7000 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 (Ref. 1). It has been recognized that traditional resistance spot weld (RSW) destructive test methods (pry-bar or chisel check and peel test, see Fig. 1) are costly and inaccurate when applied to AHSS. The automotive industry dictates for better nondestructive means to be developed as a replacement for current destructive testing in order to ensure safe implementation of AHSS steels.

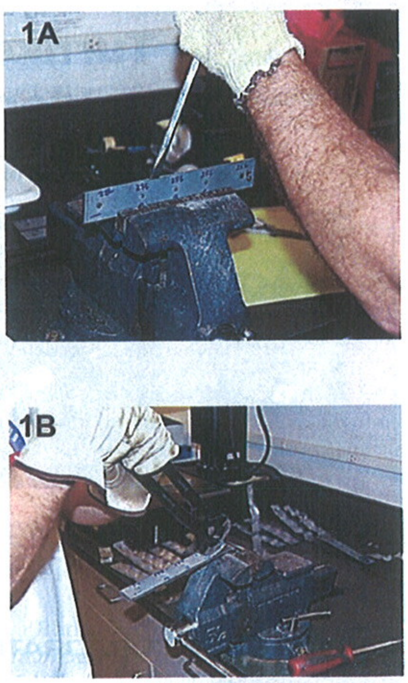
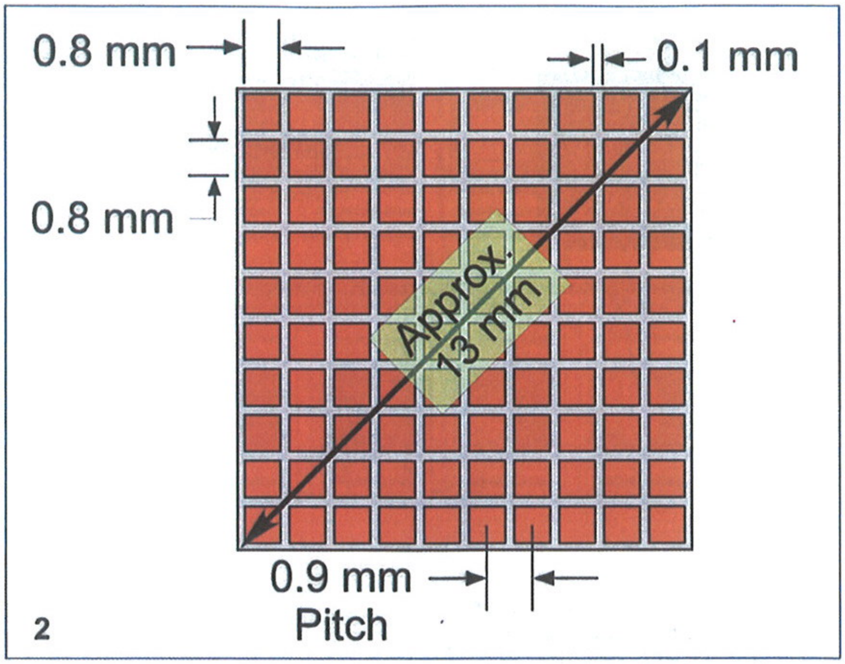
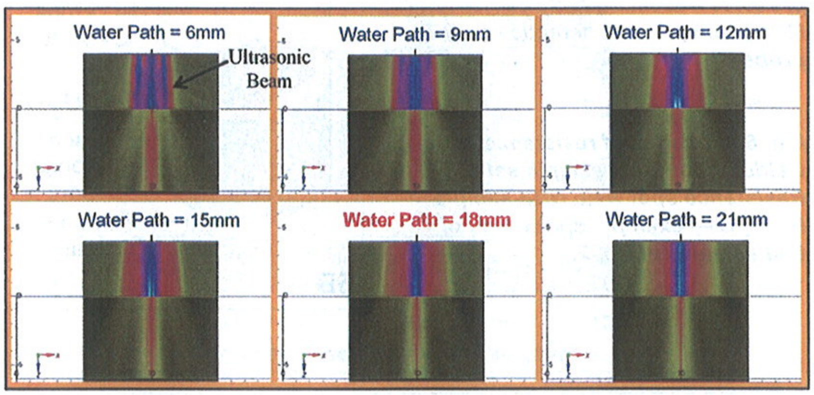


Fig. 1 — Destructive testing methods for resistance spot welds on thin sheet metals: A — Drive test; B — peel test.

Some advanced nondestructive examination (NDE) techniques that can provide solutions to the automotive market already exist in other markets. Unfortunately, a rapid technology transfer of NDE techniques, already used in the aerospace and power generation industries, to the automotive industry is limited because of fundamental differences between these markets (Ref. 2). There is still a gap to validate and correlate NDE technique 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 NDE techniques and little or no operator dependence (Ref. 2).

These problems have been addressed by using ultrasonic matrix pulsed array





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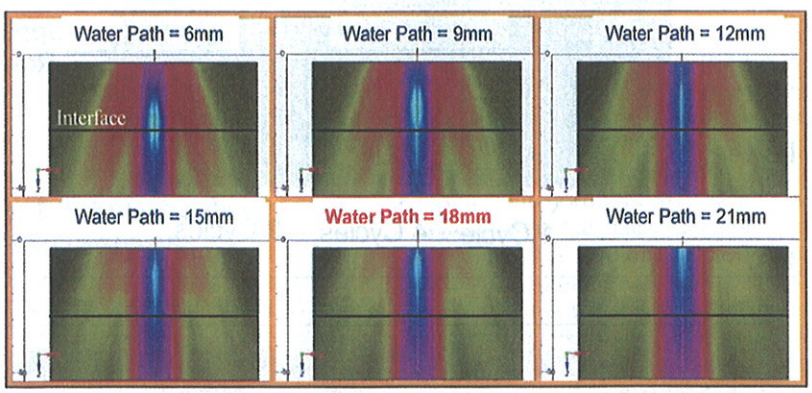

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Fig. 2 — Schematic of a 2-D matrix phased array probe element.

Fig. 3 — Modeling results of the water path length dependence at the water and metal interface.

Fig. 4 — Modeling results of water path lengths at the interface of two 2-mm metal sheets.

(MPA) technology as an alternative to destructive testing of AHSS. Initially, a two-dimensional MPA probe was designed and tested for validation purposes for the technology in terms of sizing weld nuggets and locating flaws in the weldments. By shaping the probe surface that fits to the generally concave shape of resistance spot welds, it was found that the total number of elements and operating frequency could be lowered. This, in turn, helps to lower the cost of the probe and electronics.

A New High-Frequency MPA Probe

To reduce the cost and time for developing a reliable high-frequency MPA probe with an appropriate delay line that provides an optimum propagation distance for the ultrasonic beam to be steered and focused onto a spot weld, computational modeling and simulations were performed upfront. A commercially available CIVA modeling package was used for this work.

Probe Modeling and Simulations

It was necessary to define parameters such as material thickness and spot weld diameter for which the probe would be used. A literature review and discussions with clients in the automotive industry revealed that the majority of spot weld applications are for materials in the thickness range of 0.7 to 2 mm having a nominal weld diameter of 5 to 7 mm. Some initial beam modeling calculations were done to determine general parameters for a probe that would be capable of inspecting spot welds in the targeted range. Consideration was also given to current MPA instrumentation capabilities. Many MPA instruments on the market today have a maximum limit on the number of elements in the order of 128. Figure 2 shows a schematic of a 2-D MPA probe element with some probe parameters evaluated using the beam modeling tools. The same probe parameters apply to 3-D probes with additions of curvature shape and radius.

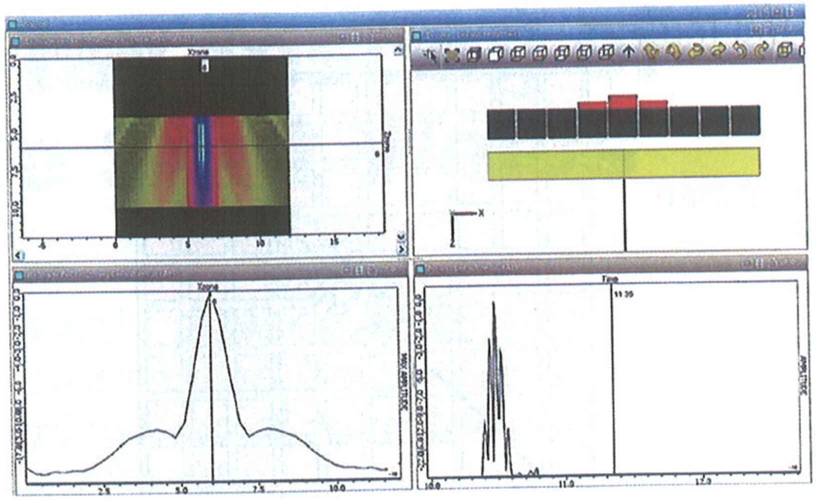
To achieve good focusing at a depth of 0.7 to 2 mm, it was necessary for the probe to have a physical delay distance between the probe element and the part surface. Since water can offer the ability to conform to surface deformations caused by the welding electrodes, the delay line tip was assumed to be filled with water. The images in Fig. 3 show beam profile results using a 3 × 3 aperture at different water path lengths as the sound passes through the water and metal interface. By observing these images, it can be seen that a water path length of 18 mm produces a narrow beam with minimum side lobes. Quality of the ultrasonic beam within the metal sheets was also simulated for different water path lengths with a 3 × 3 aperture. As shown in the images in Fig. 4, at the water path length of 18 mm, the best beam focusing effect was achieved with small side lobes.

Based on the two modeling results shown in Figs. 3 and 4, a hand-held probe was designed and fabricated with a water delay line cavity at the end of the probe. A subsequent modeling investigation for a 64-element probe with 8 × 8 matrix configuration operating at a frequency of 12 MHz proved that the same water delay line could be used. In this case, the probe element was shaped to have a convex curvature with a radius of 50 mm. The modeling result of beam quality and a schematic drawing of the 3-D MPA probe are shown in Fig. 5.

NDE and Statistical Validation

Resistance Spot Welded Sample Preparation

Two sets of spot weld samples with two sheet stackups having thicknesses at the theoretical lower limit (0.7-mm-thick sheet metal) of the probe design were prepared. Two rows of nine spot welds were made on test sample No. 1. For this sample, a constant current of 6 kA was applied for all welds while the number of cycles was varied from 1 to 9 at an increment of 1 cycle for each weld. For the sample set No. 2, weld current was adjusted such that three welded conditions were obtained: "stuck" weld, where there was localized melt and resolidification of the zinc coating; a small nugget condition, where the button pulled was smaller than the generally accepted 4 √ t in diameter; and a good weld condition, where the button pulled was larger than 4√ t in diameter. Spot welds on both sample sets were tested using the MPA inspection system and then destructively examined to determine the actual weld condition and to measure the weld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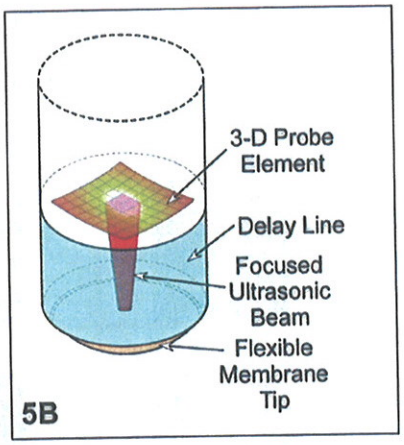

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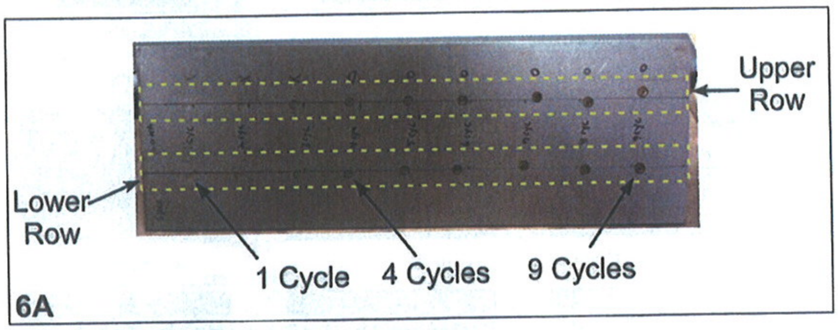
Fig. 5 — CIVA modeling result for the ultrasonic beam quality and schematic drawing of a 3-D MPA probe. A — Beam quality of 3-D MPA probe; B — schematic of a 3-D probe.



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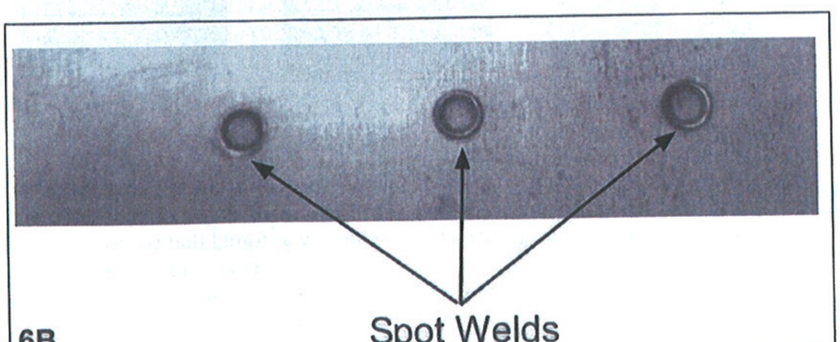

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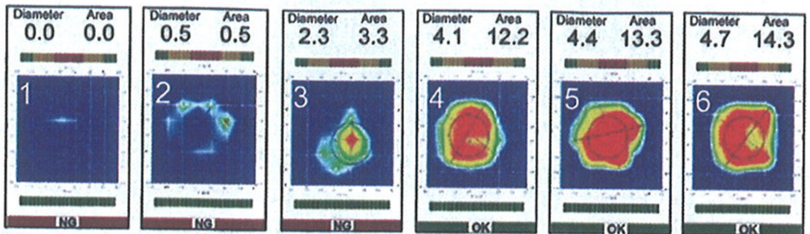
Fig. 6 — Images of resistance spot welds of both test sample sets. A — Resistance spot weld NDE sample No. 1; B — example spot welds of test sample set No. 2.



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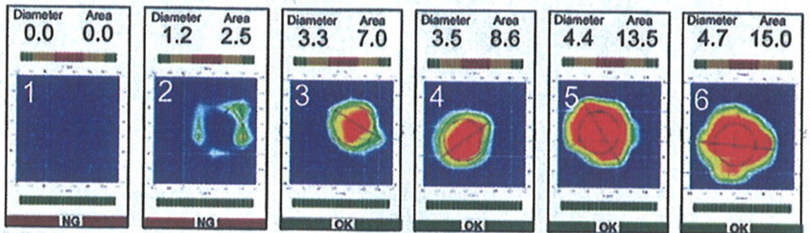

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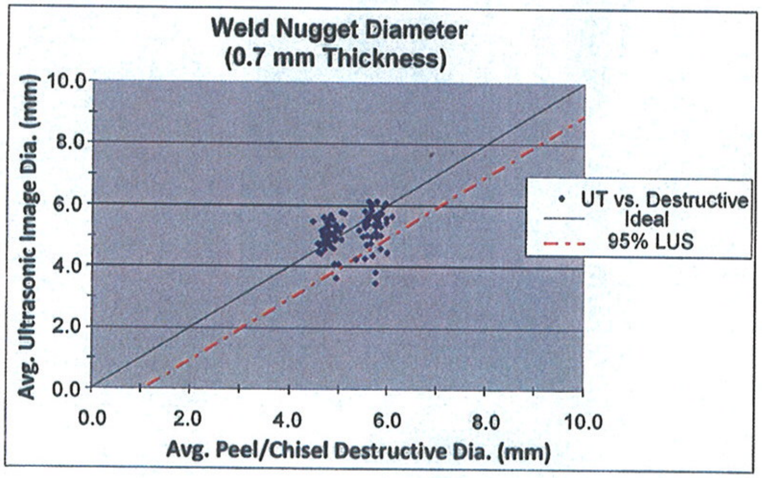

8

Fig. 7 — Ultrasonic images of spot weld nuggets for sample set No. 1. A — Upper row; B — lower row.

Fig. 8 — Probablity of detection (PoD) result for test sample set No. 2.

nugget size just for the sample set No. 2. The test sample set No. 1 and an example piece of sample set No. 2 are shown in Fig. 6.

Test Results and Discussions

The MPA ultrasonic inspection results for the sample set No. 1 are shown in Fig. 7. The number in the upper-left corner of each image indicates the number of electric current cycles used to form the weld nuggets. In both upper and lower rows, a good acceptable size spot weld was measured after four cycles. The left and right numbers shown in the upper portion of each ultrasonic image indicate nondestructively estimated nugget diameter and area, respectively. It was noticed that the nugget size did not improve as much after five cycles. For both rows, the overall increase in nugget size was less than 10% after five cycles. Each inspection took less than 10 s.

The welds in sample set No. 2 were examined first with the MPA inspection system before the planar metallography technique — where one of the welded sheets was ground away to reveal the weld nugget — was used to estimate the nugget size destructively. This method provided a full planar view of the weld region without distorting the weld button. The NDE results are plotted against the destructively measured data as shown in Fig. 8.

The test result of set No. 2 in Fig. 8 shows a good correlation with the actual nugget size. The dotted line in the graph indicates the 95% safety limit against undersizing (LUS), which is a combined parameter between systematic (average) error and standard deviation. A slight undersizing trend (positive false call) is observed from these data and the calculated LUS was approximately 1 mm. This LUS value in the range of 1 mm is considered to be a good NDE reliability.

Conclusions

A high-frequency, ultrasonic, 3-D MPA probe designed to perform nondestructive examination of resistance spot welds on automotive chassis has been developed and tested. The NDE results of spot welds made on two 0.7-mm metal sheets with different cycle numbers at a constant electrical current level showed that a good weld nugget with an acceptable diameter and area can be formed after four or five cycles. This means that the number of cycles currently used on automotive chassis could be reduced to save time and cost without overwelding with extra numbers of cycles. The PoD investigation performed on the two 0.7-mm stackups showed a tight nugget size distribution between 4 and 6 mm with a good correlation between the NDE results and the destructive results with an undersizing factor of 1 mm. Additional benefits obtained from a 3-D MPA probe design are thought to be lowering the operating frequency and total number of elements, which can play major roles in reducing the costs of probe and electronics.♦

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