Design and Development of High Frequency Matrix Phased-Array Ultrasonic Probes

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ABSTRACT. High frequency matrix phased-array (MPA) probes have been designed and developed for more accurate and repeatable assessment of weld conditions of thin sheet metals commonly used in the auto industry. Unlike the line focused ultrasonic beam generated by a linear phased-array (LPA) probe, a MPA probe can form a circular shaped focused beam in addition to the typical beam steering capabilities of phased-array probes. A CIVA based modeling and simulation method has been used to design the probes in terms of various probe parameters such as number of elements, element size, overall dimensions, frequency etc. Challenges associated with the thicknesses of thin sheet metals have been resolved by optimizing these probe design parameters. A further improvement made on the design of the MPA probe proved that a three-dimensionally shaped matrix element can provide a better performing probe at a much lower probe manufacturing cost by reducing the total number of elements and lowering the operational frequency. This three dimensional probe naturally matches to the indentation shape of the weld on the thin sheet metals and hence a wider inspection area with the same level of spatial resolution obtained by a two-dimensional flat MPA probe operating at a higher frequency. The two aspects, a wider inspection area and a lower probe manufacturing cost, make this three-dimensional MPA sensor more attractive to auto manufacturers demanding a quantitative nondestructive inspection method.

Key Words: Matrix Phased Array (MPA), Weld Conditions, Three-dimensional MPA
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INTRODUCTION

To reduce weight of vehicles and improve fuel efficiency, advanced high-strength steels (AHSS) were recently introduced to the automotive industry. AHSS have continued to gain momentum in popularity 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. 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 resistance spot weld (RSW) destructive test methods (pry-bar or chisel check and peel test) are costly and inaccurate when applied to AHSS. The automotive industry dictates that better nondestructive means be developed as 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. From this technology comes an improved NDI technique for detecting and quantifying weld conditions at the interfaces of metal sheets. Initially, a two-dimensional MPA probe was designed and tested for a validation purpose of the technology in terms of sizing weld nuggets and locating flaws in the weldments. By shaping the probe surface that fits to the generally concaved shape of resistance spot welds, it was found that the total number of elements and operating frequency can be lowered. This, in turn helps to lower the cost of the probe and electronics. A computer modeling tool, CIVA, was used to verify the beam launch angles with respect to the probe diameter.

EXISTING NDI METHODS FOR RESISTANCE SPOT WELD (RSW)

Non-Array Methods

A review of publications on the topic of NDT of RSW was conducted by Jones and Satonaka [3, 4]. It was found that in the 70s-90s the highest use of an NDT technique by industry was conventional ultrasonic techniques with a single element transducer. Based on literature review, the pulse-echo technique is more popular than through-transmission technique. Both techniques can be used either by direct contact or by immersion test methods. The basic principles for classification of quality of RSW using the pulse-echo method are described in reference [5].

A short description of good/bad RSW classification based on conventional ultrasonic testing results is shown below:

- **Good weld:** The echo spacing correlates to the approximate combined (full) thickness of the welded sheets. Because of coarse grain structure in a good weld, the attenuation is higher and the multiple echoes drop off relatively quickly.
- **Very small weld:** In addition to the full weld thickness echoes, there are additional low amplitude intermediate echo that arises from the boundary surface between the sheets.

- **Cold (stuck, stick) weld:** The echo pattern appears very similar to that of a good weld; however, in this case the grain structure is finer, and thus the attenuation is less. This results in less amplitude drop between the multiple echoes.
- **No weld:** No weld leads to a long echo sequence along with short echo intervals, corresponding to only a single sheet thickness.

Recently, Tuttle and Frazzini reported a deployment of conventional ultrasonic inspection of RSW on a production line [6]. The effort started on a pilot line where the inspection and adjustments to the inspection procedure were carried out in order to optimize the testing technique with respect to the product being tested. Once the procedure was optimized, the ultrasonic inspection method was deployed on the production line. With a proper alignment between the inspection and welding processes, cost savings were realized due to use of the ultrasonic method. No error rates (miss or false calls) were reported.

Non-Phased Array Matrix Transducer Method

Ptchelintsev and Maev invented a matrix array (not phased array) ultrasonic transducer that has a high density of acoustical sound generating units in order to increase the resolution [7]. This design accommodates use of individual independent multiple piezoelectric elements. Each piezoelectric element is electrically connected with a power source that comprises of a pulser-receiver in electrical connection with a multiplexer. The pulser-receiver provides a display that represents the acoustical images received from the piezoelectric transducer. A 56 multi-channel array transducer was incorporated in a new portable ultrasonic device called a Resistance Spot Weld Analyzer (RSWA) which is designed for quality control and NDI of RSW [8]. RSWA is capable of producing images of a spot weld's internal structure and estimate the average diameter of a weld nugget in real time.

A similar approach was patented as a Method and Apparatus for Assessing the Quality of Spot Welds [9]. This patent claims a spot weld quality evaluation method and device that can be used for industrial and production-level conditions. The device design includes a 2-D array (not phased array) of ultrasonic elements that are arranged on a hard delay line surface. Each element acts as a transmitter and receiver and tests the corresponding area of the spot weld. The nugget size is estimated through an algorithm evaluating the distribution of amplitudes and attenuation factors across all the elements.

Matrix Phased Array (MPA) Method

The further development in the matrix array ultrasonic method is the use of a matrix phased array approach for spot welds inspection. These probes have an active area divided into two dimensions. The element pattern can be in a form resembling a checker board**.** The main advantages of MPA probes are; the ability to control the beam in 3-D space; beam focusing in spherical, elliptical, or linear patterns; focusing at different depths**;** and two-plane steering capability for simultaneous variation of both the primary and secondary angles of the ultrasonic beam

Ikeda et al. have used a MPA probe in combination with Toshiba phased array inspection equipment known as "MatrixEye" to visualize the welding area of spot welds in B- and C-scan imaging view [10]. The specification of the probe used is: frequency of 15 MHz; number of elements of 8 × 8; array pitch of 1.5 mm; element size of 1.0 mm; case dimensions of 16 × 16 mm; flange dimensions of 24×35 mm. The MatrixEye system can visualize the spot weld and the brightness of image is a function of the strength of reflected echo. It is possible to calculate the weld diameter from the image by measuring both the major and minor axis. A comparison of weld nugget size measured by the ultrasonic method and weld nugget size measured after the destructive testing was reported by Ikeda et al. Typically the nugget was oversized by 1-1.5 mm when the nugget size was above 3 mm. When the nugget size was less than 2 mm the over sizing was more than 2 mm. No statistical analysis or reliability data has been reported.

DESIGN AND FABRICATION OF A NEW HIGH FREQUENCY MPA PROBE

It was recognized that there was a need to develop a new ultrasonic inspection system for resistance spot welds of thin metal sheets, having a lower uncertainty level in determining nugget size and the capability of identifying a stuck weld. 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 on to a spot weld, a computational modeling and simulations were performed upfront. 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. 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 1 shows a schematic of MPA some probe parameters evaluated using the beam modeling tools.

To achieve good focusing at a depth of 0.7 mm to 2 mm, it was necessary for the probe to have a physical delay distance between the probe element and the surface of part. 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 Figure 2 show beam profile results using a 3x3 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 3x3 aperture. As shown in the images in Figure 3, at the water path length 18 mm, the best beam focusing effect was achieved with small side lobes.

Based on the two modeling results shown in Figures 2 and 3, a probe to be used manually on spot welds was designed and fabricated. The 2D element array is mounted at the end of the probe tip and the water delay line is designed to be screwed on at the end. The cavity of the water column is filled with water before the cap is screwed on. If desired, it is also possible to attach a hard delay line tip to the probe.

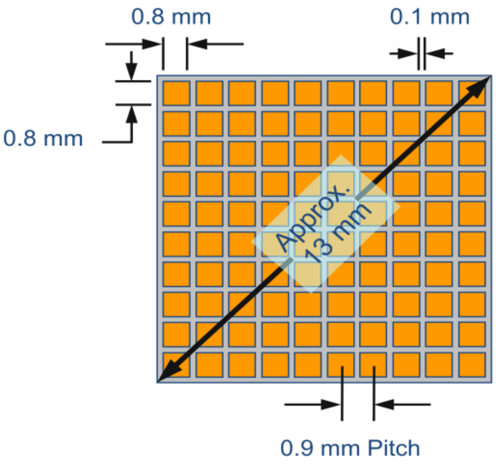


FIGURE 1. Schematic drawing of a high frequency matrix phased array probe element, f = 15 MHz.

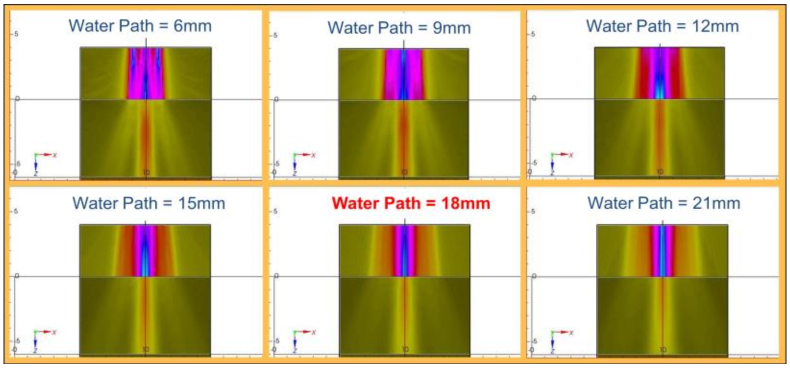


FIGURE 2. Modeling results of the water path length dependence at the water and metal interface.

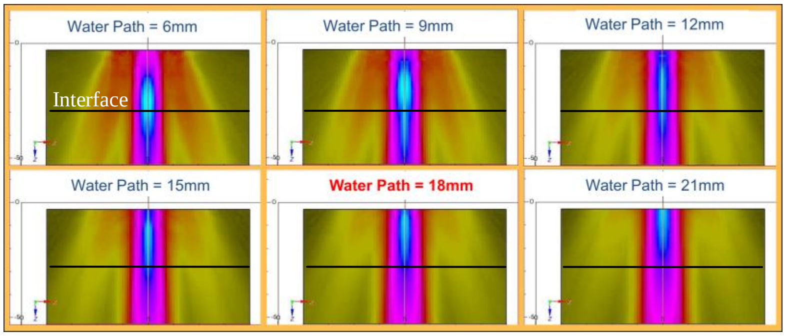


FIGURE 3. Modeling results of the water path lengths for a focused ultrasonic beam at the interface of two 2 mm metal sheets.

Tests on Resistance Spot Welded Parts

A proprietary software module for enhanced imaging, weld classification, size measurements and weld quality reporting was developed. The module was based on time, amplitude and frequency domain principles and a unique approach for multiple and flexible gate tracking. Test results of 2 mm x 2 mm stack ups are shown in Figure 4.

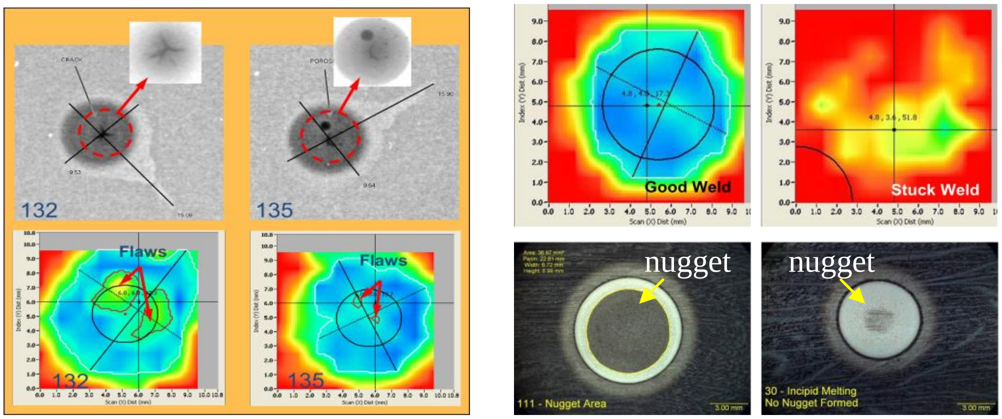
STATISTICAL VALIDATION

Resistance Spot Welded Sample Preparation

Two sets of spot weld samples with two sheet stack ups having thicknesses at the theoretical lower and upper limit of the probe design were prepared. These welds were later tested using a MPA system and then destructively examined to determine the actual weld condition and to measure the weld nugget size. Twenty six samples in set #1 were fabricated from 2.0 mm thick DP 780 HSS and represented the upper thickness range. Samples in set #2 were fabricated from 0.7 mm thick galvanized sheet and represented the lower end of the thickness range for testing. The same welding machine and monitoring equipment was used to produce welded samples.

For the interstitial free, draw quality (IF DQ) steel samples fabrication, weld current was adjusted such that three welded conditions were obtained: ‘stuck’ weld, where there localized melt and resolidification of the zinc coating; a small nugget condition, where the button pulled was smaller than the generally accepted $4\sqrt{t}$ in diameter; a good weld condition, where the button pulled was larger than $4\sqrt{t}$ in diameter.

The welds were produced in random, not sequential, order. That is, several welds were produced at the ‘good’ condition, then several more at the ‘stuck’ and ‘small’ conditions. One weld at each of the three conditions was destructed after every twenty welds made to confirm quality. Current levels were adjusted as necessary to maintain the desired weld size.



(a) (b)

FIGURE 4. Images of resistance spot welds: (a) flaws in weldments show up clearly in both X-ray (top) and ultrasonic images; (b) difference in a good weld and a stuck weld shows up clearly in the ultrasonic images as well as in the corresponding metallographic images (bottom).

Test Results and Discussions

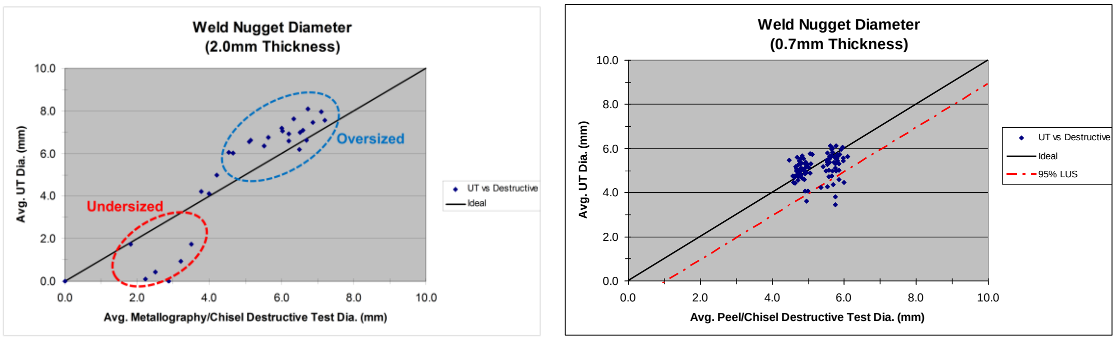
The MPA ultrasonic inspection results for both sets were compared to the destructive data obtained by both chisel tests and metallography measurements. The samples were examined using the planar metallography technique where one of the welded sheets was ground away to reveal the weld nugget. This method provided a full planar view of the weld region without distorting the weld button. The NDI results were plotted against those measured during the destructive tests and the results are shown in Figure 5.

It is clear from the graph in Figure 5(a) that the distribution of nugget size ranges from 2 mm to 7 mm for these 2 mm stack ups. The NDI results show that the nuggets larger than 4 mm in size have a tendency of over sizing, while nuggets smaller than 4 mm have a tendency of under sizing. These two opposite trends for the larger and smaller nuggets may be caused by the curvatures of the surface indentations at outer surfaces of the spot weld area.

The test result of set #2 in Figure 5(b) shows a good correlation with the actual nugget size. The dotted line in the graph indicates the 95% safety limit against under sizing (LUS), which is a combine parameter between systematic (average) error and standard deviation. A slight under sizing trend is observed from data shown in Figure 5(b) and the calculated LUS was approximately 1 mm. This LUS value in the range of 1 mm is considered to be a good NDI reliability.

SUMMARY AND FUTURE WORK

A high frequency ultrasonic MPA probe has been designed, fabricated and tested. Nondestructive inspection results have been compared with the destructive test results which actually measured the spot weld nugget size. For 2 mm stack ups, the distribution of actual nugget size was wide spread ranging from 2 mm to 7 mm in diameter and the correlation data showed an over sizing trend for nuggets larger than 4 mm while under sizing trend for nuggets smaller than 4 mm. On the contrary, the 0.7 mm stack ups showed a tight nugget size distribution between 2 mm and 4 mm. A good correlation between the NDI results and destructive results were observed for these thin stack ups.



(a) Set #1 (2 mm)

(b) Set #2 (0.7 mm)

FIGURE 5. Comparison of NDI results with destructive examination results for two sheet stack ups made of 2 mm and 0.7 mm thick metal plates.

Generally, the surface indentation caused by resistance spot weld process has a concave shape. Ultrasonic beam launched from a flat MPA probe has a limitation in beam steering capability depending on the frequency and aperture size. Although, the current 3x3 aperture operating at frequency of 15 MHz gives a good beam quality for the range of metal stack-ups used in this investigation, it was recognized that a wider range of surface curvature coverage would give a better signal to noise ratio. A preliminary modeling result obtained by using CIVA shows that the naturally curved 3-D MPA probe element (patent pending) can launch ultrasonic beams that interact with the surface curvature at a wide range of angles. Additional benefits obtained from a 3-D 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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