Determination of Diameter and Thickness of Weld Nuggets in Resistance Spot Weldings by High Frequency Ultrasound Inspection

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Abstract
For nondestructive testing of resistance spot weldings several commercial and mobile ultrasonic NDT systems are available. Most of them offer only a very limited C-Scan image resolution. With scanning acoustic microscopy (SAM) it is possible to obtain high-resolution B- and C-Scans and to perform an additional quantitative analysis of HF A-Scans. This allows for a sophisticated analysis of the weld nugget. Therefore, SAM can be used as quantitative reference and calibration tool for commercial testing systems. In the present work the SAM results are compared with a commercial US testing system based on a matrix sensor. In this context a novel spectral evaluation technique with successive image correlation analysis is applied. It is further demonstrated that it is possible to determine not only the lateral dimension (diameter) of the nugget but also its approximate thickness. The latter is obtained by analyzing the effective ultrasound attenuation caused by the interaction with the modified grain structure inside the nugget.

Keywords: Resistance spot weldings, weld nuggets, scanning acoustic microscopy (SAM), grain structure

1. Introduction

Resistance spot welding is an established joining technology, e.g. in the automotive industry, in frame-and-body construction and in sheet metal forming. It is characterized by a high cost effectiveness and process reliability. The quality of spot weldings can be determined by destructive and non-destructive testing methods as well as by an indirect analysis of the process parameters. In contrast to a fuzzy parameter analysis destructive and non-destructive techniques allow for a direct quantitative evaluation of the spot welding. In the laboratory the weld quality is often determined by a chisel test. During this procedure the chisel is mechanically forced between the two metal sheets until one of the sheets is removed by unbuttoning (Fig. 1). After that the unbuttoned area (white arrow) can be investigated by optical microscopy in order to determine geometry, diameter and type of fracture.

Figure 1. Destructive chisel test of a resistance spot weld (on the left). After one of the metal sheets has been lifted the unbuttoned area (arrow) can be further analysed with respect to geometry, diameter and type of fracture (on the right).

During production, however, non-destructive testing (NDT) methods are essential. The most important NDT method for resistance spot weldings is ultrasonic testing. Besides single-channel systems with integral analysis of the back-wall echo, multi-channel matrix systems [1,2] and miniature scanner with combined translation/rotation are available as well.
In the present work the RSWA matrix system of Tessonics Inc. (Canada) was evaluated. A scanning acoustic microscope Evolution II of PVA TePla AG (Germany) served as reference for high-frequency investigations. For the first part of this work as described in chapter 2, two-sheet combinations with varying sheet thicknesses and materials were used. The upper sheet had a thickness of 0.65 mm in each case and was made of a deep drawing steel DX56+Z100MB. The lower sheet consisted of a corrosion-resistant steel X5CrNi10-18 with a thickness of 2 mm and a deep drawing steel DX56+Z100MB with thicknesses of 1 and 2 mm, respectively. All sheets were zinc-plated.

2. Ultrasonic determination of the weld nugget diameter

Ultrasonic testing of resistance spot weldings is usually based on pulse-echo measurements and subsequent analysis of A-, B-, or C-Scans.

2.1 Mobile US matrix array system

The RSWA system of Tessonics Inc. Canada, is a mobile US testing system for manual industrial inspection (Fig. 2). It is based on an 8×8 matrix transducer with 52 piezoelectric elements. Each element is acting separately in pulse-echo mode (no phased array) using a frequency of approx. 15-20 MHz. Due to the circular shape of a spot weld the three elements in the four corners of the matrix are omitted which yields the final number of 52 active elements. The full aperture of the transducer amounts to approx. 10×10 mm² and is protected by a polystyrene delay line that is coupled to the specimen by a conventional coupling paste.

For a complete amplitude C-Scan of the area under test the A-Scans of all 52 elements are processed and evaluated separately. The resulting picture is interpolated in order to obtain a smoother gradient in the final C-Scan. The amplitudes are displayed by a color scale in which a green color indicates a welded and a red color indicates a non-welded region (Fig. 3).

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Figure 3. Typical results of the RSWA system showing welded (green) and non-welded regions (red) inside the aperture. In this case the measurement across a single spot weld was repeated three times in order to demonstrate the statistical fluctuations due to the varying coupling conditions.
Inside the C-Scans a grid structure is visible according to the 52 single elements of the matrix transducer. For a quantitative evaluation of the weld nugget a black circle is automatically placed inside the C-Scan. It represents the largest circle that lies completely inside the green area (welded region). The resulting effective diameter of the nugget, \( d_L \), is given in the top left corner of the displayed image. Additionally the depth of indentation of the upper electrode is shown in the middle of the same bar.

In general the RSWA system, designed for economic practical use, delivers acceptable results of spot weld quality but only in case of good surface conditions. Due to the hard delay line the results are sometimes affected by tilt effects. In this case multiple measurements across one and the same spot weld could lead to different results of weld quality as demonstrated in Fig. 3. According to DIN EN ISO 14327 [3] \( d_L \) has to be larger than 2.45 mm in order to guarantee a good weld quality for this specific metal sheet combination. In two of the three measurements this criterion is fulfilled but in the third measurement \( d_L \) is smaller than 2.45 mm indicating a non-acceptable weld that would be rejected. Besides the problem of reproducibility the RSWA system shows several advantages like high mobility, easy operation and a short measurement time of approx. three seconds per spot weld.

### 2.2 Scanning acoustic microscope

In order to evaluate the results of the RSWA system for manual testing a scanning acoustic microscope Evolution II of PVA TePla AG, Germany, was used as a laboratory reference device. The SAM consists of a fast and very precise scan unit placed above an immersion tank in which the specimen is situated. De-ionized water is used as coupling medium in order to guarantee stable and reproducible coupling conditions (Fig. 4).

![Figure 4: Scanning Acoustic Microscope (SAM, on the left) and corresponding scan unit (on the right).](image)

The mechanical scan unit can be moved along three separate axes, x, y, and z. For each scan point one pulse-echo measurement is performed. Usually the whole area of interest is scanned across the x-,y-plane by using a fixed distance between probe and surface according to the specific focal length of the transducer and the expected depth of the defect. By using various transducers the testing frequency can be adapted to the current testing configuration.

#### 2.2.1 Evaluation of SAM data

For evaluation of the SAM data A-, B-, and C-Scans are considered. Fig. 5 (left picture) shows a typical C-Scan of a spot weld. The grey-scale indicates the amplitude of the interface echo between the two metal sheets. The size of the scan area is identical to those used for the RSWA system (compare Fig. 3). In the C-Scan three different weld qualities can be identified, i.e. good welding (dark area, no or weak interface echo), no welding (light area, strong echo from the air gap between the metal sheets) and a so called weld bond in which only the zinc layers of the sheets joined together (small interface echo).
Figure 5: Principle of ultrasonic immersion testing of a spot weld. On the left: typical C-Scan with three different weld qualities. On the right: Relevant types of echoes for welded and non-welded regions.

Moreover a void can also be identified as small light spot below numeral 2. In Fig. 5 (picture on the right) the possible travel paths and types of echoes of ultrasonic waves in regions 1 and 2 of a spot weld are displayed. In the following section the three characteristic regions of the spot weld are described in detail.

Non-welded region 1:
If the two metal sheets are not welded an air gap between them remains which leads to a strong interface echo or more precisely, to a multiple echo from the back wall of the upper sheet. Nearly no energy is transmitted to the lower sheet and thus, no echo from its back wall can be identified (Fig. 6).

Figure 6: B-Scan (on the left) and A-Scan (on the right) at a non-welded region of the spot weld. The temporal distance between the multiple echoes correlates to the thickness of the upper metal sheet. The A-Scan on the right was measured at position A as indicated in the B-Scan.

Welded region 2:
In this case the two metal sheets were completely welded and thus, only the surface echo and the (weak) back wall echo from the lower sheet are visible. Their temporal distance correlates to the thickness of the complete sheet combination. In contrast to region 1 no interface echo can be identified (Fig. 7).

Figure 7: B-Scan (on the left) and A-Scan (on the right) at a welded region of the spot weld. No interface echo is visible. Instead, the back wall echo from the lower metal sheet appears.
However, in case of two different sheet materials a weak interface echo might be expected due to the impedance mismatch.

Weld-bonded region 3:
If the welding process only leads to a fusion and bonding of the zinc layers (with lower melting temperature than the base material) a so called weld bond is generated. In this case an air gap no longer exists but an additional interface echo occurs even if the two metal sheets are made of the same material (Fig. 8). It is evident that the back wall echo from the lower sheet is stronger than the corresponding echo from the welded region 2. A possible explanation is based on the fact that in case of a weld bond no microstructural transformation takes place and thus no additional ultrasound attenuation due to scattering exists.

![Figure 8: B-Scan (on the left) and A-Scan (on the right) at a weld-bonded region of the spot weld. Compared to the welded region 2 an additional interface echo and a stronger back wall echo from the lower sheet occur.](image)

2.2.2 Spectral evaluation of HF A-Scans

For a better and automatic evaluation of the A-Scans a spectral evaluation technique has been developed. In contrast to the conventional algorithm in which the maximum amplitude in a specific time window is extracted the new algorithm evaluates the whole A-Scan in the frequency domain. For this purpose spectra of various weld qualities were analysed and classified according to a single scalar value. This value is transformed into a grey scale and displayed in the final spectral C-Scan so that each pixel represents a quality parameter for a certain measurement point. In this context light grey areas represent non-welded parts of the spot weld while dark grey values represent welded regions (Fig. 9, left picture).

2.2.3 Emulation of an US matrix transducer from SAM data

For a better comparison of the SAM C-Scans (500 × 500 Pixel) with the RSWA C-Scans the resolution of the SAM C-Scans had to be reduced to 8 × 8 Pixel (1.25 × 1.25 mm²) which represents the original solution of the RSWA system. After that the resolution was interpolated to 500 × 500 Pixel (0,02 × 0,02 mm²) as shown in Fig. 9.

![Figure 9. Downsampling of an original spectral SAM C-Scan (on the left) to the typical resolution of the RSWA system (on the right).](image)
The comparison of such a downsampled SAM image with the corresponding RSWA image of the same weld is shown in Fig. 10.

Figure 10. Comparison of downsampling SAM-C-Scan (on the left) with the corresponding RSWA-C-Scan (on the right).

2.3 Quantitative comparison of SAM and RSWA images based on Pearson correlation

The similarity between two images $X$ and $Y$ can be quantified by the dimensionless correlation coefficient $r_{xy}$ according to Pearson. By using two corresponding image points $X_{i,j}$, $Y_{i,j}$ and the mean values $\bar{x}$, $\bar{y}$ of the two images, $X$ and $Y$, the Pearson correlation coefficient amounts to:

$$r_{xy} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} (X_{i,j}-\bar{x})(Y_{i,j}-\bar{y})}{\sqrt{\sum_{i=1}^{n} \sum_{j=1}^{m} (X_{i,j}-\bar{x})^2 \sum_{i=1}^{n} \sum_{j=1}^{m} (Y_{i,j}-\bar{y})^2}}$$

with

$$\bar{x} = \frac{1}{n \times m} \sum_{i=1}^{n} \sum_{j=1}^{m} X_{i,j} \quad \text{and} \quad \bar{y} = \frac{1}{n \times m} \sum_{i=1}^{n} \sum_{j=1}^{m} Y_{i,j}.$$ 

The correlation coefficient $r_{xy}$ ranges between -1 and 1. The smaller the absolute value of $r_{xy}$, the smaller the correlation between the two images. A correlation coefficient of +1 indicates that the two images are identical. If $r_{xy} = -1$, the images are inverse.

The information content of a C-Scan depends on its resolution and the number of measurement points, respectively. In order to quantify the effect of a reduced image resolution the correlation coefficient between a reference SAM C-Scan and an interpolated SAM C-Scan with reduced resolution according to the procedure described in Fig. 9 was determined. For this purpose various C-Scans of one and the same spot weld with an emulated resolution from $4 \times 4$ to $500 \times 500$ Pixel (elements) were generated and analyzed. In the following Fig. 11 the typical trend of the correlation coefficient as a function of the number of elements is shown.

Figure 11. Correlation between Reference-C-Scan and C-Scan with reduced resolution as a function of N.
In Fig. 11 three different interpolation techniques were used. For each technique the corresponding curve shows an asymptotic behavior. In the range up to $14^2$ elements (black vertical line) the curves show a strong rise and an erratic development. This is due to the small information content for small $N$. For $14^2$ and more elements the slope of the curves becomes smaller and the differences between the three interpolation techniques are negligible which means that the image quality is independent of the used interpolation technique. Moreover in this range more than 90% of the information content of the high-resolution reference image is reached.

Fig. 12 shows exemplary 20 MHz C-Scans for different numbers of elements. From these images it is evident that the image quality is particularly increased between $8 \times 8$ and $16 \times 16$ elements. With $16^2$ elements the geometry of the welded region is displayed properly. With $32^2$ elements the image quality is very high and already close to the quality of the reference image (Fig. 12, on the right).

As a consequence a reliable estimate of the spot weld quality seems to be possible even if the number of elements is moderate. In order to reach a sufficiently high $(r_{xy} > 0.9)$ and reliable image quality a resolution of at least $14 \times 14$ elements seems to be necessary according to Fig. 12. Even $12 \times 12$ elements would be a significant improvement compared to the current RSWA system since the correlation coefficient increases from approx. 0.82 to nearly 0.9.

### 3. Ultrasonic determination of the thickness of the weld nugget

A deeper analysis of the results shown in Fig. 7 and 8 raises the question if it is possible to extract the thickness of the weld nugget based on the ultrasonic attenuation of the back wall echo. In case of the bonded region shown in Fig. 7 the back wall echo of the lower metal sheet is significantly weaker than in Fig. 8 where the weld-bonded case is displayed. Our assumption is that in case of a good welding the grain structure of the welded zone is modified as can be seen in Fig. 5 (on the right) for instance. Due to the larger grains the attenuation caused by scattering is stronger and thus, the back wall echo becomes smaller. Therefore, if the total thickness of the metal sheet combination is known, it should be possible to determine the approximate lateral dimension of the weld nugget, i.e. its thickness, from the analysis of the back wall echo.

#### 3.1 Effect of surface topography

Since we were interested in the ultrasonic attenuation caused by microstructural changes during the weld process we had to be sure that no other effects mask our measurements. In order to guarantee stable and reliable coupling conditions we performed the new measurements in immersion testing by using our SAM system. The first goal then was to
verify if the surface topography and the inclination of the upper surface shows a significant influence on the amplitude of the back wall echo.

For the new investigations we used two different metal sheet combinations. In combination A both the upper and the lower sheet were 1.5 mm thick and made of uncoated DC01 material (a cold rolled low carbon steel). In combination B the upper sheet had a thickness of 0.8 mm and was made of DX56+Z100MB (zinc-plated) while the lower sheet was 1.0 mm thick and made of the same material. In a first step the surface topography of each spot weld was measured by extracting the time of flight of the surface echo and therewith, the distance of each surface point to the US transducer (see Fig. 13, picture on the left). From this topography an inclination angle map was determined which shows the absolute value of the maximum inclination angle in a linear color scale (Fig. 13, picture on the right).

From Fig. 13 it is evident that ultrasonic testing is only critical at the edges of the electrode indentation where the inclination angle is very high. However, in the inner circular indentation area the surface is sufficiently smooth. Moreover the overall inclination of this inscribed circle is always below 5°. A couple of simulation studies based on acoustic ray tracing revealed that such a tilt angle has no significant influence on the amplitude of the back wall echo. In order to verify this theoretical finding we first measured surface and back wall echoes from all available specimens with a good welding without a prior surface treatment. After that we mechanically treated the surface by face milling in order to obtain a perfectly plane and smooth surface. We then repeated the measurements and compared them with the initial measurements without surface treatment. The results are given in Fig. 14 for both metal sheet combinations.

![Figure 13. Typical surface topography (on the left) and inclination angle map (on the right) extracted from the time-of-flight data of the upper sheet surface echo.](image)

![Figure 14. Measurement results for the normalized amplitude of the surface echo SE (●) and the back wall echo of the lower sheet BE (+) for untreated (blue) and face-milled surfaces (red) for five specimens of sheet combination A (DC01, on the left) and B (DX56, on the right).](image)
From Fig. 14 one can see that the differences between mechanically treated and untreated surfaces are rather small and lie within the range of a few percent only. Therefore, it can be concluded that the effects of surface roughness and inclination can be neglected and no mechanical surface treatment is necessary, at least for the kind of immersion testing performed in our lab.

3.2 Effect of grain structure

After excluding the possible influences of surface and coupling condition we can now focus on the effect of the grain structure. From Fig. 6 (on the right) it is obvious that the grain structure within the weld nugget is different from the microstructure in the surrounding heat-affected zone. A typical color encoded C-Scan of the back wall echo is shown in Fig. 15.

The red parts in Fig. 15 indicate non-welded metal sheets with a strong interface echo. The dark blue regions coincide with the “crater rim” of the electrode indentation with no back wall echo. The inner light-blue circle indicates the welded part and is of particular interest since it shows a heterogeneous character caused by the grain microstructure and contains information about the traversed thickness of the weld nugget. In order to demonstrate the latter aspect the lateral dimension of the nugget was extracted destructively by optical micrographs after the ultrasonic measurements had been finished. Based on this data the echoes of the back wall echo of the lower sheet could be drawn as a function of the thickness of the weld nugget as shown in Fig. 16.
In case of the DC01 sheet combination the experimental data very precisely follow an exponential function with a damping coefficient of $\gamma_{DC01} \approx 6060 \text{ m}^{-1}$. However, in case of the DX65 sheet combination the exponential behaviour is less significant and maybe affected by the outlier with back wall amplitude of 0.54. Moreover, due to the fact that the DX56 values of the nugget thickness are significantly smaller than the DC01 values the statistical uncertainty of both the ultrasonic and the optical microscopy investigations might be higher in the DX56 case. Nevertheless a mean decrease of the amplitude values with increasing nugget thickness is even visible here ($\gamma_{DX56} \approx 5610 \text{ m}^{-1}$). Further studies with an extended amount of specimens should improve the statistical significance in the future. For practical use the curves shown in Fig. 16 could be calibrated by one or two destructive tests for each relevant metal sheet combination. For all following spot welds the thickness of the nugget could then be estimated non-destructively from the attenuation of the corresponding back wall echo.

Conclusions and Outlook

In this paper it was demonstrated that the lateral size of a spot weld nugget, i.e. its diameter, can be easily extracted from US C-Scans if a matrix system (like the mobile RSWA system) or a mechanical scan unit (like a Scanning Acoustic Microscope) is used. The comparison of both systems revealed that for future developments of commercial matrix systems a higher resolution of at least 12×12 or - even better - 14×14 elements seems to be preferable. It was further shown that beside the lateral size of the nugget its thickness can be determined as well. This can be done by analysing the increased attenuation of the back wall echo due to scattering at the weld microstructure. However, in this case it must be guaranteed that the coupling conditions are reproducible and the surface inclination and its roughness do not affect the attenuation measurement significantly. A local miniaturized immersion tank coupled with a phased array matrix transducer for prior distance measurements together with flexible beam steering and focusing capabilities seems to offer the best way to fulfil these requirements in the future.

References