A New Model-Based Approach for Ultrasonic Testing of Dissimilar Welds

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Abstract. A new model-based approach for ultrasonic phased-array testing of dissimilar welds based on the direct measurement of the wave speeds inside the real weld by using scanning laser vibrometry is presented. With this technique the interaction of different wave modes with the weld can be studied in detail leading to important consequences for the measuring set-up. Together with the geometry of the weld as extracted from photo micrographs, an appropriate time-of-flight model including ferritic and austenitic regions, welding zone, buttering and cladding is defined and used for the optimization of focal laws. The whole approach was implemented into the new phased array system PCUSpro Array developed at Fraunhofer IZFP in Dresden. A first successful application of the equipment in a test setup of a customer is presented and discussed.

Keywords. Dissimilar Welds, Ultrasonic Phased Array, Laser Vibrometry, Model-Based Approach

1. INTRODUCTION

Dissimilar welds represent a big challenge for ultrasonic testing due to their heterogeneous and anisotropic microstructure. Varying elastic properties of the different material constituents lead to curved acoustic ray paths and different local group velocities and therefore, strongly affect the focusing capability of phased array systems. Model-based techniques try to compensate the beam distortion by using time-of-flight models of real weld geometries [1]. Previous approaches used image-based information of the grain orientation together with published values of elastic parameters but usually suffered from insufficient or inaccurately known data. The present work uses a new approach, based on the direct measurement of local wave speeds inside the real weld by using scanning laser vibrometry. With this technique the interaction of different wave modes with the weld can be studied in detail leading to important consequences for the measuring set-up. Together with the geometry of the weld as extracted from photo micrographs, an appropriate time-of-flight model including ferritic and austenitic regions, welding zone, buttering and cladding can be defined and used for the optimization of focal laws.

2. DISSIMILAR WELD CONFIGURATION

In the case under consideration dissimilar welds in cylindrical pipe mock-ups with typical dimensions as shown in Fig. 1 were investigated. The wall thickness of the pipe was in the range between 85 and 108 mm.
The configuration of the dissimilar weld under consideration is shown in Fig. 2. In the present case the testing had to be performed from the inner surface of the mock-up, i.e. from the cladding side.

3. WAVE PROPAGATION MEASUREMENTS BASED ON LASER VIBROMETRY

In order to build a time-of-flight model for the weld inspection the wave propagation inside a small weld sample was measured by a scanning laser vibrometer. For this purpose a special measurement set-up was realized as shown in Fig. 3. The surface of the small weld sample was polished in order to increase the reflectivity of the surface and thus, also the signal-to-noise-ratio of the detected ultrasonic signal. The ultrasonic transducer was applied to the short surface of the sample on both the ferritic and the cladding side. In order to suppress disturbing reflections from the outer surfaces of the small sample, these surfaces were coated with modelling clay which leads to a strong damping of the incident waves from inside the sample.
By the help of the laser vibrometer various measurements of ultrasonic wave propagation were performed in order

- to demonstrate the difference between measurements from the outside ferritic part of the weld and measurements from the inside through the cladding
- to demonstrate that the shear wave cannot be used for the measurements due to the large scattering inside the weld
- to set-up a time-of-flight weld model to be used as focal-law calculator for the phased array system

Typical examples of measured wave propagation are shown in Figs. 4 and 5. The results in Fig. 4 demonstrate that it is much easier to inspect the weld from the outside surface since in this case an efficient beam forming and focusing of both pressure and shear waves can be performed based on the isotropic and only weakly attenuated wave fronts.

If measuring through the cladding an efficient beam forming for the shear wave is nearly impossible due to the strong scattering and attenuation. Nevertheless, the P wave shows a significantly smaller interaction with the cladding microstructure. Therefore, the P wave seems to be the only option to test from the cladding side.
Figure 4. Wave propagation due to single element phased array excitation at 2.25 MHz detected by scanning laser vibrometry. Left column: Excitation from the outside ferritic part of the weld showing isotropic wave propagation with circular wave fronts with no significant scattering. Right column: Excitation from the inside cladding surface showing anisotropic wave propagation with strong scattering, especially of the shear wave.

In Fig. 5 the interaction of a pressure and a shear wave with the weld is shown in very high resolution. It can be seen that the scattering of the shear wave is much stronger than that of the pressure wave and that the shear wave is not able to penetrate the welding region. Therefore, for probing of the inner part of the weld only the P wave can be used. However, the S wave could be used for the probing of ferritic interfaces if measuring from the ferritic side (as done in Fig. 5).
4. ULTRASONIC TIME-OF-FLIGHT MODEL OF THE WELD

Based on the laser vibrometer measurements and additional photo micrographs, an ultrasonic weld model was defined as shown in Fig. 6. It is separated into five different areas, i.e. the ferritic area A, the austenitic area B, the welding region C, the cladding D and the buttering area E. The geometry of these different regions is determined by the 15 points P1 – P15 marked in red. The origin of the coordinate system is indicated by the small green circle. The welding region C is further separated into the region C1 on the right of the y-axis and C2 on the left of the y-axis. This is necessary because the grain orientations in the two regions are significantly different from each other.
In the frame of the PCUSpro Array system which is described in the following chapter, the geometry of the dissimilar weld can be specified in an input file that can be read by the PCUS hardware before the measurement. This file is easily adaptable by the user and can be used for different weld geometries.

For each of the five different regions of the weld, A-E, the pressure wave speed in the four main directions $0^\circ$, $90^\circ$, $+45^\circ$ and $-45^\circ$ was determined by the laser vibrometer. As a consequence each weld region is characterized by four different wave speeds which can be used to calculate the (adapted) focal laws of the PCUSpro Phased Array system.

For instance if a transducer coupled to the cladding is used to focus the ultrasonic waves to the point P10, the weld areas D, A, E, C1, and C2 are crossed by the corresponding ultrasonic rays. By the help of the five P wave speeds for each region the necessary time delays of the single transducer elements can be calculated. The wave speeds are also specified in the weld input file. The values in Table 1 represent the real wave speeds as extracted from the vibrometer measurements (given in m/s). It is interesting that the P wave speed in the cladding in $90^\circ$ direction is smaller than in $0^\circ$ and in $\pm45^\circ$ direction although the main grain orientation lies in $90^\circ$ direction. This is exactly confirmed by the wave front snapshots shown in Fig. 4.

In the weld model different transducer positions at the inner surface according to Fig. 6 can be defined as well:

- Area I: Cladding side, inner surface (between P4 and P5)
- Area II: Welding, inner surface (between P2 and P4)
- Area III: Austenitic side, inner surface (between P1 and P2)

An overlap of the transducer between different areas is also possible. In the input file the location of the transducer is specified by the coordinates of the center of its aperture (or wedge). With the internal parameters of the transducer (number of elements, pitch etc.) as provided by the PCUSpro system it is possible to determine the exact positions of the single transducer elements with respect to the weld. Based on this data, the (adapted) focal laws as specified by the user or automatically by the system can be calculated.
Table 1. Measured wave speeds (in m/s) in the different weld regions according to Fig. 6.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Ferrite A</th>
<th>Austenite B</th>
<th>Weld C1</th>
<th>Weld C2</th>
<th>Cladding D</th>
<th>Buttering E</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° (x)</td>
<td>5882.0</td>
<td>5747.0</td>
<td>5556.0</td>
<td>5848.0</td>
<td>5417.0</td>
<td>5618.0</td>
</tr>
<tr>
<td>90° (y)</td>
<td>5917.0</td>
<td>5666.0</td>
<td>6173.0</td>
<td>5550.0</td>
<td>5192.0</td>
<td>5405.0</td>
</tr>
<tr>
<td>+45°</td>
<td>5917.0</td>
<td>5772.0</td>
<td>6070.0</td>
<td>6083.0</td>
<td>5940.0</td>
<td>5992.0</td>
</tr>
<tr>
<td>-45°</td>
<td>5845.0</td>
<td>5798.0</td>
<td>6148.0</td>
<td>5772.0</td>
<td>5940.0</td>
<td>6187.0</td>
</tr>
</tbody>
</table>

5. TEST MEASUREMENTS AT SMALL WELD SAMPLES

In order to demonstrate the extended imaging capabilities of the model-based approach, it was prototypically implemented in our PCUSpro Array system (Fig. 7). Three drill-holes with a diameter of 3 mm each were drilled into a small weld sample (Fig. 8). The ultrasonic phased array measurements were performed with a 16 element probe at 2.25 MHz directly attached to the cladding side. Geometrical and acoustical information from the weld definition file was then used to perform an extended analysis of the conventional sector scan data from Fig. 9. This leads to a significantly better image of the drill-hole positions as shown in Fig.10.

**Figure 7.** PCUSpro Array system developed at IZFP Dresden. It contains several sophisticated imaging modes beyond the standard sector scans.

**Figure 8.** Small dissimilar weld sample and positions of the three drill-holes and the 2.25 MHz phased array transducer used for the manual measurements.
Figure 9. Result of PCUSpro Array system obtained with 2.25 MHz from the cladding side. The picture shows a conventional sector scan image. Indications from the three drill-holes and from the back-wall are clearly visible. However, the positions of the indications do not perfectly agree with the real positions of the holes due to the different wave speeds in the weld regions penetrated by the acoustic beam.

Figure 10. Final result of the model-based approach. The picture shows a reconstruction where the echo indications above a certain threshold are marked in color. The wave field distortion caused by the different wave speeds inside the weld has been compensated based on the geometrical and acoustical data in the weld description file. The two inset pictures show the wave propagation characteristic of a single element of the phased array transducer in the isotropic ferrite (bottom left corner) and the anisotropic cladding (top left corner), according to Fig. 4. It is essentially this information that is coded in the weld description file.

6. AUTOMATED MEASUREMENTS AT PIPE MOCK-UP

Besides the performance test at the small weld sample further measurements have been performed at the pipe mock-up shown in Fig. 1, using a scanning system provided by the customer. Before start of the automatic measurements several preparatory tests with calibrated test samples were performed. Fig. 11 shows the probe holder together with one of the phased array transducers used for the measurements (Olympus, 64 elements, center frequency 1 MHz).
An exemplary result of the different measurements obtained with the PCUSpro Array system is shown in Fig. 12 in the form of B-, C-, and D-Scans. The results were determined with a 20° pressure wave wedge and a focal depth of 75 mm. The steering angle was between 5° and 35°. The starting point of the scan was 194 mm from the upper edge of the mock-up. 19 turns were done using a resolution of 1°. As can be seen from the Figure a number of very clear indications can be found in all of the displayed B-, C- and D-Scans.

7. CONCLUSIONS AND OUTLOOK

In the present paper a new model-based approach for automated phased array testing of dissimilar welds has been presented. It is based on Laser vibrometer measurements of ultrasonic wave propagation through real weld samples and leads to a detailed time-of-flight model for
the focal law calculator. With this knowledge a better beam steering and focusing can be obtained leading to better images and a more precise defect localisation. The approach was implemented into our new phased array platform PCUSpro Array and was successfully tested at a dissimilar weld pipe mock-up. In the future further enhanced imaging algorithms based on Synthetic Aperture Focusing Technique (SAFT, [2]) and Full Matrix Capture [3] shall be implemented.

References

