Phased Array Techniques for an Optimized Inspection of Dissimilar Welds

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Abstract: The inspection of austenitic stainless steel welds by ultrasonic techniques is disturbed by the heterogeneous and anisotropic structure of the weld. To make matters worse the specimen also consists of different areas of austenitic and ferritic steel. The disturbance may result from beam deviations, beam splitting, scattering or attenuation. For defect localization and size characterization the before mentioned disturbances induce uncertainties and unknowns and may not meet the inspection requirements in the first place. The development of more advanced phased array UT inspection techniques starts with the evaluation of the acoustic beam propagation required to determine the target flaw positions. By using the laser vibrometer it was possible to study the propagation of longitudinal and shear waves and their interaction with the weld in great detail and thus taking the results into account for the configuration of the novel system and the reconstruction of the ultrasonic data.

Motivation

The inspection of austenitic stainless steel welds by ultrasonic techniques is disturbed by the heterogeneous and anisotropic structure of the weld. To make matters worse the specimen also consists of different areas of austenitic and ferritic steel. The disturbance may result from beam deviations, beam splitting, scattering or attenuation. For defect localization and size characterization the before mentioned disturbances induce uncertainties and unknowns and may not meet the inspection requirements in the first place.

The project task was to inspect a dissimilar weld from the cladding side of the specimen. The development of an advanced UT electronics was part of the task respectively.

Drawbacks of the Present Model-Based Approaches

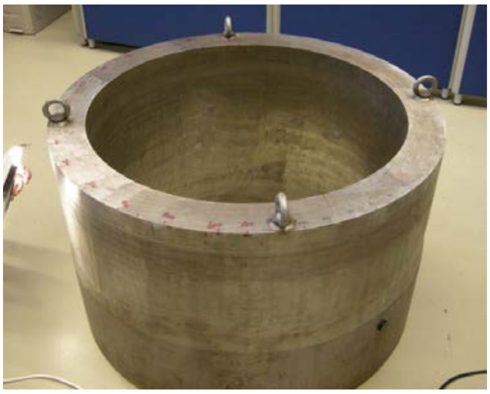
- Grain orientation alone does not provide elastic/acoustic parameters
- Published values are typically not very reliable
- Elastic parameters of real welds may differ significantly
- This leads to an inaccurate time-of-flight model for phased array testing

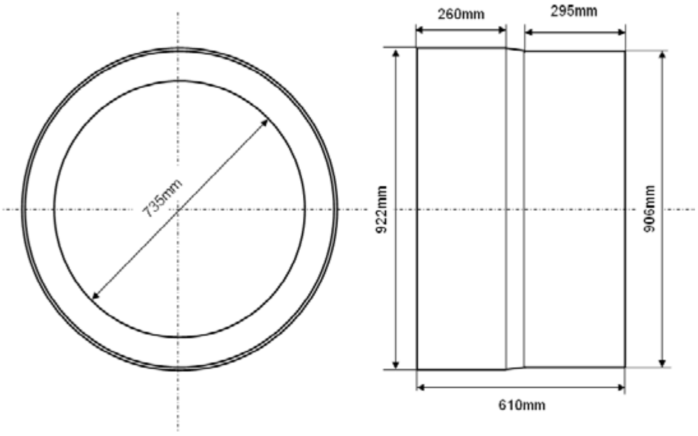
Remedy

Measurement of wave propagation at the real weld microstructure and weld geometry followed by extraction of acoustic travel times from the wave front snapshots.

Inspection Task

The following pictures show the structure and shape of the specimen to be inspected which consists of ferrite and austenitic stainless steel, a buttering and cladding region and a dissimilar weld respectively. The project task was to inspect a dissimilar weld from the cladding side of the specimen.





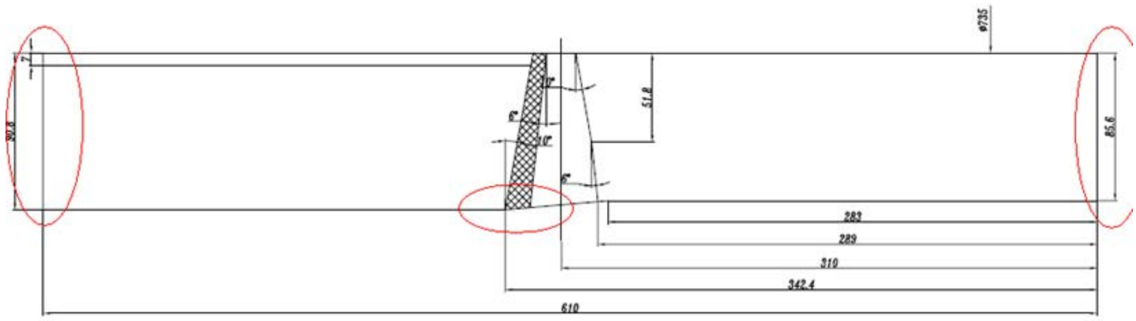


Figure 1. Setup of the laser vibrometry measurements.

Laser Vibrometry Measurement

In order to increase the accuracy of the phased array testing the wave propagation inside one of the two small weld samples was measured by a scanning laser vibrometer. For this purpose a special measurement set-up was realized as shown in Fig. 1.

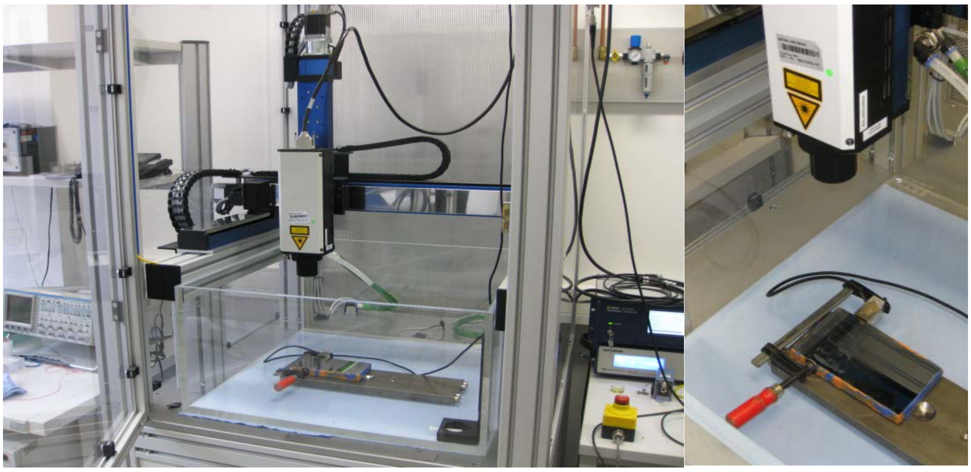


Figure 2. Setup of the laser vibrometry measurements.

The following picture shows the visualization of wave propagation through the specimen. The wave propagation inside the ferritic material is as commonly known, whereas the wave propagation through the cladding of the specimen shows a totally different picture.

The longitudinal wave front – through the cladding – is now longer circular but flattened. The transversal wave front – following the longitudinal wave – is highly distorted.

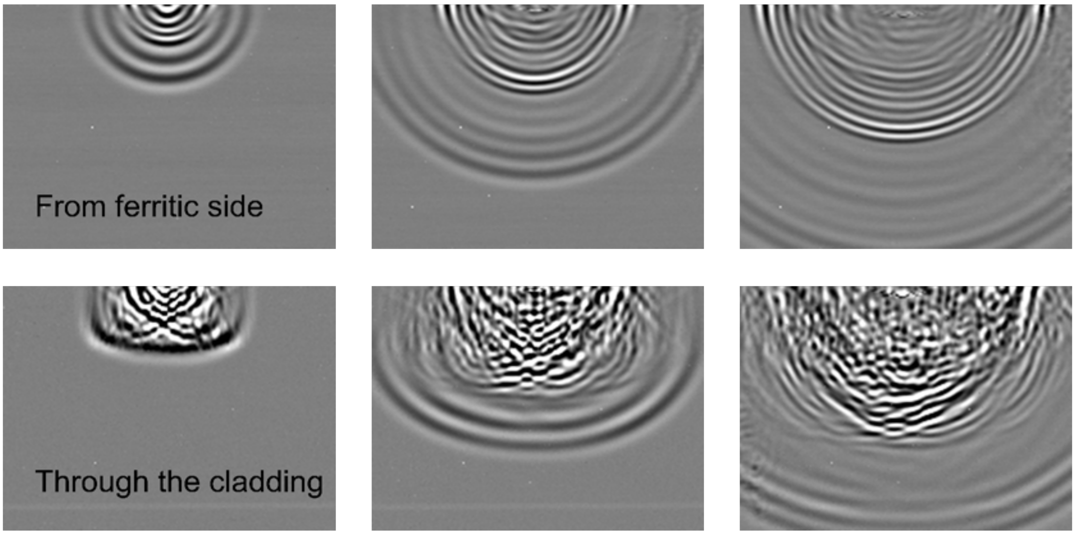


Figure 3. Wave propagation inside the specimen

Ultrasonic Dissimilar Weld Model

Based on photo micrographs and laser vibrometer measurements of wave propagation an ultrasonic weld model was defined.

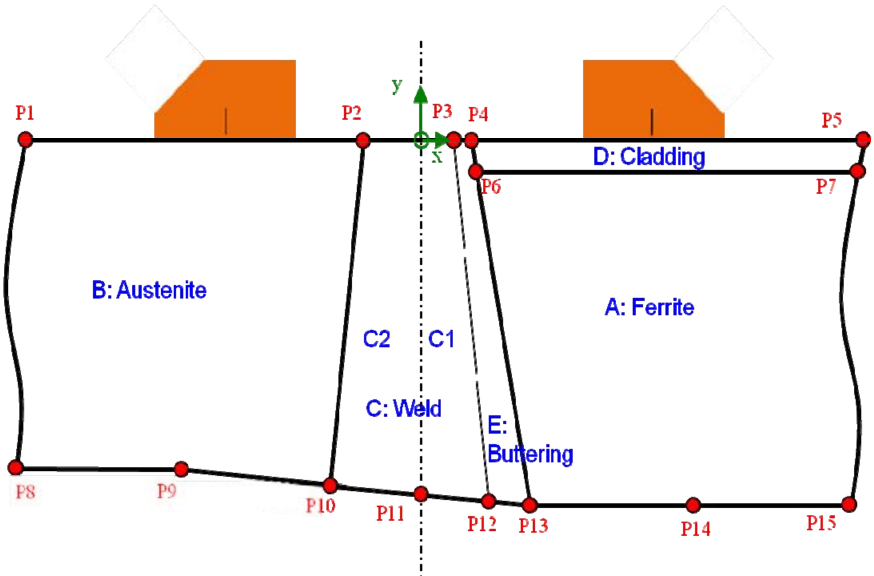


Figure 4. Ultrasonic dissimilar weld model extracted from the photo micrographs and the laser vibrometer measurements of wave propagation.

The model shown in figure 3 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.

For each of the five different regions of the weld A to E, the pressure wave speed in the four main directions 0°, 90°, +45° and –45° respectivrly 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 focal laws of the Phased Array system.

It is interesting that the P(rimary) wave speed in the cladding in 90 degree direction is smaller than in 0 degree and in ±45 degree direction, although the main grain orientation lies in 90 degree direction.

The use of a-priori knowledge of the investigated weld offers totally new perspectives for advanced focal law and imaging algorithms.

Table 1 (right). Measured wave speeds in the weld regions

Weld region	Direction	P wave speed (m/s)
Ferrite (region A)	0° (x)	5882.0
	90° (y)	5917.0
	+45°	5917.0
	-45°	5845.0
Austenite (region B)	0° (x)	5747.0
	90° (y)	5666.0
	+45°	5772.0
	-45°	5798.0
Weld, left part (region C1)	0° (x)	5556.0
	90° (y)	6173.0
	+45°	6070.0
	-45°	6148.0
Weld, right part (region C2)	0° (x)	5848.0
	90° (y)	5550.0
	+45°	6083.0
	-45°	5772.0
Cladding (region D)	0° (x)	5417.0
	90° (y)	5192.0
	+45°	5940.0
	-45°	5940.0
Buffering (region E)	0° (x)	5618.0
	90° (y)	5405.0
	+45°	5992.0
	-45°	6187.0

Testing equipment

Figure 5. The UT Phased Array electronics »PCUS pro Array«

2.25 MHz 5 MHz 10 MHz

Figure 6. »PCUS pro Array« system and ultrasonic transducers used for the measurements in Germany.

Beside the standard A-, B-, and C-Scan functionality the »PCUS pro Array« system also supports extended imaging modes based on a-priori knowledge about the weld under consideration. It was one of the goals of the project to demonstrate such a sophisticated imaging mode.

Possible Imaging Modes of »PCUS pro Array« Platform

Mode 1: Focused Sector Scan

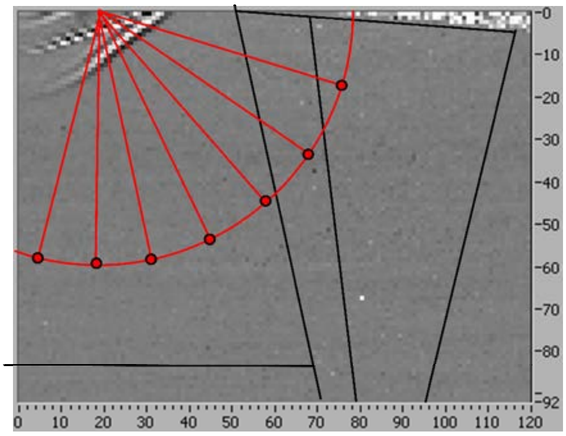


Figure 7. Conventional phased array imaging. The focal depth is fixed and the focal point (red dot) is rotated around the centre of the phased array transducer resulting in a traditional sector scan.

- Isotropic model with single scalar wave speed
- Can be used if no or only little information about the weld is available
- Default setting for manual testing
- Material-dependent wave speed for automatic testing can be used
- Identical or even better performance than conventional PA systems

Mode 2: Sector scan with dynamic depth focusing

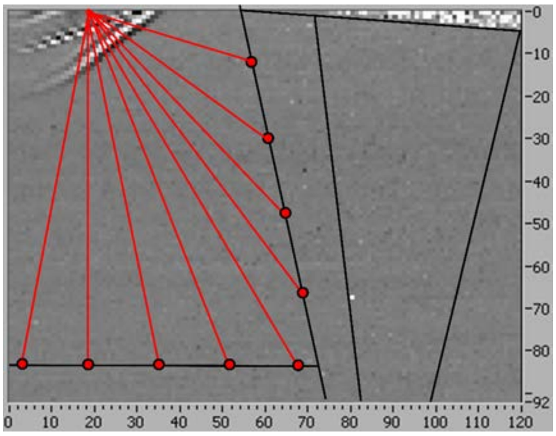


Figure 8. Dynamic depth focusing. The focal depth is dynamically changed during rotation according to the weld geometry and the corresponding wave speed in the different parts of the weld. As a consequence the focal points (red dots) are placed immediately at the interfaces between the different crystallographic regions resulting in a much better sector imaging of interface defects.

- Isotropic/anisotropic model with different weld regions
- Can be used if basic of weld geometry and typical wave speeds is available
- Dynamic depth focusing to the most relevant regions/interfaces
- Much better performance than conventional Phased Array systems
- This mode can only be used with automatic testing

Mode 3: Tomographic Imaging

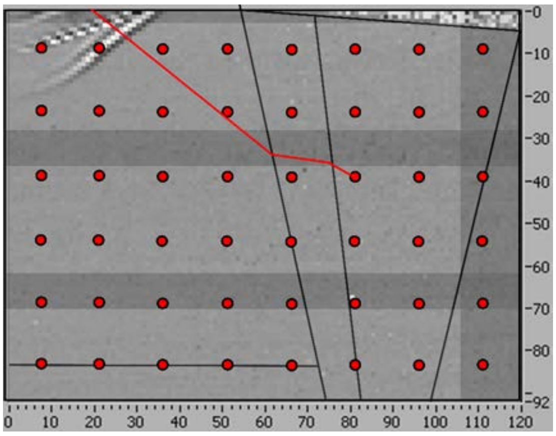


Figure 9. Full focusing approach. The region of interest is discretized by a Cartesian grid. The nodal points of the grid (red circles) are the focal points and are identical with the laser spot positions of the vibrometer scan. By using the time-of-flight information of the laser measurements from each phased array element to each nodal point the ultrasonic energy can be individually focused to each node. As a result the traditional sector scan is replaced by a tomographic image where the focus lies on each single pixel of the image simultaneously. Note that by this procedure also anisotropic effects inside the weld are taken into account as indicated by the red ray trajectory.

- Simultaneous optimal focusing (software-based) to all pixels/voxels
- Best possible performance (tomography)
- Needs full vibrometer scan for each weld type
- In dissimilar welds currently only usable for longitudinal wave testing

Inspection Result

The picture shows a «Mode 3» image where the echo indications above a certain threshold are marked in colour. The wave field distortion caused by the different wave speeds inside the weld has been compensated based on the geometrical and acoustical data. 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), as measured by scanning laser vibrometry.

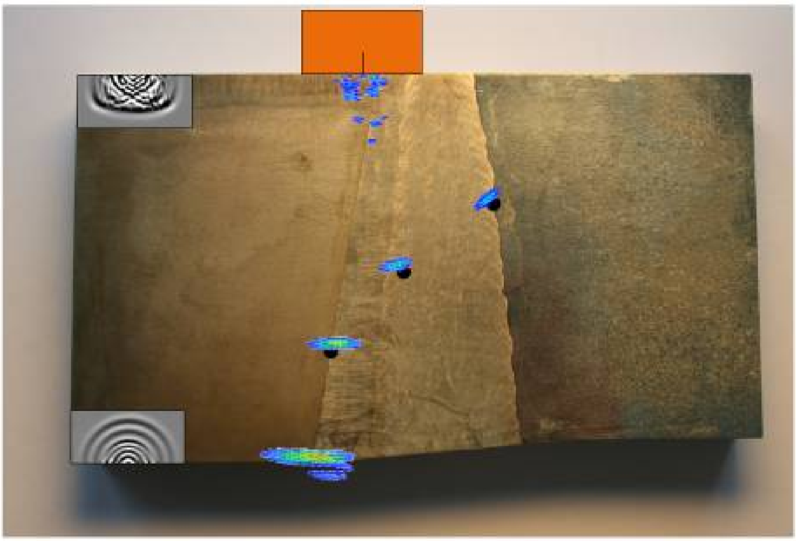


Figure 10. Result of PCUS pro Array system for a dissimilar weld test sample with three drill-holes obtained at 2.25 MHz from the cladding side.

Summary

Dissimilar welds still represent a big challenge for ultrasonic testing due to their heterogeneous and anisotropic microstructure. Model-based approaches try to compensate the disturbing effects by using time-of-flight models of real weld geometries. Previous approaches use image-based information of the grain orientation together with published values of elastic parameters.

Our new approach is based on the direct measurement of the relevant wave speeds of the real welds by using laser vibrometry. This model-based approach was implemented into the »PCUS pro Array« hardware and software platform and was very successfully tested at the small test samples.