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Anne Juengert, Sandra Dugan, Tobias Homann, Steffen Mitzscherling, Jens Prager, Sergey Pudovikov, and Thomas Schwender

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Advanced Ultrasonic Techniques for Nondestructive Testing of Austenitic and Dissimilar Welds in Nuclear Facilities

Anne Juengert[1, a)], Sandra Dugan[1], Tobias Homann[2], Steffen Mitzscherling[2], Jens Prager[2], Sergey Pudovikov[3] and Thomas Schwender[3]

[1] *Materials Testing Institute (MPA) University of Stuttgart. Pfaffenwaldring 32, 70569 Stuttgart, Germany*
[2]*Federal Institute for Materials Research and Testing (BAM), Unter den Eichen 87, 12205 Berlin, Germany*
[3] *Fraunhofer Institute for Nondestructive Testing (IZFP), Campus E3 1 66123 Saarbrucken, Germany*

[a)] Corresponding author: anne.juengert@mpa.uni-stuttgart.de

Abstract. Austenitic stainless steel welds as well as dissimilar metal welds with nickel alloy filler material, used in safety relevant parts of nuclear power plants, still challenge the ultrasonic inspection. The weld material forms large oriented grains that lead, on the one hand, to high sound scattering and, on the other hand, to inhomogeneity and to the acoustic anisotropy of the weld structure. The ultrasonic wave fronts do not propagate linearly, as in ferritic weld joints, but along the curves, which depend on the specific grain structure of the weld. Due to the influence of these phenomena, it is difficult to analyze the inspection results and to classify the ultrasonic indications, which could be both from the weld geometry and from the material defects. A correct flaw sizing is not possible. In an ongoing research project, different techniques to improve the reliability of ultrasonic testing at these kinds of welds are investigated. In a first step (in the previous research project) two ultrasonic inspection techniques were developed and validated on plane test specimens with artificial and realistic flaws. In the ongoing project, these techniques are applied to circumferential pipe welds with longitudinal and transverse flaws. The technique developed at the Federal Institute for Materials Research and Testing (BAM) in Germany uses a combination of ray tracing and synthetic aperture focusing technique (SAFT). To investigate the unknown grain structure, the velocity distribution of weld-transmitting ultrasound waves is measured and used to model the weld by ray tracing. The second technique, developed at the Fraunhofer Institute for Nondestructive Testing (IZFP) in Germany, uses Sampling Phased Array (Full Matrix Capture) combined with the reverse phase matching (RPM) and the gradient elastic constant descent algorithm (GECDM). This inspection method is able to estimate the elastic constants of the columnar grains in the weld and offers an improvement of the reliability of ultrasonic testing through the correction of the sound field distortion. The unknown inhomogeneity and anisotropy are investigated using a reference indication and the special optimization algorithm. Both reconstruction techniques give quantitative inspection results and allow the defect sizing. They have been compared to conventional ultrasonic testing with techniques that are state of the art for components in nuclear power plants. The improvement will be quantified by the comparison of the probability of detection (POD) of each technique.

ULTRASONIC TESTING AT AUSTENITIC AND DISSIMILAR WELDS

Austenitic stainless steel welds and dissimilar metal welds are common in nuclear facilities. Ultrasonic testing at these kinds of welds is difficult, as coarse columnar grains in the welds lead to acoustic anisotropy and inhomogeneity within the weld material. The detection and localization of flaws is difficult due to sound scattering and curved sound propagation paths through the weld. However, reconstruction methods like the synthetic aperture focusing technique (SAFT) or the total focusing method (TFM) in combination with full matrix capture (FMC) are based on straight ray paths. For the use at austenitic and dissimilar metal welds these techniques have to be adapted to the special conditions in the weld material. In general, the grain structure in the weld has to be known, but up do now it is only accessible by destructive testing.

During the last ten years a lot of research was done to improve ultrasonic testing (UT) and imaging of austenitic and dissimilar steel welds in the framework of nuclear safety research. Advanced techniques were developed at plane test specimens with different kinds of flaws. In addition to notches of various sizes, orientations and tilts,

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intergranular stress corrosion cracks, and fatigue cracks were investigated in austenitic base and weld materials. Advanced UT and reliability of UT was investigated in different research projects. [1,2,3,4]

The results from previous projects at plane test specimens are adapted to more realistic structures in an ongoing research project. The focus is on techniques that include the investigation of the unknown grain structure of the welds and the signal reconstruction to improve the signal-to-noise-ratio. These advanced reconstruction techniques are compared to conventional ultrasonic inspection techniques that are commonly used in nuclear facilities.

Test Specimens and Setup

In previous projects the advanced reconstruction techniques improved the localization and sizing of known cracks in plane test specimens. Localization accuracy and signal-to-noise-ratio were significantly better. The aim of the ongoing project is to apply the advanced techniques to more realistic test specimens with unknown grain structure in the weld. A set of pipe welds with austenitic stainless steel and dissimilar metal welds were equipped with notches of different depths (15, 10, 7, 5, 2, 1.5 mm). The sizes and localization of the notches were chosen according to the German Nuclear Safety Standards [5]. Notches across the weld and notches along the weld were used. The notches along the weld were placed between the weld root and the buffering. The notches across the weld were placed completely in the weld/buffering material. A scheme of the test specimens is shown in Fig. 1.

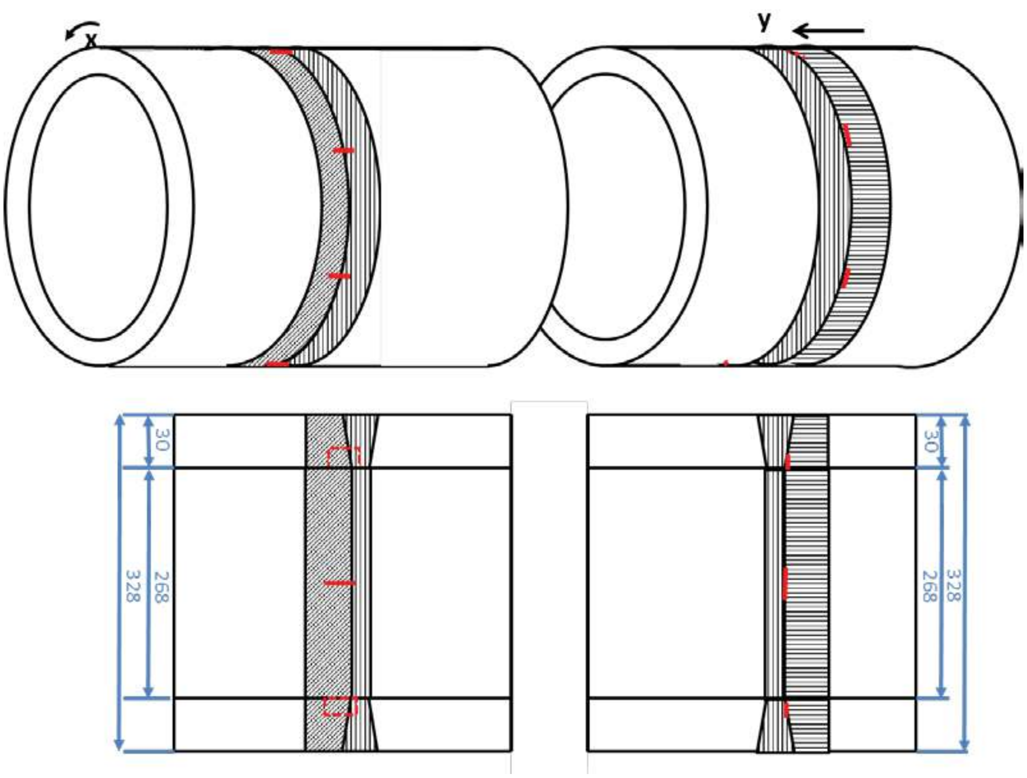


FIGURE 1. Scheme of the test specimens with notches across (left) and along (right) the weld.

Within the research project, advanced UT techniques are compared to standard UT techniques using single and dual element probes with a fixed angle. The probe positions were chosen according to the German Nuclear Safety Standards [5]. Additionally, a dual matrix array (DMA) probe using low frequency longitudinal waves was applied. The matrix array probe allows a focusing of the sound beam in two directions. In the dual matrix array probe one matrix array is used as emitter and the other as receiver of the ultrasound beam. By sensible modulation of the sound beam a focusing in the flaw area can be achieved. The probes used for the standard UT are listed in Table 1.

TABLE 1. Ultrasonic transducers used for reference tests

Transducer	Name	Type	Wave type	Frequency [MHz]
Dual Matrix Array	1.5DMA	Transmit-Receive	Longitudinal wave	1.5
Dual Element	45 DE	Transmit-Receive	Shear Wave	1.0
Single Element	45 SE	Standard	Shear Wave	1.0

IN-SITU PARAMETER DETERMINATION OF WELD MATERIAL USING RT-SAFT

As prerequisite for applying the RT-SAFT algorithm to unknown welds, the weld parameters like grain orientation and elastic constants must be determined. An inverse method is applied to determine these parameters by analyzing the influence of the anisotropic acoustical weld properties on the wave propagation of an ultrasonic sound field passing the weld. The developed inverse method assumes that the grain orientation can be described using the geometrical model suggested by Ogilvy and modified by Höhne et al. [4, 6]. Using this model, the grain orientation is described by a set of geometry values. The forward model of the method uses a boundary value ray tracing based on ordinary differential equations (ODE). The formulation as an ODE-boundary value problem allows to incorporate the varying elastic parameters. Details of the boundary ray tracing algorithm are described in [7]. The elastic constants are assumed to be invariant; however, the inhomogeneous variation of grain orientation leads to a rotation of the elasticity matrix. Thus, one set of geometry parameters and a constant elasticity matrix completely describes the weld. The inverse method recursively approaches the model parameter, beginning with empiric or literature start values, to the realistic values by minimizing the deviation between output of the simulation and the measured sound field.

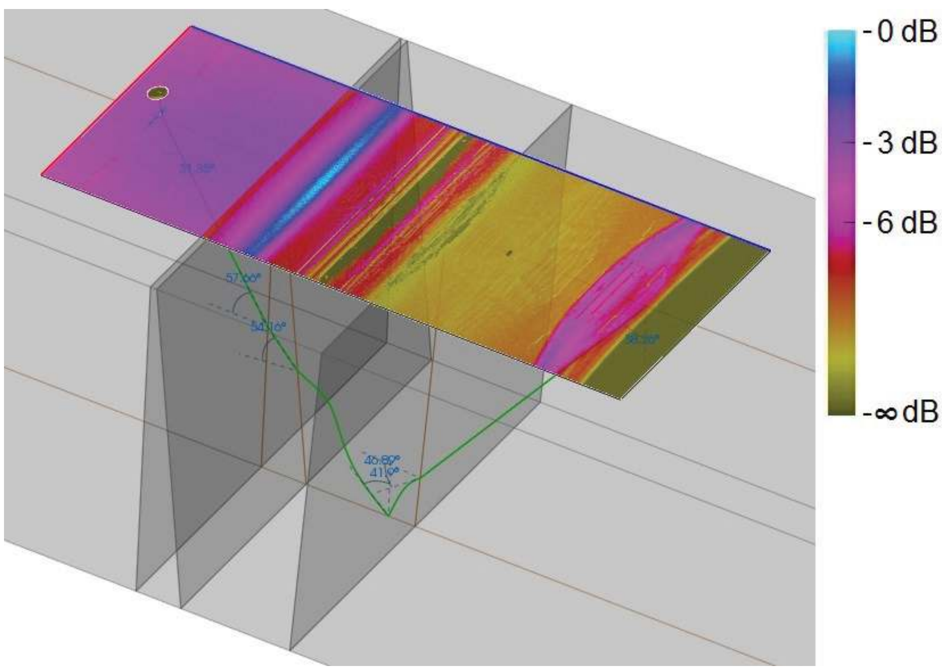


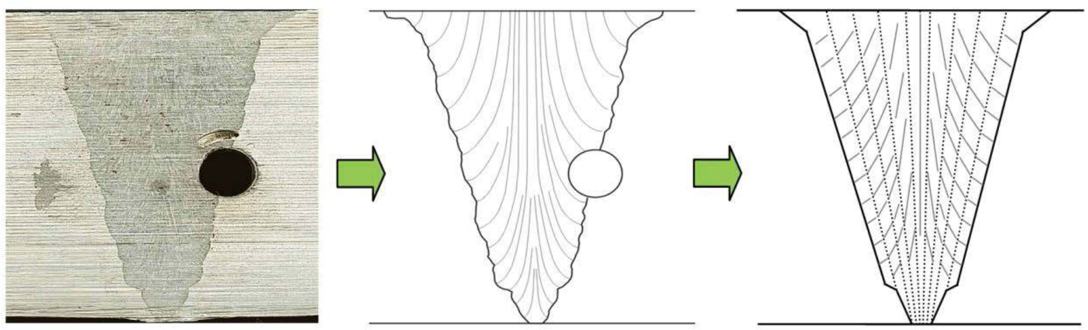
FIGURE 2. CIVA-simulation of a sound field propagating through a weld. The color code shows the surface velocity.

The experimental setup is comprised of a piezoelectric wedge transducer with a center frequency of 1 MHz for exciting a longitudinal wavefield and a scanning Laser Doppler vibrometer to measure the sound field. The vibrometer is combined with a mirror scanning system to scan the sound field in a range of 50 x 8 mm². A special signal processing for the Laser system was developed to analyze both the normal and the in-plane component of the vibrating surface [8]. The use of both vibration components as input data for the inverse method increases the sensitivity of the method since influences on longitudinal and mode-converted transversal wave components are included at any scan position. Transducer and Laser system are applied on either side of the weld on the outer surface of the pipe.

GRADIENT ELASTIC CONSTANT DESCENT METHOD FOR DETERMINATION OF ACOUSTICAL PROPERTIES

The phenomena of non-linear sound propagation through an anisotropic inhomogeneous structure of an austenitic weld makes possible the correct TFM reconstruction of the weld only under the condition of the exact a-priori information about its acoustical properties. If the anisotropic and inhomogeneity parameters are known, the sound propagation can be simulated and propagation time can be calculated, so that the image reconstruction using the Reverse Phase Matching (RPM) can be done.

The acoustical model of the weld is used for the simulation of the sound propagation process and determination of propagation time between ultrasonic transmitter/receiver and each point of the object to be reconstructed. This model describes the weld structure as a set of differently oriented columnar crystals and their acoustic properties (stiffness matrix). In the Fig. 3 an example of such model is presented. After the acoustical model of the weld is determined, the sound propagation through it can be simulated, the propagation time can be calculated and the RPM reconstruction can be done.



Micrograph image of austenitic weld with artificial defect.

Column crystal distribution taken from the micrograph.

Weld model. Here the weld geometry and orientation of the crystals are determined. Acoustical properties of crystals are a part of the model as well.

FIGURE 3. Determination of the model of an austenitic weld.

Since the TFM reconstruction is based on the principle of a coherent summation, the most accurate structural and acoustic model of an anisotropic inhomogeneous austenitic weld is needed. The deviation of model parameters from the real weld properties leads to an incorrect determination of the propagation time. As a result, the time signals from each array element are summated incorrectly, the signal-to-noise ratio reduces and the reconstruction artifacts increase. On the other hand, a real inspection is not possible to determine the structure and acoustical parameters of the weld to be tested. They can be assumed from the information about the joint geometry, parameters of the welding process and materials that have been used, but such an approximated anisotropy and inhomogeneity model is never exact.

To increase the accuracy of the acoustical model of an anisotropic and inhomogeneous object – such as an austenitic weld – and to improve the RPM reconstruction, the Gradient Elastic Constant Descent Method (GECDM) was developed at Fraunhofer Institute for Nondestructive Testing [9]. This algorithm does the optimization of the multi-parametric function f^{DS}, which describes the reconstruction quality based on the parameters of the reconstructed indication from a known reflector. These are the indication amplitude, signal-to-noise ratio (SNR) and the deviation of the position of the reconstructed indication from the real position of the known reflector. The arguments of the f^{DS} function are acoustical parameters a_1-a_k of the column crystals (i.e., the stiffness matrix) and parameters b_1-b_m , which describe the crystal distribution and orientation:

$$f^{DS} = f(a_1 \quad a_2 \quad \ldots \quad a_k \quad b_1 \quad b_2 \quad \ldots \quad b_m) \tag{1}$$

The goal of the iterative GECDM algorithms is the optimization of the f^{DS} function and the determination of the set of parameters a and b at which the function reaches its maximum value – the known reflector is reconstructed with the maximal amplitude and SNR and has zero-deviation from its real position. The Nealder-Mead-Method is used for the optimization of the multi-argument function [10].

The GECDM with artificial defect, which serves as a known reflector for the optimization procedure, has been validated in the previous research project of the German Society for Plant and Reactor Safety (GRS) [11]. For the current project the GECDM was advanced and developed further, so that no reference defects in the object is needed [12]. As a reference indication serves the signal from the acoustical transmitter T, which is received by array R with N elements placed on the other side of the weld, as shown in Fig. 4. The ultrasonic wave from the transmitter propagates through the anisotropic inhomogeneous weld structure, reflects from the back wall and comes to receiver R_1-R_N with different times.

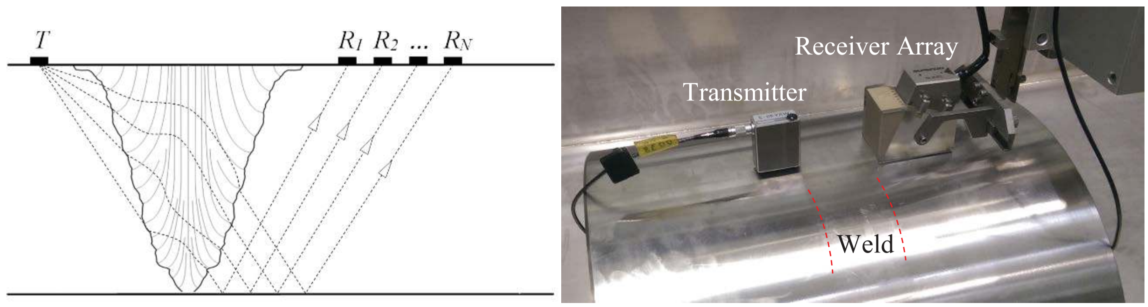


FIGURE 4. Realization of reference-reflector-free GECDM.

The received signals are used for RPM reconstruction and the reconstructed image is optimized according the GECDM principle. If the f^{DS} function is optimized, the indication from the transmitter is presented at the right position and has the maximum amplitude and signal-to-noise ratio. If all the anisotropic and inhomogeneity parameters are determined correctly, the indication from the back wall has to be at the right depth as well (Fig. 5).

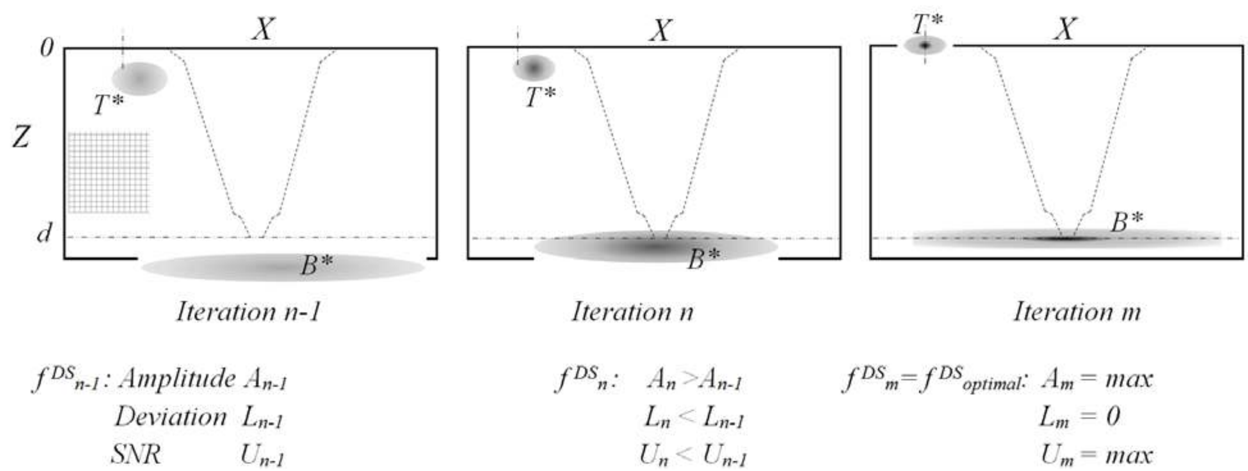


FIGURE 5. Optimization of the GECDM function f^{DS} in m iterations. Shown here are T^* and B^* the reconstructed indications from transmitter and back wall respectively, and d is the wall thickness. X and Z are coordinates.

By determination of elastic properties of columnar crystals with the structure parameters, predefined from the micrograph image, the reference-reflector-free GECDM shows good correlation with the results from the previous project, where a reference reflector was used. The ability of the new algorithm to determine the structure as well has not been proved yet and will be tested.

DETECTION OF NOTCHES ACROSS THE WELD USING RT-SAFT COMPARED TO STANDARD UT

The RT-SAFT technique was used at test specimens with notches across the weld. In Fig. 6 the results of UT using a 45° dual element probe with 1 MHz is compared to the results from UT combined with RT-SAFT. The deepest notch (15 mm) was located at 120°, the smallest notch (1.5 mm) at 180° in reference to the zero position marked on the pipe. In the top image, the results from the RT-SAFT are shown. The reflections of all 6 notches are clearly visible. The signal to noise ratio is high. The reflections appear as thin lines, as the SAFT algorithms leads to a focusing of the indications and the notches are small compared to the pipe circumference.

In the bottom image, the results of conventional ultrasound are shown. The reflections of the deeper notches at 0°, 60° and 120° are clearly visible. Also the 5 mm notch at 300° gives a clear indication. Due to the lower signal-to-noise-ratio, the small notches (2 / 1.5 mm) cannot be resolved with the standard UT. The RT-SAFT improves the quality of ultrasonic images significantly compared to single angle beam probes.

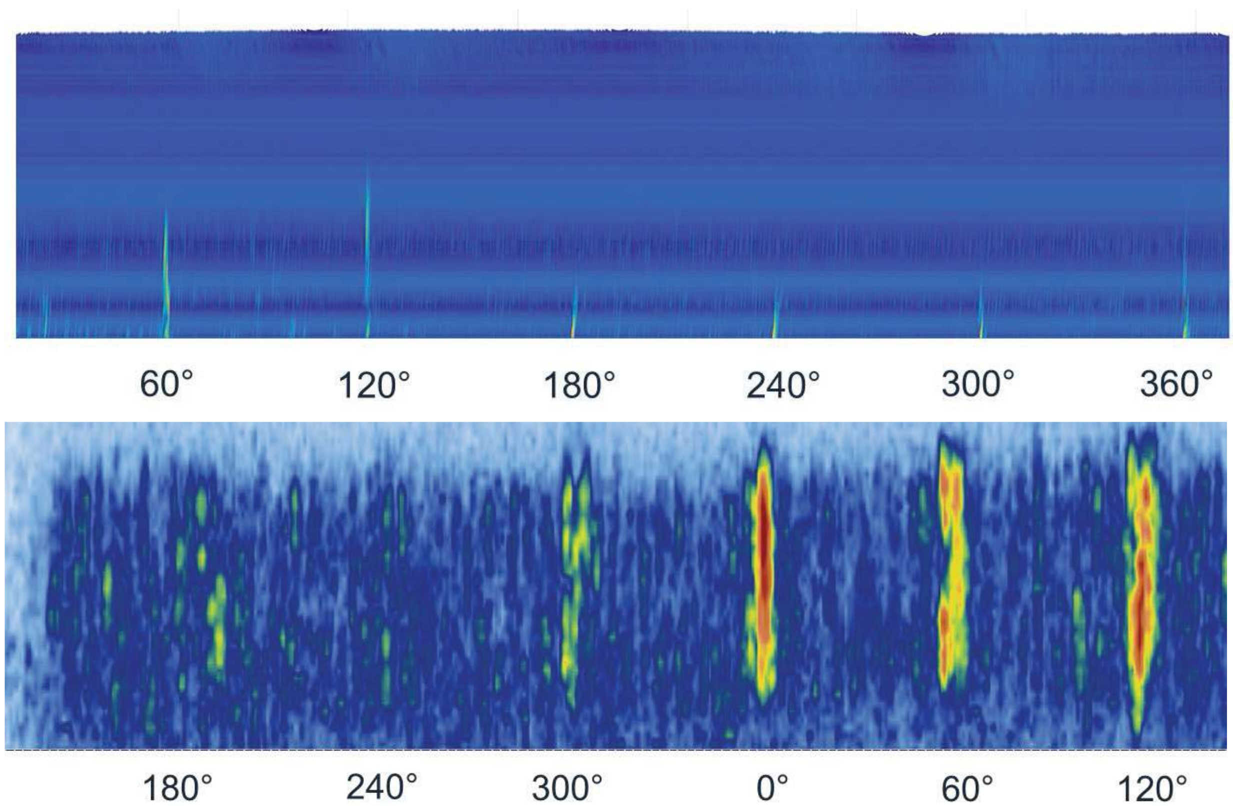


FIGURE 6. Top: RT-SAFT results; bottom: UT testing with 45° dual element probe.

As previously described, the use of dual matrix array (DMA) probes improves UT at austenitic and dissimilar welds. Results from measurements with 1.5 MHz DMA probes using longitudinal waves are compared to the RT-SAFT results in Fig. 7.

The indications of the notches are clearly visible in the B-scans of the pipe weld. Even crack tip indications can be identified for both the RT-SAFT results and the DMA probe measurements. A quantification of the differences will be the next step of the project.

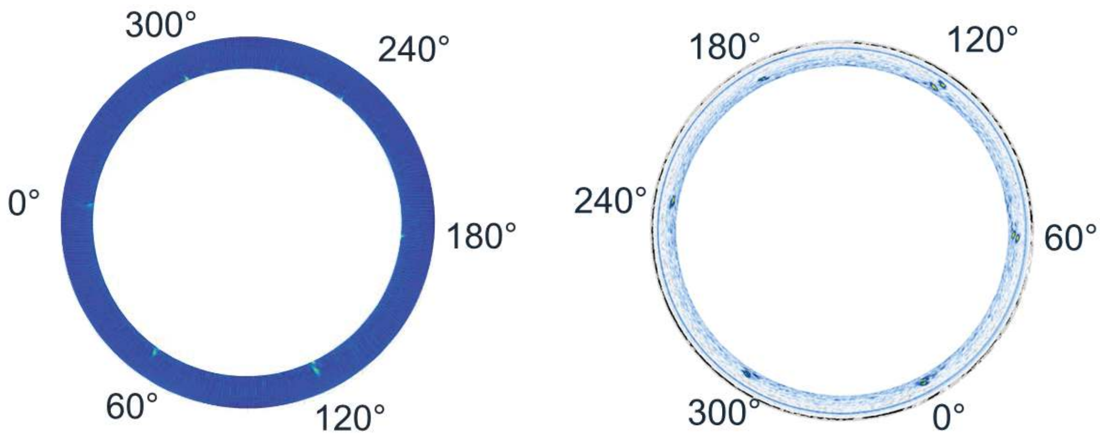


FIGURE 7. Left: results from RT-SAFT. Right: results of UT using dual matrix array probe.

DETECTION OF NOTCHES ALONG THE WELD USING GECDM COMPARED TO STANDARD UT

The GECDM technique was applied to test specimens with notches along the weld. For the data acquisition a 4-axes (3 linear axes + 1 rotation axis) scanner, a FMC capable ultrasonic electronic and a linear array 5 MHz, 16 elements was used. For the angle insonification of the weld a plexiglas wedge (60˚ refraction angle of the longitudinal wave in steel) was applied. The wedge was adjusted to the specimen curvature.

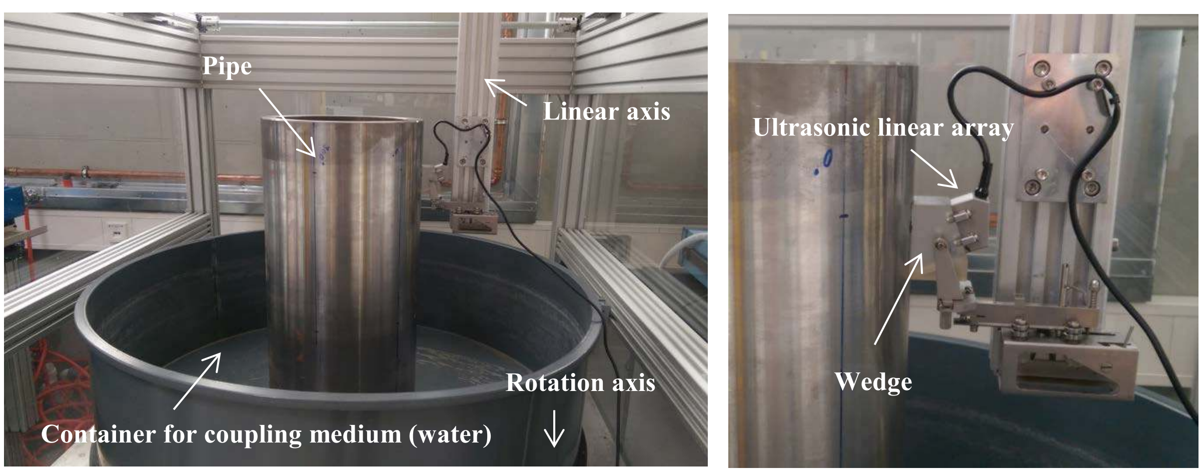
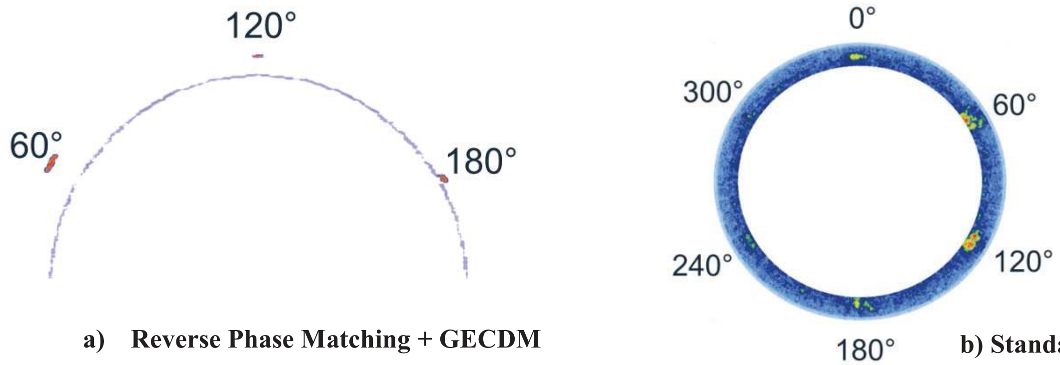


FIGURE 8. Inspection setup.

In Fig. 9a) the GECDM shows results for the notches deeper than 7 mm. The notches can be identified and sized with a good signal-to-noise-ratio. The results for the smaller notches are not yet available. In Fig. 9b), the results with standard UT using a 45° dual element probe are shown. The deep notches (15/10/7 mm) could be detected with a good signal-to-noise-ratio, too.



a) Reverse Phase Matching + GECDM **b) Standard UT**

FIGURE 9. Inspection result of the test specimen VGB 7.

The smaller notches are more difficult to detect and size. The comparison for the smaller notches will be done in the next step, when all data will be available. It is assumed that the GEDCM will increase the probability of detection for small flaws due to the better signal-to-noise-ratio. By realization of the GECDM optimization procedure, the structure of the weld joint was assumed, and not determined using GECDM. Only the elastic properties of the columnar crystals were adjusted. The difference between the assumed model of inhomogeneity and the real weld structure can be the reason why not all defects were detected. The ability of the reference-reflector-free GECDM to determine the structure will be proved in the next project step. Nevertheless, the Reverse Phase Matching reconstruction in combination with Gradient Elastic Constant Descent Method allows detection, correct sizing and imaging of defects larger than 7 mm depth (Fig. 10).

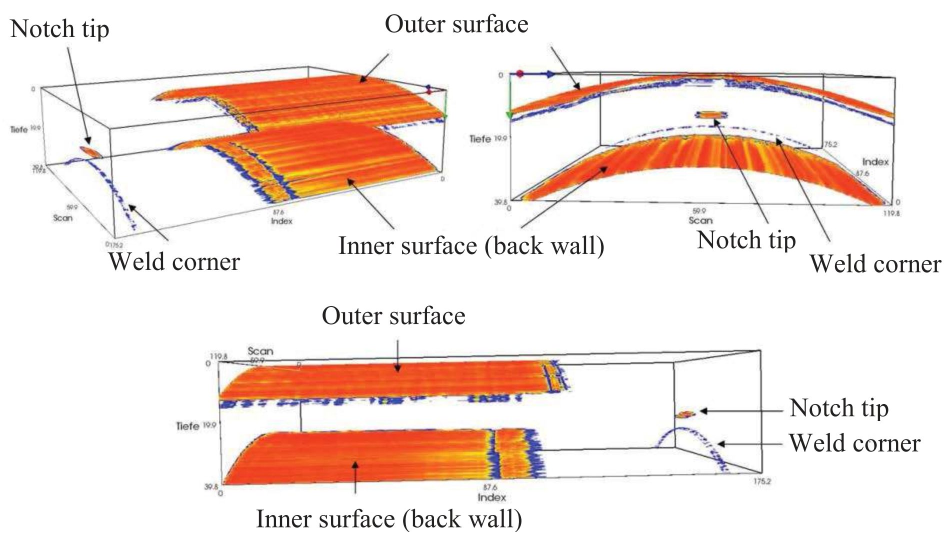


FIGURE 10. 3D imaging of the VGB 7 segment, inspected with FMC+RPM+GECDM.

DISCUSSION

Two different techniques to improve ultrasonic testing at austenitic and dissimilar steel welds were applied to test specimens with notches of different depths along and across the welds. Both techniques improved the signal-to-noise-ratios compared to standard UT with fixed angle beam transducers. The smaller notches, especially, could be detected using the advanced techniques.

The use of dual matrix array probes also improves the signal-to-noise-ratio and detection of the small notches. However, due to the anisotropy in the weld, it is expected that sizing and localization of the notches will be less accurate with the standard UT, even with the dual matrix array probes.

The next steps of the project include the quantification of signal-to-noise-ratios of the different techniques. The quality of localization and sizing of the notches will also be compared for the standard and the advanced techniques. The results of the measurements done within the research project will also be included in POD calculations that are done in a parallel running research project at similar test specimens. [13].

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