Ultrasonic inspectability of austenitic stainless steel and dissimilar metal weld joints

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Abstract

Since their invention in 1912, austenitic stainless steel materials are widely used in a variety of industry sectors. In particular, austenitic stainless steel material is qualified to meet the design criteria of high quality, safety related applications, for example, the primary loop of the most of the nuclear power plants in the world, due to high durability and corrosion resistance.

Certain operating conditions may cause a range of changes in the integrity of the component, and therefore require nondestructive testing at reasonable intervals. These in-service inspections are often performed using ultrasonic techniques, in particular when cracking is of specific concern. However, the coarse, dendritic grain structure of the weld material, formed during the welding process, is extreme and unpredictably anisotropic. Such structure is no longer direction-independent to the ultrasonic wave propagation; therefore, the ultrasonic beam deflects and redirects and the wave front becomes distorted. Thus, the use of conventional ultrasonic testing techniques using fixed beam angles is very limited and the application of ultrasonic Phased Array techniques becomes desirable.

The “Sampling Phased Array” technique, invented and developed by Fraunhofer IZFP, allows the acquisition of time signals (A-scans) for each individual transducer element of the array along with image reconstruction techniques using “SynFoc” algorithms. The reconstruction considers the sound propagation from each image pixel to the individual sensor element. For anisotropic media, where the sound beam is deflected and the sound path is not known a-priory, we implement a new phase adjustment called “Reverse Phase Matching” technique. This algorithm permits the acquisition of phase-corrected A-scans that represent the actual sound propagation in the anisotropic structure; this technique can be utilized for image reconstruction.

1 Introduction

Ultrasonic inspection is a mandatory part of safety and quality related regulations and specifications for pressurized components and their welded joints. Its application requires specific material and geometric features for reliable detection and evaluation of defects and in particular of cracks, which are set down in national and international codes and standards [1], [2], [3]. Fundamental is the assumption of acoustic isotropy of the material for regular sound propagation to ensure sensitivity and full coverage of inspection. The material is acoustically anisotropic when sound velocity depends on the propagation direction [4]. During welding of austenitic material columnar crystalline structure of weld material cannot be avoided until today because it cannot be transformed by recrystallization into a fine grain isotropic one [5]. Thus, due to the acoustic anisotropy of the crystal itself weld material of austenitic joints is anisotropic, too. Because of the violation of this fundamental requirement for reliable defect detection by ultrasound alternative inspection techniques like X-ray inspection have been used firstly.

However, progress in ultrasonic testing technique made in the last 25 years, the development of transducers with sound fields optimized for defect detection in specific areas of concern, the automation of inspection for minimizing human factor and new smart ultrasonic techniques like phased arrays and synthetic aperture focusing techniques, facilitated the qualification of ultrasonic inspection procedures within certain limits [6], [7] in view of better detection of planar flaws or cracks. Nevertheless, ultrasonic inspection of austenitic or dissimilar welds cannot be considered as a reliable standard inspection that meets the general requirements on ultrasonic testing. We have presented already the basic principle of ‘reverse phase matching’ for taking account sound propagation in anisotropic materials that will help develop inspection techniques and procedures, which satisfy the general standards of ultrasonic inspection [8], [9]. This paper informs about progress we made using sampling phased array [10], [11] and ‘SynFoc’ [12] image reconstruction technique.

2 Principle of ‘reverse phase matching’

For better understanding of ‘reverse phase matching’ we may imagine one point scatter located at image pixel (x,y). This pixel is the source of an elementary acoustic wave transmitting its energy homogeneously into all directions. At the surface we distribute *n* acoustic wave receivers with aperture dimensions less than half the wavelength. They measure A–scans with phase differences depending on position. When we apply the measured or computed phase differences in case that these receiver elements are now transmitter elements we focus the resulting sound field on the image pixel (x,y). We have called this well known principle ‘reverse phase matching’ (Fig. 1a).

For isotropic material, where sound propagates straight [4], the computation of phase differences is trivial but may support image or A-scan reconstruction. In case of anisotropic material we have to simulate sound propagation applying elasto-dynamic codes [13]. Thus, we may receive phase differences, which applied focus the sound field on the image pixel (Fig. 1b) and solve the reverse situation.

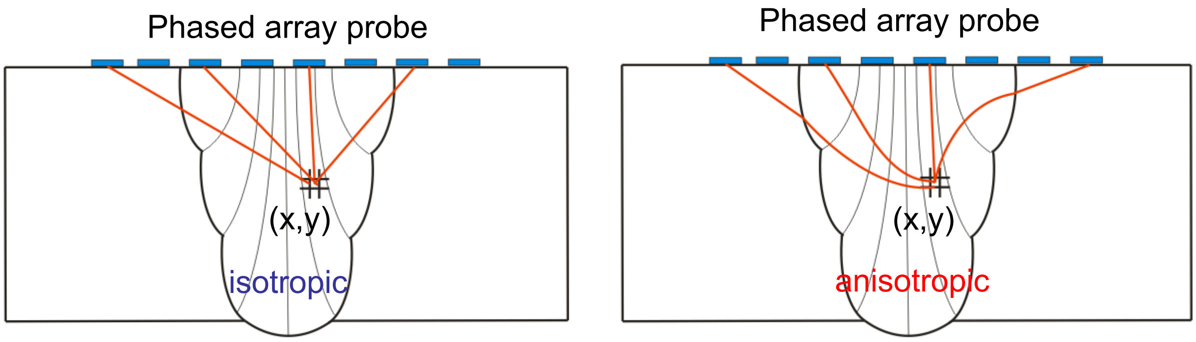
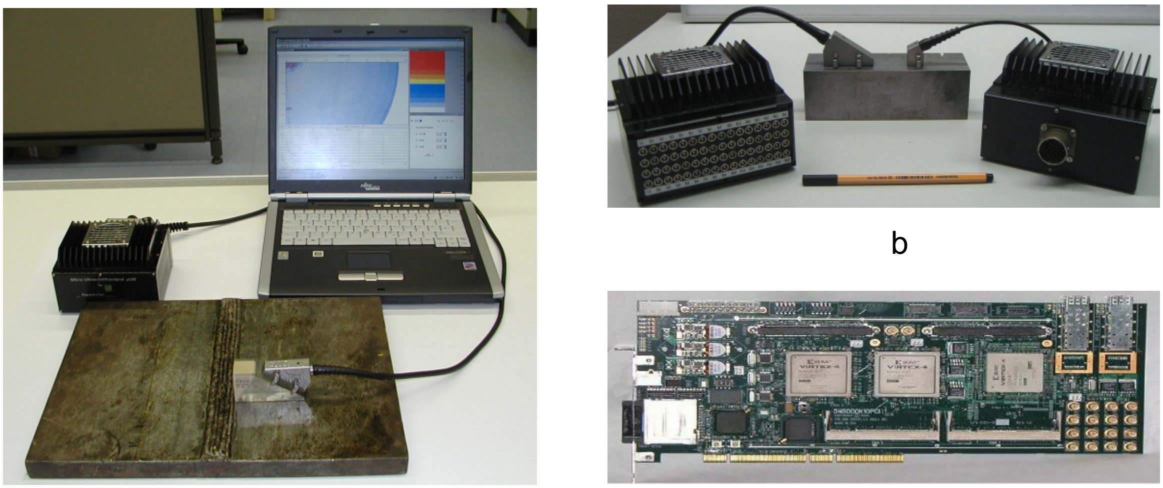


Figure 1: Reverse Phase Matching for isotropic ferritic weld joint (a) and anisotropic austenitic weld joint (b)

For practicable inspections we have to simulate sound propagation at reasonable high repetition rates according to the ultrasonic pulse frequency and for real-time image reconstruction (sector scan, A-, B- and C-images). This demands for optimized algorithms, data management and hardware, which we may summarize as ‘efficient computing’ [14].

3 Sampling phased array technology

The described principle of phase matching can be applied only when the time signals or A-scans of all aperture elements of the sensor array can be measured and processed applying the SynFoc algorithm for sector or A-scan image reconstruction [11]. We have developed appropriate multi-channel ultrasonic microelectronics µUSE, fast optical data links and an efficient computing module, which form the basic sampling phased array equipment (Fig. 2).



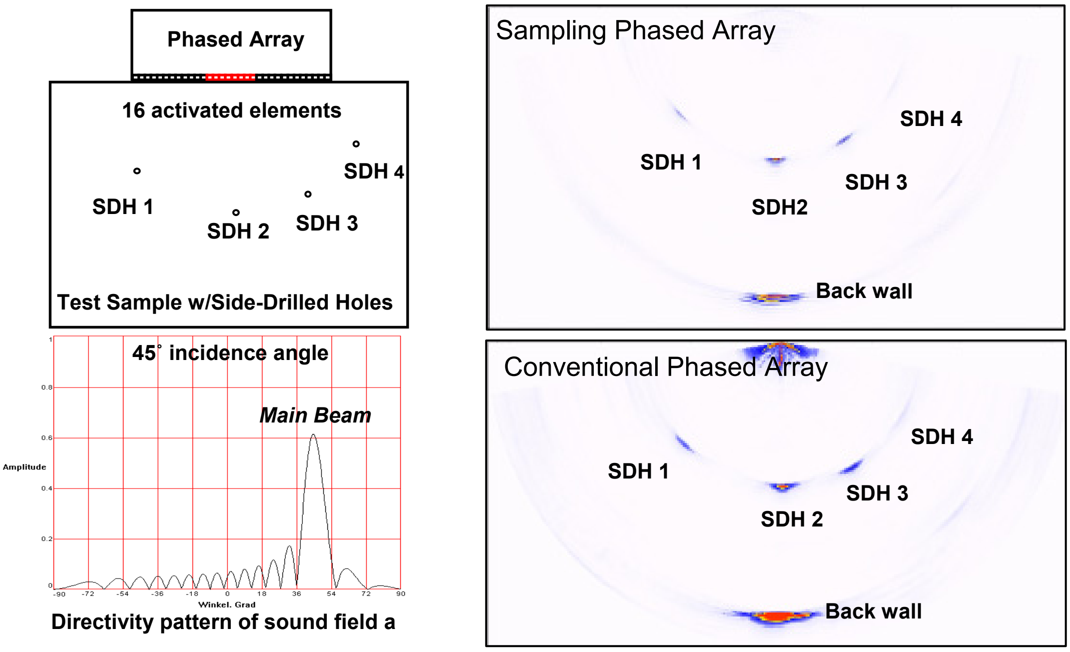
b

a

c

Figure 2: Sampling Phased Array Equipment (a), 16- and 64-channel µUSE microelectronic (b), FPGA-board with fast optical interface (c)

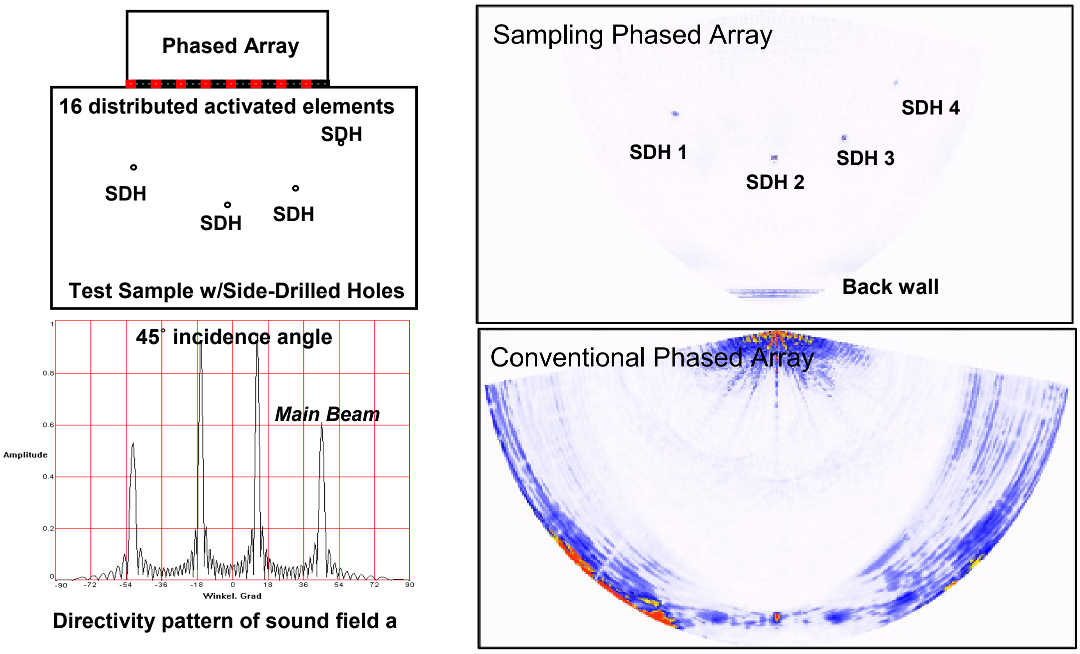
Some features of Sampling Phased Array and SynFoc Software may be emphasized in the context of reverse phase matching technique. The reconstructed image comprises all angle of incidence. A-scans with arbitrary angles of incidence may be computed. The sound field is focused synthetically on each image pixel in the near field of the synthetic aperture formed by the array elements. The element pitch of the array may be larger than several wavelengths without reconstructing image artifacts. Thus, we may 'distribute' the array elements, which form a larger synthetic aperture. As Fig. 3 and 4 indicate we will get better focusing in a larger inspection volume when distributing the sensor elements [15].



Directivity pattern of sound field a

Conventional Phased Array operation mode

Figure 3: Image reconstruction of ultrasonic signals, wavelength 1.5 mm, element pitch 0.6 mm



Directivity pattern of sound field a

Conventional Phased Array operation mode

Figure 4: Image reconstruction of ultrasonic signals with Distributed Aperture, wavelength 1.5 mm, element pitch 2.4 mm,

4 Reverse phase matching experiments

We have investigated the viability of reverse phase matching, the needed technical parameters of measurement and computing equipment to establish criteria for best simulation algorithm fit for purpose, for anisotropy mapping and design of sensor array including standard parameters of ultrasonic testing (frequency, bandwidth, sound field characteristics of the individual array elements). Objective of the related reverse phase matching experiments is a generic basic procedure, which facilitates the optimum choice between accuracy of measurement and reasonable inspection performance. This research is still going on and is depending on the anisotropy of material structure as well as on standard parameters of ultrasonic inspection that may pose some limitations (sound attenuation, component geometry, surface or coupling conditions).

We distinguish different types of anisotropy – homogeneous and inhomogeneous anisotropy and even more complex anisotropic structures, which may change with the position or are not sufficiently known to establish models for simulation of ultrasound propagation.

4.1 Homogeneous anisotropic media

We consider anisotropic media homogeneous when the anisotropy will not change locally. Good examples of homogeneous anisotropic media are for example fiber reinforced materials as shown in Fig. 5.

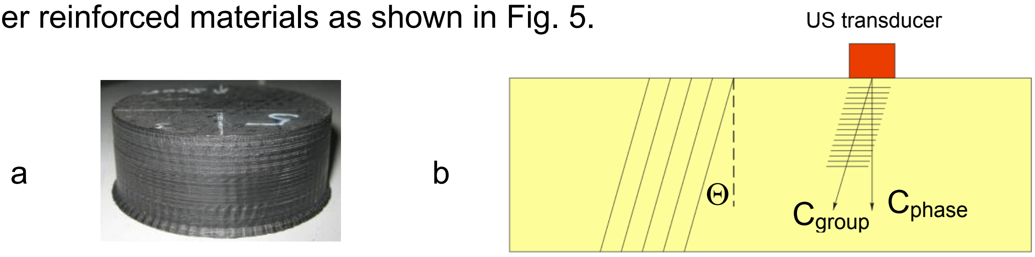


Figure 5: Carbon fiber test specimen (a), sound propagation in the homogeneous anisotropic media (b)

Sound velocity in homogeneous anisotropic media, like carbon fiber material, changes only with propagation direction. Group and phase velocity have different values and directions. Nevertheless, when the acoustic properties of media (stiffness matrix) and the fiber orientation (Θ) are known, it is easy to calculate the sound velocity for any direction.

Due to the significantly higher difference of sound velocities in the matrix and in the fiber material compared with the anisotropy parameters of austenitic weld material the distortion of regular wave propagation is also considerably higher. Fig. 6 shows simulated wave propagation in homogeneous carbon fiber material.

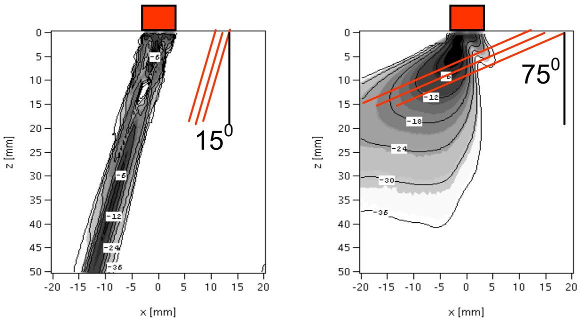
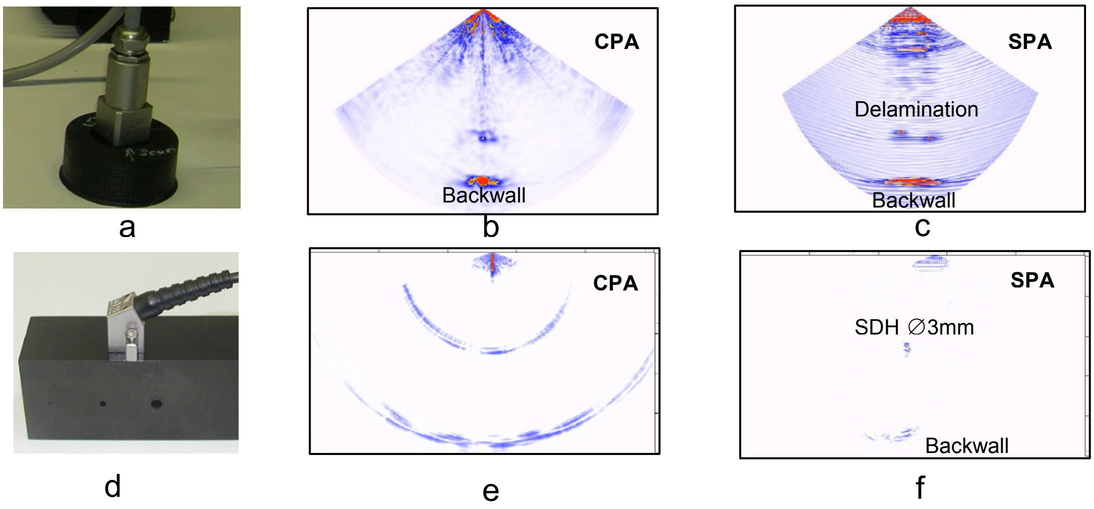


Figure 6: Simulation of ultrasound wave propagation in a homogeneous anisotropic media (carbon fiber composite media with different fiber orientation) using Point Source Synthesis [16]

This type of anisotropy is well investigated and understood and we could get good sector scan images with improved sensitivity for defect detection and precise positioning of reflectors. We investigated two types of specimens with different alignment of fibers. In Fig. 7a sound propagates perpendicular, in Fig. 7d almost parallel to the fiber orientation.



a b c

d e f

Figure 7: Sector Scan reconstructions of carbon fiber experiments:

a) Test sample Nr.1 with probe position b) conventional phased array c) sampling phased array with reverse phase matching

d) Test sample Nr.2 with probe position e) conventional phased array f) sampling phased array with reverse phase matching

These experiments helped to understand that even significantly higher changes of sound velocity than those expected in austenitic weld material can be processed by reverse phase matching and that we can obtain sufficient accuracy in areas of homogeneous acoustic anisotropy, which we will call anisotropy domains. Next experiments will prove the idea that we can identify structural changes monitoring for example back wall reflection. In those areas the anisotropy model used for simulation of sound propagation will not be correct and the resulting phase matching procedure will fail to reconstruct back wall signals. By changing the anisotropy model iteratively we may identify the correct one when back wall can be seen again. Thus, we hope to apply reverse phase matching principles also for structure analysis and for inhomogeneous anisotropic materials.

4.2 Inhomogeneous anisotropic media

Unfortunately, austenitic weld material is inhomogeneous anisotropic. Moreover, defects are found more likely at position with major changes of assumed anisotropy, for example at repair areas or welding discontinuities. Typical structures with columnar grains can be seen in Fig. 8.

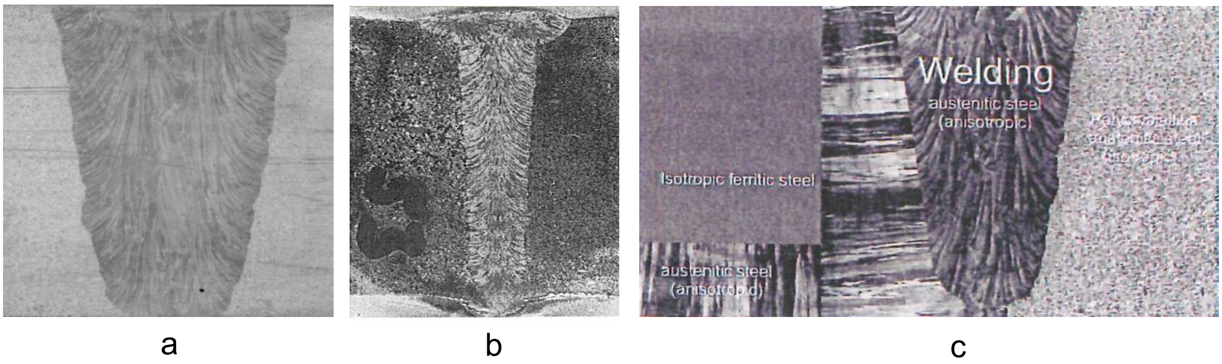
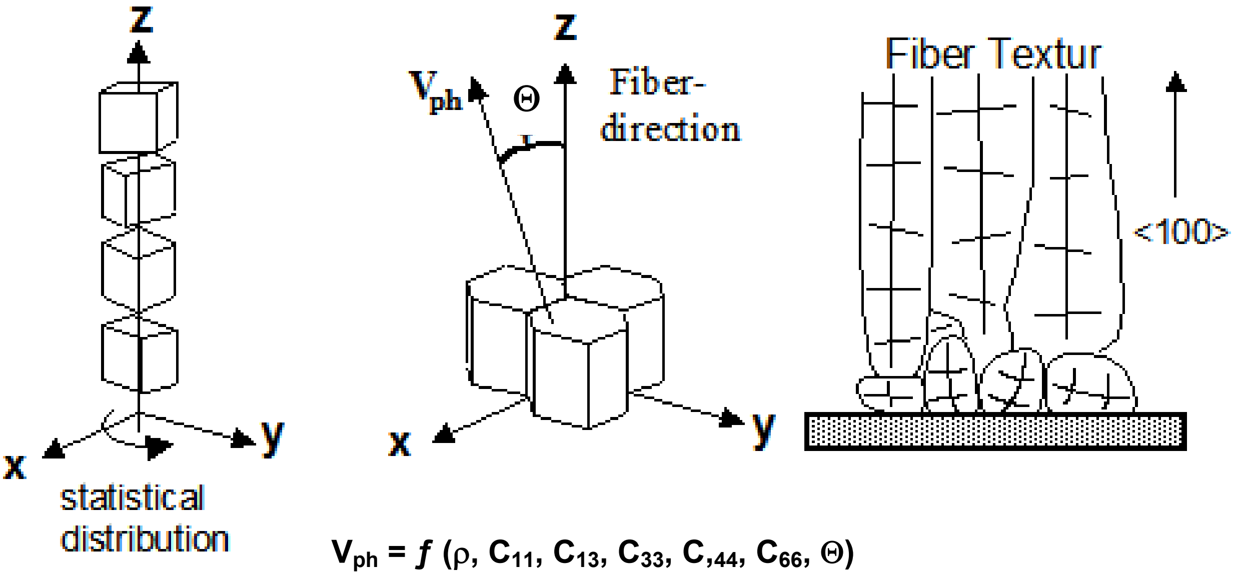


Figure 8: Columnar grains structure of austenitic weld materials: standard pipe to pipe weld (a), narrow gap weld (b), dissimilar weld (c)

Fig. 9 lists the main parameters for the simulation of elastic waves in austenitic weld material.



$$V_{ph} = f\,(\rho, C_{11}, C_{13}, C_{33}, C_{44}, C_{66}, \Theta)$$

Figure 9: Model of the transverse isotropic structure of stainless steel weld joints, V_{ph} = Phase Velocity; C_{ij} = Elastic Constant; ρ = Density, Θ – fiber orientation

Considering the complexity of sound propagation in inhomogeneous media we define domains with locally independent sound propagation. The full material volume under inspection can be built up by these domains. We called this structuring of anisotropy domain mapping. The domains may have different size. This procedure is taking into account to a certain degree simplifications of the anisotropy. Thus, we have to prove the principles of mapping by experiment and simulation.

The basic model can be taken from metallographic analysis as shown in Fig. 10.

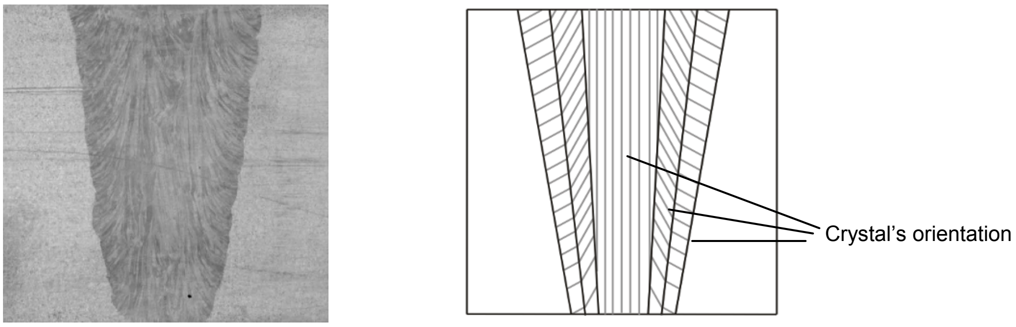
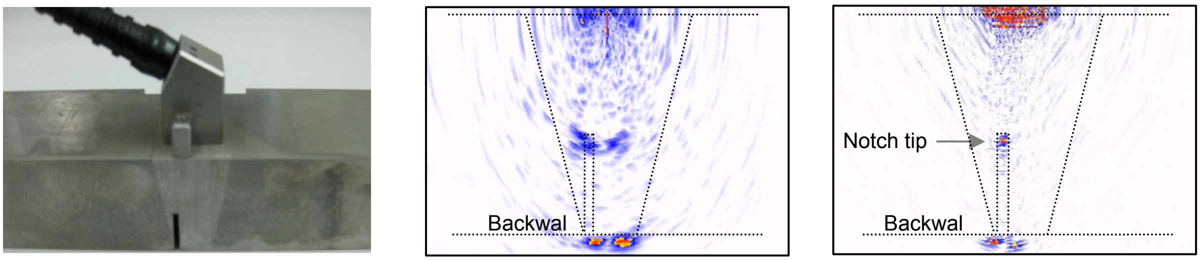


Figure 10: Modeling of weld anisotropy: metallographic view (a), domain model (b)

The mapping allows fast simulation which results can be experimentally confirmed as described above. Fig. 11 shows the reconstructed images (Sector-scans) that demonstrate the improvements when applying reverse phase matching. In this experiment as a first step the weld structure was rather homogeneous and we considered all the weld cross section as one domain.



a b c

Figure 11: Reconstruction of sector scans of austenitic welded test specimen: experiment (a), conventional phased array reconstruction (b), Sampling Phased Array reconstruction with Reverse Phase Matching (c)

5 Further work and conclusion

We could demonstrate the potential of Reverse Phase Matching to consider ultrasonic wave propagation in anisotropic materials. Its application improves the reliability and sensitivity of ultrasonic inspection in particular of austenitic welds. Moreover, real-time reconstruction allows automatic inspection with A-, B-, C-, D, and 3D scans. However, Reverse Phase Matching needs knowledge about the structure of anisotropy to simulate sound propagation.

Further work is directed to the needed accuracy of anisotropic domain mapping. Also, we want to investigate the potential of this technique to measure or identify structural changes (e.g. local repairs). And last but not least, we will have to establish procedures and rules necessary for the qualification and certification of future equipment and procedures.

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