VISUALIZATION OF SOUND PROPAGATION WITH ELECTRODYNAMIC PROBES

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Abstract. When dealing in ultrasonic testing with inhomogeneous material structure data interpretation can be rather difficult. This is especially the case when using anisotropic dissimilar welds made from austenitic steel or nickel based alloys, which are currently used for modern power plant concepts. For better understanding of the complex interaction between the sound field and the component under test, the visualization of sound propagation in solids is a substantial task to increase the probability of detection of relevant defects. However, there exist only a small number of appropriate techniques published today, such as scanning laser interferometer, piezoelectric and optical approaches in case of transparent solids. In this work we present an electrodynamic technique providing a simple use and a high signal to noise ratio. By detecting the grazing beam with an electrodynamic probe with a size smaller than 10 mm, we measured the particle displacement as a function of time with a spatial resolution in the order of 1 mm. Adapting the electrodynamic probe and its coil alignment allows for measuring the displacement components in all three dimensions. This comprises the detection of the horizontal and vertical particle displacement with respect to the surface and thus also the transformation from longitudinal waves into transversal waves and vice versa is possible. A SNR of higher than 36 dB could be achieved within ferromagnetic and high conductive chrome steel when using a transversal wave generated by an angled beam transducer. We report on measurements of the sound field in complex weld joints. One example shows a 10 mm thick narrow-gap weld joining a nickel alloy with a chrome steel yielding a substantial anisotropy of the weld structure. The test system enables us to visualize the wave propagation within the weld and indicates the reflection scenario and the energy losses due to both the anisotropic structure and material defects.

Keywords: ultrasonic, sound field, visualization, electrodynamic probe, nondestructive testing (NDT), nickel alloy, anisotropic weld, narrow-gap weld

1. Introduction

The physics of ultrasonic wave propagation in solids is a well understood research field. Today there exists a bunch of sophisticated theoretical tools to describe and model even complex testing problems. However, when it is necessary to model complicated geometries in conjunction with anisotropic materials texture the required time and effort often becomes inappropriately high. Modeling may even be a doubtful task due to the limited knowledge of the elastic parameters of anisotropic structures. Therefore, there is recently a growing demand for experimental approaches to detect and visualize the propagation of sound waves in complicated test samples.

There are several visualization methods described in literature. For a long time optical methods, such as the Schlieren-technique, have been used in optical transparent solids [1,3,5,6,9]. Currently, laser-interferometers are increasingly used to measure the sound waves on the surfaces of non-transparent components [6,7,12]. But they usually need an averaging over several time-functions in order to reach a reasonable signal-to-noise ratio (SNR) and measuring the particle displacement which is oriented in parallel with the testing surface needs a considerable experimental effort. A popular and easy-to-handle visualization technique is to use a piezoelectric pin-transducer with a point-like aperture [6]. Because of the required acoustic coupling only normal oriented particle displacement is measurable by scanning a whole surface.

Many of the mentioned techniques fail when it comes to image shear waves and longitudinal waves simultaneously with a sufficiently high SNR. Therefore this work proposes a simple but powerful approach with electrodynamic probes [2,4,6,10,11,13] to visualize the sound propagation in inhomogeneous anisotropic structures.

2. Measurement method

2.1 Measuring principle

The electrodynamic probe transforms the particle displacement at a conductive testing surface into a voltage which scales proportional to the particle velocity. The mechanism is based on a permanent magnetic field, which is applied to the conductive surface area. When the ultrasonic wave is moving through this magnetic field, eddy currents are generated by the particle displacement shown in Fig. 1a. The physical principle behind this effect is based on the Lorentz force and can be observed for moved electrical conductors in a magnetic field like an eddy current brake or an electric generator.

The eddy currents in turn cause an alternating magnetic field above the sample's surface. This alternating magnetic field strength then can be detected by a detection coil shown in Fig. 1b. The induced voltage in the coil scales proportional to the particle velocity. The voltage can be determined as a function of time with any ultrasonic device using a simple preamplifier for impedance adaption. Therefore the application of electrodynamic probes is very cost-efficient.

This proposed technique requires no particular material properties, such as transparent media in the case of Schlieren-technique and well-reflecting surfaces in case of laser vibrometer. Using the electrodynamic probes in some special experimental arrangements enables us also to visualize sound waves in non-conductive materials [2].

For the detection of the particle displacement in parallel or normal direction to the test surface the alignment of the coil may be adapted.

In contrast to other visualization techniques the electrodynamic probes can detect particle displacement in all three spatial directions. Furthermore they provide a high bandwidth yielding a high SNR even when using high frequencies.

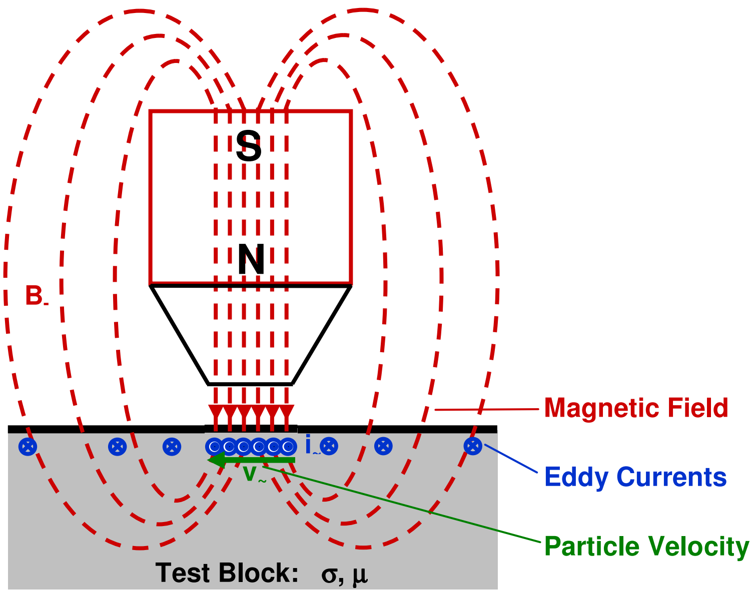

Figure 1a. Principle of the electrodynamic probe, generation of eddy currents

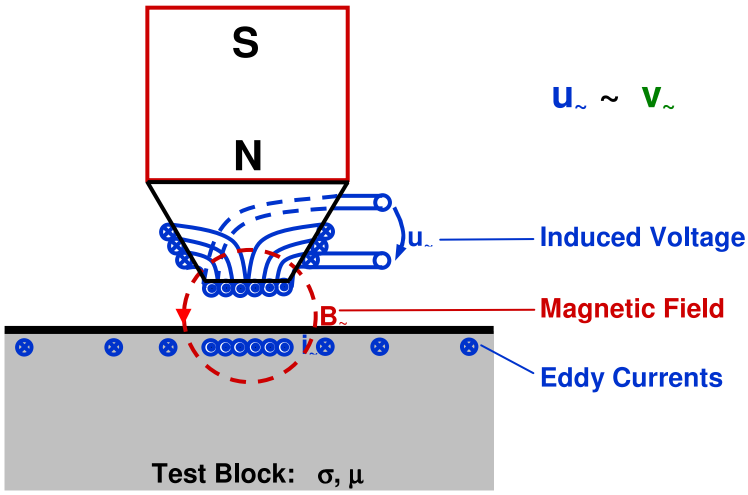

Figure 1b. Principle of the electrodynamic probe, measurement of eddy currents

2.2 Experimental setup

Unfortunately up to now no technique is available to visualize sound fields inside non-transparent materials. Thus we visualize the sound field at the surface of the component under test. We use the method of grazing incidence in which the movement of the particles in proximity to the steel-air interface as function of time is generated by a grazing sound beam, representing a sound field cross section as an approximation of the beam at its central axis.
Fig. 2 shows the experimental configuration. An angle beam probe is attached on a fixed position on the top close to the front edge of the test object (a test block with a narrow-gap weld joint). The edge of the test object is therefore situated close to the

centre of the active sound field, which is generally at the centre of the transducer. In our measurements we deliberately used a probe orientation to the incident beam of the transducer, which simultaneously detects shear waves and longitudinal waves with similar amplitudes to visualize also the wave conversion within the weld and at the edges. The grazing sound field at the testing surface generates primarily a particle displacement which is oriented in parallel with the surface. Longitudinal waves are more attenuated by the energy loss then shear waves which appear here as horizontally polarised shear waves.
The electrodynamic probe is scanned across the side surface of the test block, while the transducer is pulsed. In doing so, we can receive a complete particle velocity-time-function (A-scan) for each x/z-position of the probe. Once you have the time-function information you can generate for each detection time a single color-coded amplitude map, corresponding to a snapshot of the wave field along the side surface of the test block. By calculating the snapshots for different detection times we are able to visualize the progression of the wave front, which also can be implemented into a movie.

2.3 Limitations of the approach

Each visualization technique has its limitations and apparently so too does the electrodynamic probe. The spatial resolution of the probes for sound field visualization must by smaller than $\lambda/2$. In this work we used probes with a spatial resolution in the order of 1 mm. Therefore the maximum operating frequency should not exceed 3 MHz for longitudinal waves and 1.5 MHz for shear waves.
A second remarkable point is the fact that a quantitative estimation of a single mode is quite difficult. An electrodynamic probe optimized for shear wave detection also fractionally detects the longitudinal wave and vice versa. Furthermore the voltage amplitude may depend on several factors such as the gap between probe and test block surface, the alignment between the detection coil and the direction of the detected particle displacement, and the conductivity of the tested component.

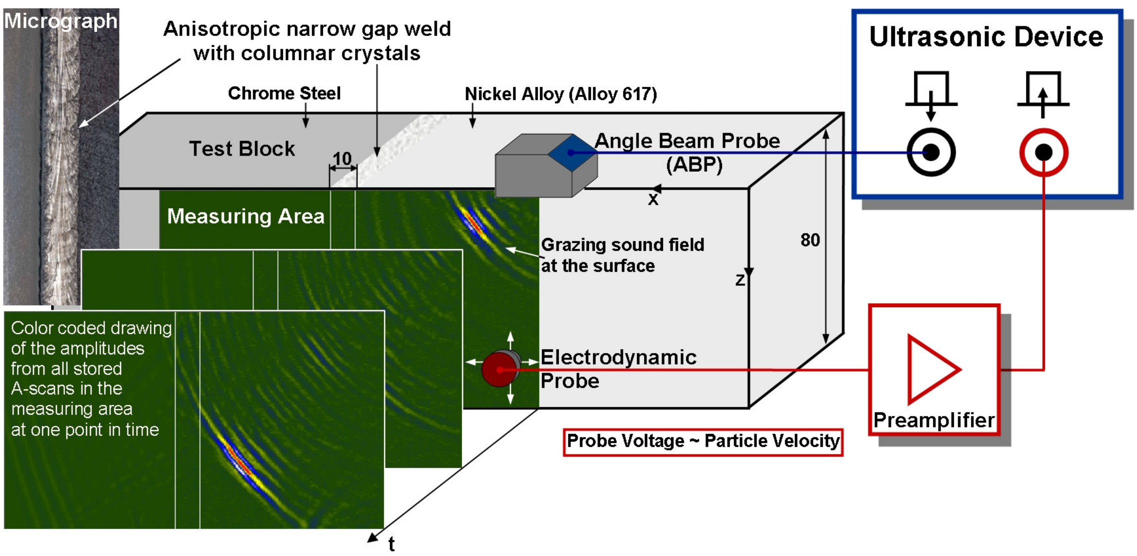

Figure 2. Experimental setup for visualization of the wave propagation in a test block using an electrodynamic probe

3. Wave propagation within a narrow-gap weld with anisotropic texture

One motivation for this work is the investigation of the wave propagation in complex weld joints and its anisotropic texture. Here we present an 80 mm thick dissimilar narrow-gap weld consisting of chrome steel and a nickel-alloy (Alloy 617). Similar to an austenitic steel weld joint, the weld exhibits typical anisotropic properties, showing horizontal aligned columnar crystals along the edge of the weld and vertical directed columnar crystals within the centre of the weld.
The following examples show subsequent snapshots of the sound field generated by an angle beam probe and the interaction with the narrow-gap weld for different types of waves. The position of the weld is indicated in the figures by two white lines.

The first example in Fig. 3 and 4 shows the wave front generated by a 2 MHz, 60° longitudinal wave probe. In addition to the weld test block shown in Fig. 2, we introduced in this block at the left flank of the weld three side-drilled holes with a diameter of 3 mm. They were positioned at a depth of 10 mm, 40 mm and 70 mm and are indicated as white dots. Fig. 3 also represents a clear picture of the different types of waves emanating from the angle beam probe [8]. Besides the shear wave (S-wave) and the longitudinal wave (P-wave) one clearly can see the head wave, linking the wave fronts of both types. In the pictures of Fig. 4 the wave fronts at several points in time t_i are shown. At t_2 we observe the reflection of the longitudinal wave at the first hole and further diffraction of the wave front within the weld. At t_3 the reflection of the longitudinal wave emerges at the second hole. The subsequent diffraction of the lower part of the longitudinal wave is shown at t_4. At t_5 the reflection of the longitudinal wave then appears at the third hole. After further propagation (t_6) the reflection of the second hole reaches the left edge of the test block. The snapshot at t_7 again points out the advantage of the electrodynamic probes by showing the conversion of the shear wave into a longitudinal wave at the bottom of the test block. The reflection at the third hole of the shear wave and waves reflected at the bottom of the sample are shown at t_8 and t_9.

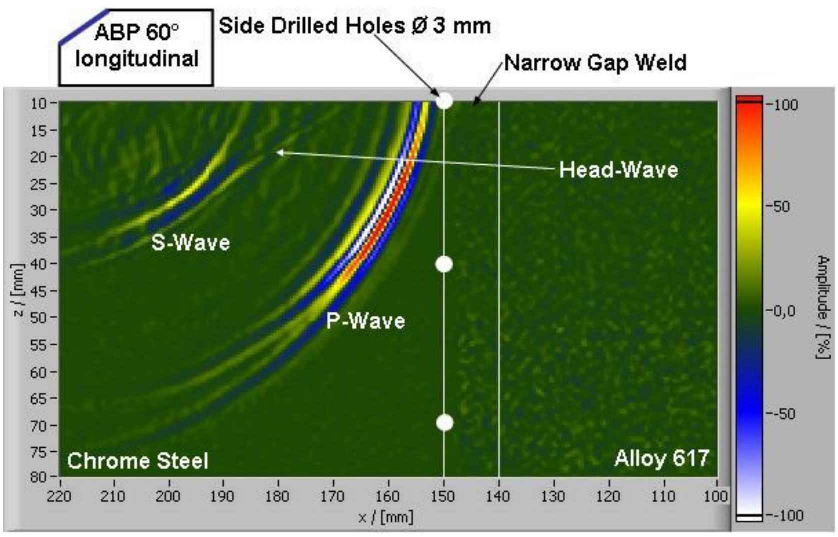

Figure 3. Wave front of a longitudinal wave angle beam probe (ABP) 60° and 2 MHz

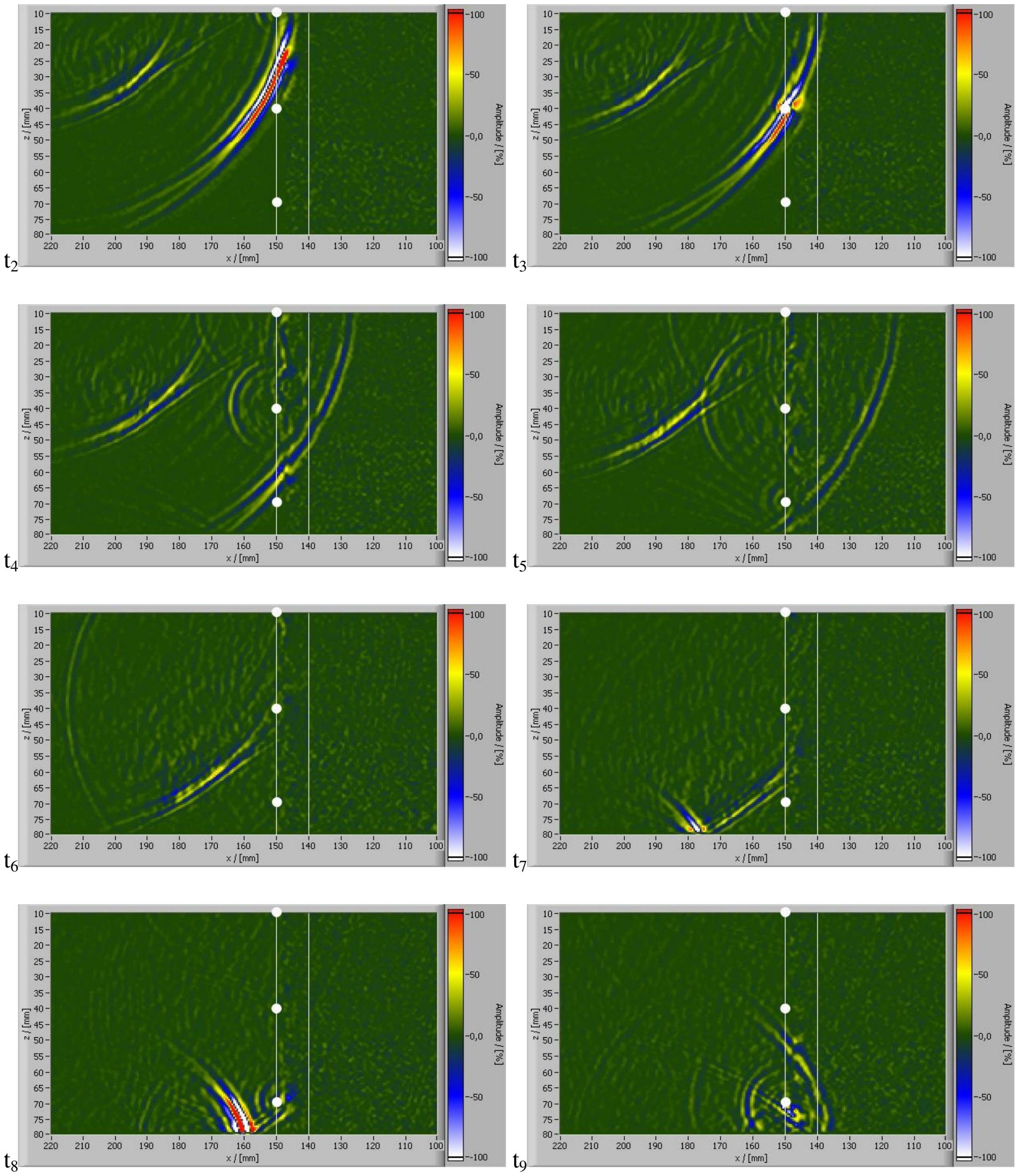

Figure 4. Snapshots of the scattering of the longitudinal wave front within the anisotropic narrow-gap weld at different times

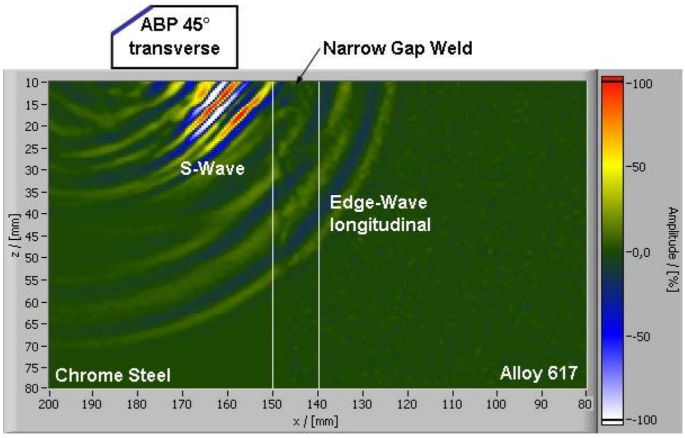

Figure 5. Wave front of a transverse wave angle beam probe (ABP) 45° and 1 MHz

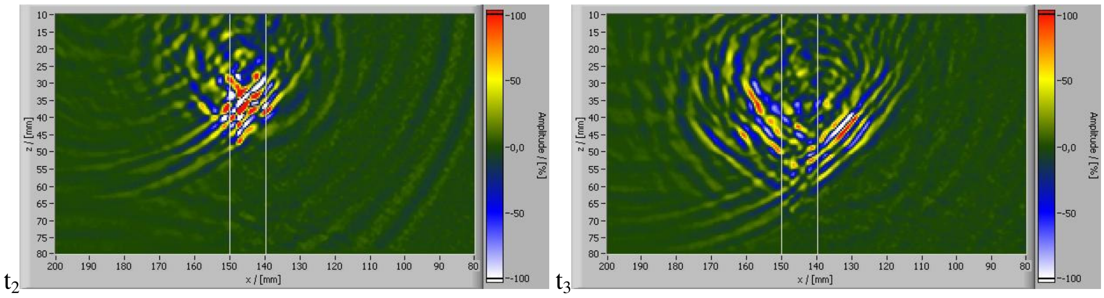

Figure 6. Snapshots of the scattering of the transverse wave front within the anisotropic narrow-gap weld at different times

As a second example we show in Fig. 5 and 6 snapshots of the wave front generated by a 1 MHz, 45° transversal wave probe. Fig. 5 also represents a clear picture of the different types of waves emanated from the angle beam probe [8]. In the pictures of Fig. 6 the shear wave (S-wave) front at several points in time t_i are shown. At t_2 the wave front is propagating within the weld. In the next picture (t_3) the shear wave front has left the weld. One can observe a typical interaction between the wave and the narrow-gap weld, showing a lot of scattering due to anisotropic inhomogeneous material properties.

4. Conclusions

The experimental results are demonstrating that the visualization of wave propagation at the surface of solids using electrodynamic probes is easily feasible, allowing the simultaneous detection of both shear waves and longitudinal waves. The detected wave signals show a sufficiently high SNR, a large frequency bandwidth, and the possibility to detect all three dimensions of the particle displacement. Therefore the electrodynamic probe approach provides a complete picture of the wave propagation and includes all kinds of mode conversions and scattering effects inside complex anisotropic material structures. Thus it can be used as a cheap and easy-to-handle alternative to laser techniques and other optical approaches. The visualization results furthermore support the theoretical activities to model the wave propagation and to find optimal testing parameters for different components and configurations.

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