Cast Stainless Steel

Visualization of Ultrasonic Fields in Anisotropic Stainless Steel Castings
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ABSTRACT

The propagation of ultrasonic wave fields on surfaces of opaque anisotropic materials was visualized. The demonstrative visualization technique is most applicable for the analysis of the complex propagation behavior of ultrasonic waves in anisotropic materials.

Characteristic sound propagation phenomena in anisotropic materials were calculated and verified by the visualization measurements. For the modeling of the ultrasonic wave propagation CIVA (Expertise software for NDT) and a point wave synthesis were used.

INTRODUCTION

In recent times a number of models have been presented, which make ascertained predictions about the complex ultrasonic wave propagation phenomena in anisotropic materials. Particular instructive technical expertise can be gained from the simulations, when the wave field propagation is displayed in the form of snapshots at selected points in time.

The objective was to measure and visualize the ultrasonic wave propagation in the incidence plane of the probe to verify the modeling results. Furthermore the intention was to assist education of inspection personal by providing an intuitive understanding of the ultrasonic wave propagation phenomena in anisotropic materials.

MEASUREMENT TECHNIQUE

To visualize the ultrasonic sound propagation on the surface of opaque anisotropic materials a method introduced by Köhler [1, 2] was used. Figure 1 illustrates the principle of the visualization technique. The measurement setup consists of an ultrasonic device, a transmitting probe and a electrodynamic sensor (receiver) which is connected to a scanner. The transmitting Probe is coupled to the side of the sample, whereas the receiving electrodynamic sensor is scanned over the top. While the radiated ultrasonic impulse propagates in the material, the displacements can be measured on the horizontal surface of the sample. At specified distances (given by the scan pattern) the measured A-scans are saved on hard drive. The ultrasonic signals are stored in a 3D data matrix. The figure shows this schematically for one A-Scan. The upper side of the 3D data matrix corresponds to the scanned area of the sample (XY). The vertical axis is the time axis along the A-scan. A horizontal cross section of the 3D data matrix shows a snapshot of the ultrasonic wave field radiated by the transmitting probe. By varying the position along the time axis the actual ultrasonic wave propagation can visualized in time and space.
MATERIALS

Silicon single crystal

The cylindrical silicon single crystal (see figure 2) used for the measurements has cubic crystal symmetry. One of the three symmetry axis of the cubic crystal system is orientated along the cylinder axis. The elastic constants and the density used for the calculation of the sound propagation were taken from the tables in [3].

\[ \rho = 2.33 \text{ g/cm}^3 \]
\[ c_{11} = 165.7 \times 10^9 \text{ N/m}^2 \]
\[ c_{12} = 63.9 \times 10^9 \text{ N/m}^2 \]
\[ c_{44} = 79.6 \times 10^9 \text{ N/m}^2 \]
Stainless steel casting
In microscopic dimensions the material has a cubic crystal structure but macroscopically the material has to be treated as transversal isotropic due to the columnar grain structure. Figure 3 (left) shows the columnar grain orientation, which results from the solidification along the direction of the temperature gradient. The columnar grain direction is the symmetry or texture direction of the stainless steel casting. Perpendicular to the grain direction is a plane, in which the elastic properties are equal in all directions, the so-called isotropic plane (see figure 3, right). The elastic constants were determined by sound velocity measurements.

\[
\rho = 7.82 \text{ g/cm}^3 \\
c_{11} = 253.6 \times 10^9 \text{ N/m}^2 \\
c_{12} = 106.6 \times 10^9 \text{ N/m}^2 \\
c_{13} = 138.6 \times 10^9 \text{ N/m}^2 \\
c_{33} = 242.0 \times 10^9 \text{ N/m}^2 \\
c_{44} = 111.8 \times 10^9 \text{ N/m}^2 \\
c_{66} = 73.5 \times 10^9 \text{ N/m}^2
\]

Figure 3 - Stainless steel casting X5CrNi1810

CALCULATION OF THE SOUND PROPAGATION

CIVA UT Beam computation module
The CIVA ultrasonic beam computation module was used to calculate the ultrasonic wave fields radiated from the monolithic contact transducers in the anisotropic materials. The “build video” tool of the software was utilized to visualize the wave field propagation in the incidence plane of the probes. The heterogeneous material properties of the stainless steel casting were not taken into account.
Point wave synthesis

Additional the CIVA simulations a point wave synthesis was used for the calculation of the ultrasonic wave fields. The method is based on Huygens principle. Figure 4 shows the geometric configuration of ten point sources, which simulates a linear probe aperture (2D approach). For the calculation of the displacement at a arbitrary point P(x,z) in the anisotropic material the elementary waves emitted from the source points of the probe are super positioned according to the time of flight and directivity (equation 1).

\[
    u(x, z) = \sum_{m=1}^{k} \frac{1}{r_m} \exp \left( -\frac{2\pi f}{c_g(\Theta_m)} r_m \right) \cdot \xi(\Theta_m)
\]

Equation 1

In equation 1 \( r \) is the distance between the source point Q and the point P(x,z) within the anisotropic material, \( i=\sqrt{-1} \), \( \xi \) the directivity and \( f \) the frequency in MHz. In the case of modeling the sound propagation in anisotropic materials it has to be taken into account that the shape of the elementary waves emitted by the point sources are identical to the geometric shape of the energy diagrams of bulk waves, therefore the energy velocity \( c_g \) must be used for the construction of the wave propagation according to the Huygens principle [4].

![Figure 4 - Geometric configuration of a linear probe aperture with ten source points Q](image)

**RESULTS: MEASUREMENTS AND SIMULATIONS**

Figure 5 shows measurement and simulation results for the silicon single crystal. The schematic drawings on top of figure 5 illustrate the measurement configuration and the crystallographic orientation of the three silicon single crystal samples in respect to the probe incidence direction. The incidence direction of the shear wave probe was always normal to the coupling surface. The oscillation (displacement) direction of the shear waves were tangential the scan plane, therefore a vertically polarized shear wave was generated in the silicon single crystal. The probe was glued to the coupling surface of the sample.

The snapshots of the wave propagation illustrate the complexity of the ultrasonic wave propagation in anisotropic materials at the first glance. The strongly varying shapes and velocities of the wave fields for the different setups and a good conformity between measurement and simulation is clearly observable.

On the left, for intromission of sound in crystallographic [100]-direction the ultrasonic wave field is focused by the material and propagates with maximum velocity. The phenomenon known as “Cusp” (energy diagram) could be verified experimentally for the first time. In the middle, for intromission of sound in crystallographic [210]-direction the sound field becomes an asymmetric shape and is skewed
considerably to the left towards the crystallographic \([100]\)-direction. The phenomenon is known as sound beam deviation. On the right, for intromission of sound in crystallographic \([110]\)-direction, a very divergent ultrasonic wave field propagates with comparable low velocity.

![Figure 5 - Measured and calculated snapshots of shear wave propagation in a silicon single crystal. time of flight: 6.5 µs; top: measurement setup, coupling surface normal to \([100]\) (left), \([210]\) (middle) and \([110]\) (right) crystal direction; Probe: Panametrics / V153 / 1 MHz / 12mm](image)

To investigate the influence of the columnar grain orientation to the propagation of a longitudinal wave field the experimental setup shown in Figure 6 was utilized. The incidence direction of the 0° longitudinal probe was normal to the coupling surface. The columnar grain direction was 0°, 22.5° and 45° in respect to the coupling surface. The measurements, which are in good conformity to the simulations, shows clearly, that the ultrasonic wave field propagation depends strongly on orientation of the columnar grains. For intromission of sound in stainless steel casting with the grains perpendicular to the coupling surface (see Figure 6, left) a very divergent wave field which propagates with comparable low velocity were observed. For intromission of sound in stainless steel casting with the grains 22.5° rotated relative to the coupling surface (see Figure 6, middle) the wave field is deflected in a direction against the columnar grain direction, the energy slides along the wavefronts to the right. The phenomenon is well known as beam deviation. For intromission of sound in stainless steel casting with the grains 45° relative to the coupling surface (see Figure 6, right) the ultrasonic wave field is focused by the material and propagates with maximum velocity.
Figure 6 - Measured and calculated snapshots of longitudinal wave propagation in stainless steel casting X5CrNi1810. Time of flight: 7.2 µs; top: measurement setup, coupling surface normal, 22.5° (middle) and 45° (right) to columnar grain orientation; Probe: panametrics/1 MHz/12mm

Figure 7 illustrates ultrasonic wave propagation phenomena’s which occurs when a conventional 45° shear wave angle probe is used for the inspection of stainless steel casting. The columnar grain direction was 0° and 22.5° in respect to the coupling surface.

Measurement and CIVA simulation of the shear wave propagation shows that the direction of the wavefronts differs from the energy propagation direction of the wave fields.

For columnar grains orientated perpendicular to the coupling surface (see figure 7, left) the energy of the wave travels down along the wavefronts and propagates nearly normal to the coupling surface, but the normal of the wavefronts directs approximately in 45° direction. As mentioned before the phenomenon is well known as beam deviation. For a columnar grain orientation of 22.5° relative to the coupling surface (see figure 7, right) the energy of the wave propagates nearly with a refracted angle of 80°!

The snapshots illustrate, that the shear wave in stainless steel casting has a very complex propagation behavior that strongly depends on the columnar grain orientation, which defines direction, velocity, divergence behavior and the shape of the wave fields.
Figure 7 - Measured and calculated snapshots of shearwave propagation in stainless steel casting X5CrNi1810. Coupling surface normal (left) and 22.5° (right) to columnar grain orientation; Probe: Panametrics / 0.5 MHz / 25.4mm

REFERENCES

1) B. Köhler and Ch. Schurig. *Visualization of ultrasonic fields on solids*. World Congress on Ultrasonics, 459-462, 1995