Grain Structure Visualization of Austenitic Welds by Laser Detection of Grazing Incident Ultrasonic Wave Fields

Martin BARTH 1, Bernd KÖHLER 1, Frank SCHUBERT 1

1 Fraunhofer IZFP; Dresden, Germany
Phone: +49 351 88815-512, Fax: +49 351 88815-509; e-mail: martin.barth@izfp-d.fraunhofer.de

Abstract
Ultrasound wave propagation along the free surfaces of a solid can be measured with non-contact laser Doppler vibrometry. While a fixed transducer transmits ultrasound pulses with high repetition rate into the sample, its surface is scanned point by point with high spatial resolution and the out-of-plane displacement is recorded. From the time-domain signals of all points a detailed video sequence can be created, wherein the wave propagation at the solid's surface can be observed. The measured wave front of an ultrasonic creeping wave travelling parallel to the scanned surface is locally influenced by the material's near-surface grain structure. It is shown here, that grain structure can be extracted directly from the recorded data by appropriate signal processing. Due to the fine laser focus and high scanning resolution, the grain structure images show details smaller than the acoustic wavelength. This method was applied on austenitic weld specimens as an alternative to classical metallography. This article introduces the method, shows examples of obtained grain structure images and compares them to electron backscatter diffraction images.

Keywords: Ultrasound, Laser Doppler vibrometry, Austenitic weld, Grain structure, Electron backscatter diffraction

1. Introduction
High strength and chemical resistance are the most important features of austenitic steel. Therefore, it is often used for pressure vessels and tubes in power plants and chemical facilities, for example. The disadvantage is that the welds are difficult to inspect by ultrasonic testing (UT). During the welding process, coarse crystallites grow when the molten steel solidifies. Ultrasound waves with a wavelength at the scale of the grain sizes and below are scattered at grain boundaries, producing a noisy echo signal. Hence, small flaws cannot be detected. In order to improve the probability of detection, various working groups are doing research on sophisticated UT methods [1-3] and welding methods that produce welds with an improved UT behavior. This article describes how the propagation of ultrasound waves inside a weld can be captured and how the weld’s grain structure can be extracted from the recorded signals.

2. Measuring the wave propagation
For measuring the wave propagation, a laser Doppler vibrometer (LDV) is utilized. This has been already demonstrated in various applications before [3-7]. In this case, it measures the pure out-of-plane vibration of a specimen’s polished surface, caused by the ultrasound waves inside. In Figure 1 the measurement setup is illustrated. Longitudinal waves propagate parallel to the surface. Surface skimming longitudinal waves effectively lead to a non-vanishing out-of-plane displacement because additional shear waves are generated by mode conversion at the free surface.

The entire region of interest is scanned point by point by the help of an X-Y-table. When a standard transducer and a standard pulser are used, the out-of-plane displacement amplitudes caused by the ultrasonic waves are about a tenth of a nanometer and smaller. But also under optimal laser reflection conditions an LDV produces some noise. Hence, the signal-to-noise ratio (SNR) is low. In order to increase the SNR signal averaging is applied. This is done by repeating the pulses and calculating the average waveform out of thousand and more captured raw waveforms taken at the same point.

Unfortunately, the pulses cannot be repeated faster than about 1000 times per second, because the ultrasound waves must have disappeared before the next pulse is triggered. Otherwise, remaining waves cause an acoustic background noise that disturbs data analysis. So, averaging of several thousand waveforms per point would take several seconds for each point and the entire scan of 400 x 250 points (100,000 points) would take several days with this classic averaging method.

Therefore an improved averaging method has been invented (patent pending). It uses a non-constant impulse interval that is changed in a particular order. The effect is that the remaining ultrasound waves are changing their position in time with respect to the following impulse. So, by averaging the acoustic noise is reduced as well. This method allows an averaging speedup of 20 times and more. This enables high resolution scans within acceptable acquisition time.

With a complete scan a block of data is captured as shown in figure 2. It includes the x- and y-axis of the scan area and the time-axis of the waveforms as well. This data can be displayed in
different ways. For example, single waveforms, x-t-diagrams or still images as well as video sequences can be produced. In still images and video sequences some features of the weld’s grain structure are noticeable in the leading longitudinal wave. Six still images of the propagating waves inside a weld are shown in figure 3. The size of the area is 20 by 12 square millimeters. In these images the weld is indicated as a shadow. The leading longitudinal wave is affected by the weld’s features and traced by scattered ultrasound waves. Most likely, the second wave with smaller wavelength is a Rayleigh-wave excited by the transducer at the edge of the specimen. The vertically polarized shear wave (polarization plane parallel to surface) causes only in-plane vibration and cannot be detected.

![Figure 3: Still images of the ultrasound waves; the dark grey area indicates the shape of the weld.](image)

3. Grazing Incidence Ultrasound Microscopy (GIUM)

3.1 Main principles

The grain features can be extracted from the raw data [8]. At present, the feature extraction algorithm evaluates the first zero crossing of the leading longitudinal wave in the time signals of each scan point. The zero crossing delay value of a scan point indicates when the longitudinal wave passes this position. Due to the inhomogeneity of the weld the wave front is not as smooth as known from an undisturbed wave. Hence, the delay values are not
distributed smoothly. The disturbances carry grain information. A filter algorithm converts the disturbances into a greyscale image. This technique was named Grazing Incidence Ultrasound Microscopy (GIUM). Four GIUM images of the same weld are shown in figure 4. The difference between these images is that the longitudinal waves were excited from different directions (white arrows). In detail the contrast differs but many grain patterns can be observed in all images.

![Figure 4: GIUM images of the weld captured with different longitudinal wave inclination (arrows).](image)

3.2 Physical explanation approach

It is well known that every grain is an anisotropic crystallite. Thus, its mechanical properties as well as sound speed and acoustic impedance are directional properties with respect to the orientation of the atomic lattice. Inside the weld, the grains are partially randomly oriented. Hence, there are local variations in transverse expansion and speed of sound leading to local variations of the wave’s out-of-plane amplitude and delay. Moreover, the longitudinal wave is also scattered at grain boundaries although its wavelength is larger than the grain size. This may lead to additional contributions to the resulting out-of-plane displacement. Many details of the physical causes are not fully understood yet. These are to be revealed in ongoing investigations, including analytical studies and numerical simulations.

4. Electron backscatter diffraction as reference method

To verify that GIUM-images really show the grain structure, the weld sample was also analyzed by electron backscatter diffraction (EBSD) [9]. This technique measures the atomic lattice orientation at the surface of a specimen. Figure 5 shows a scheme of an EBSD system. An electron microscope focuses the electron beam onto a point of the specimen’s surface. A fraction of the electrons are scattered by the atomic lattice planes causing a typical pattern at the EBSD-detector. Such a pattern can be seen in figure 5. The software of the EBSD system analyses the pattern, recognizes the orientation of the atomic lattice and allocates an
appropriate color to the corresponding image pixel. By deflecting the electron beam and moving the specimen the entire region of interest is captured. The result is an image where single grains are recognizable because of their color contrast to the surrounding grains.

![Scheme of an EBSD system (left) and an example of an EBSD pattern (right).](image)

The EBSD image (figure 6) shows all grains at the surface of the sample. Most of the features that are visible in the GIUM images can also be found in the EBSD images. They can be directly associated with the grain structure. However, there are also some artifacts that can be explained by wave phenomena at the interface between specimen and transducer or by lack of side fusion (on the left side of the weld).

![Comparison of GIUM image (left) and EBSD image (right) of the same weld specimen.](image)

5. Summary and future work

Grazing incidence ultrasound microscopy (GIUM) is a novel non-chemical method to visualize microstructures by the effects of local variations of elastic properties. This was demonstrated for an austenitic weld specimen. Pulsed ultrasound longitudinal waves are compressing and stretching the grains while a laser Doppler vibrometer scans the specimen’s surface point by point. The data record of a complete scan contains the propagation of the ultrasound waves at the specimen’s surface. Data processing enables extraction of the grain structure. Due to probing with a tiny laser focus, details much smaller than the acoustic wavelength can be resolved. Electron backscatter diffraction (EBSD) was used to capture a
reference image for comparison. In fact, there is a good agreement between GIUM images and the EBSD image of the same specimen. The detailed physical background of GIUM is not completely understood, yet. Upcoming research, including analytical, numerical and experimental studies, will discover this in the next years. A matter of particular interest is the question if it is possible to estimate the atomic lattice orientation of grains and its local elastic properties.

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References