Kai-Alexander Saalbach*, Marc Christopher Wurz, Jens Twiefel, Lutz Rissing and Jörg Wallaschek

Custom Lithium Niobate Transducer Arrays for Detecting Material Distribution of Hybrid Workpieces

Abstract: Ultrasonic non-destructive testing is presented as a method to determine differences in material distribution at elevated temperatures in hybrid workpieces made of different metals. Varying material distribution causes differences in transit time and can be detected by ultrasonic transit time measurements. Therefore, custom transducers are manufactured to perform transit time measurements on hybrid workpieces. Results of these measurements are shown.

Keywords: lithium niobate, transit time, high temperature, material composition, hybrid workpieces

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Introduction

Hybrid workpieces, such as cylinder heads, are made of different materials to provide the needed material properties at different locations within the workpiece. Such workpieces are often forged at elevated temperatures. This metal-forming process changes the distribution of the materials inside the workpiece. The correct distribution is critical for the function of the part. Therefore monitoring the material distribution within hybrid-formed workpieces after the forming process is necessary. A suitable measurement process would be non-destructive and easy to apply. One way to measure the differences in material distribution inside hybrid workpieces is to measure the local sound velocity, which differs from material to material and also within the single materials due to applied heat treatment. This causes differences in transit time of waves and can be used by ultrasonic measurements. The authors aim in the long term is to integrate this monitoring into the manufacturing process directly after forming. Therefore, a graphical visualization of the locally distributed material characteristic should be achieved by computed tomography. Such an in-line measurement has to meet several requirements: the geometrical resolution, the resolution and exactness of the determined value, the environment conditions of the in-line setup, and the measurement speed. Unfortunately, all of those are not met today.

Before ultrasonic examination of material distribution can be implemented at elevated temperatures, practical studies on ultrasonic transducers, which are suitable for elevated temperatures, are performed.

Two custom transducer arrays, each consisting of four lithium niobate ($LiNbO_3$) elements, are manufactured to perform transit time measurements. Microproduction techniques are used to assemble the transducer arrays. Test measurements are performed in order to investigate if transducer arrays manufactured this way can be used to detect differences in transit time.

For transmission test measurements with these transducer arrays specimens consisting of two materials are used. Results are shown for two different material compositions.

***Corresponding author: Kai-Alexander Saalbach,** Institut für Dynamik und Schwingungen, Leibniz Universität Hannover, Hannover, Germany, E-mail: saalbach@ids.uni-hannover.de
Marc Christopher Wurz, Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Hannover, Germany, E-mail: Wurz@impt.uni-hannover.de
Jens Twiefel, Institut für Dynamik und Schwingungen, Leibniz Universität Hannover, Hannover, Germany, E-mail: twiefel@ids.uni-hannover.de
Lutz Rissing, Institut für Mikroproduktionstechnik, Leibniz Universität Hannover, Hannover, Germany, E-mail: rissing@impt.uni-hannover.de
Jörg Wallaschek, Institut für Dynamik und Schwingungen, Leibniz Universität Hannover, Hannover, Germany, E-mail: wallaschek@ids.uni-hannover.de

Ultrasound in Non-Destructive Testing and Tomography

In ultrasonic non-destructive testing, sound waves are initiated into the workpiece. The signal, which is influenced by the workpiece, is then detected with one or multiple receivers. Further test procedures in which the workpiece is completely penetrated are considered. For this measurement two basic configurations are possible. In transmission measurements separate transducers are used as transmitter and receiver. For reflection measurements, which is the second configuration, one transducer is used, which serves for both transmitting and receiving at the same time. Both measurement methods allow the determination of transit time of the transmitted signal. Additionally, defects in the specimen can be detected on the basis of additional reflections or shadows (Determann and Malmberg 1974; Ilscher 1990; Ilscher and Singer 2002; Grote and Feldhusen 2011).

In tomographic reconstruction two-dimensional distributions from projection images, which were captured from different angles, are reconstructed. A projection is the integral along a group of projection lines. This projection is called Radon transform. By performing a back projection a slice image of the radiated surface along the projection lines can be generated. Such back-projections of objects are not very rich in detail and focus so that they are often regarded as useless (Schlegel and Bille 2002). To improve the back-projection a filtering, which is a deconvolution of convolution integrals, formed during back projection, is applied. As a convolution in the spatial domain corresponds to multiplication in the frequency domain, this filtering is carried out on the basis of the two-dimensional Fourier transform of the resulting distribution. This method is referred to as two-dimensional unfolding or "ρ-filtered-layergram" in which all projection profiles must be known before deconvolution can be started with.

Image reconstruction theory usually requires the angle under which data are recorded to continuously vary between 0° and 360°, assuming linear wave propagation. For the propagation of ultrasound a linear propagation is not necessarily given. Diffraction, refraction and scattering act against a linear propagation (Arnau 2008). In general, tomographic reconstruction is not only possible by means of parallel rays but also from fan-shaped beam distributions (Schlegel and Bille 2002). This fact can be used to utilize ultrasound for tomographic imaging.

The approach to use ultrasound instead of x-rays for tomographic imaging originates from medical technology. This method is mainly used for breast cancer detection (Greenleaf and Bah 1981; Duric et al. 2013; Koch et al. 2013; Gemmeke and Ruiter 2007). Ultrasound differs from x-rays, commonly used for tomography, by a lower velocity of propagation, whereby a measurement of the exact pressure of the wave as a function of time is possible. From the shape of the pressure wave, the attenuation of the pressure field and the delay caused by the sonicated object can be determined. These two measurements allow the determination of the attenuation coefficient and the refractive index in tissue (Kak and Slaney 1988). In ultrasonic tomography usually rotating transducer arrays are used (Koch et al. 2013). Alternatively, annular transducer arrays can be used. Gemmeke and Ruiter described (Gemmeke and Ruiter 2007) a structure consisting of three rings which are arranged above each other to form a cylinder. On the inner wall of the structure 384 transmitters and 1,536 receivers are mounted, which are grouped in the 48 array, each array consisting of 8 transmitters and 32 receivers. The rings can be rotated in six different positions by a motor, so that the number of virtual transmitters and receivers increases by six. The high number of transmitters and receivers leads to a high amount of data that must be processed after measuring (20 Gbytes for one breast) and a data rate of 4 Gbytes/s during measurements. In the application of ultrasound in medical technology the fact that the sound velocity of tissue (fat from 1,400–1,490 m/s, muscle 1,508–1,630 m/s (Schlegel and Bille 2002)) is close to that of water (1,500 m/s (Cobbold 2007)) is utilized. Because ultrasonic waves in the frequency range from 1 to 10 MHz are strongly attenuated in air, the tissue is immersed in water or other liquids. The liquid serves as a coupling medium for inducing the power from the transducer to the object, and to generate a low refractive index in order to keep diffraction effects low. When propagating within complex tissue structures, boundary surfaces are usually not perpendicular to the sound beam. Since the change in refractive index in a soft tissue usually is less than 5%, diffraction effects are small too (Kak and Slaney 1988). In tissue, besides diffraction, the sound signal is also influenced by absorption. It should also be noted that tissue mainly consists of water and therefore mainly longitudinal waves occur (Kak and Slaney 1988).

Ultrasound tomography is an imaging method in which the inverse scattering problem, caused by the interaction of ultrasound with inhomogeneous media, has to be solved numerically. Therefore, it is necessary to know the distance the rays travel from the source to the detector. In contrast to x-ray tomography, these paths are not always straight, because the ultrasound beam experiences a deflection at each interface. For media that are only little inhomogeneous, such as soft tissue, various approximations of the solution of the scattering problem (straight beam) can be used, so that simple approximations of the inverse scattering problem (back-projection) can be used. Calculations and experimental data suggest that the straight ray reconstruction is applicable as long as the refractive indexes differ no more than 10% (McKinnon and Bates 1980). Otherwise, there are regions that cannot be detected with the assumption of straight rays. In the case of strongly heterogeneous media, such as bones, which are surrounded by soft tissue, such approaches, however, are no longer valid (Laugier and Guillaume 2011).

In addition to medical technology, ultrasonic tomography is also used in non-destructive material testing. A common application is to measure the flow in pipes. Such measurements are carried out not only with simple transit time measuring systems with few transducers, but also with a higher number annularly arranged ultrasound converters. With such systems it is possible to produce tomography of perfused pipeline and to obtain spatial and quantitative determination of any existing gas bubbles or other inhomogeneities (dos Santos Júnior 2012). In Jasiuniene et al. (1996) the filtered back-projection is applied in non-destructive testing. Ultrasound tomographic measurements are carried out on various metallic objects with only one transducer serving as a transmitter and receiver. Here the transducer is not moved, but the specimen is rotated by a motor in order to generate sufficient measurements at different angular positions. The measurements were carried out in water as coupling fluid. It was possible to distinguish inhomogeneities less than one wavelength apart. With an array of 40 transducers (transmitters and receivers), consisting of 10 rows with 4 shear wave generators, tomographic images of concrete and in different rock are carried out (Michaux and Grill). For coupling to the specimen no coupling medium is used, but the transducers are prestressed by springs, so that dry contact is established. For these measurements shear waves at velocities of 1,936–3,306 m/s have been used. The resolution achieved has not been specified, but in the evaluation of reinforced concrete metal reinforcement and delaminations can be detected.

Experimental Setup

Before using computed tomography to display material composition, measurements have to be performed. For the detection of differences in material distribution in hybrid workpieces differences in transit time have to be detected. Compared to tissue, in metallic components additional transversal waves, which have approximately half the sound velocity of longitudinal waves, occur. Ultrasonic transit time measurements were performed on a steel block (120 mm × 120 mm × 70 mm). To one side of this block different metal plates were pressed creating composite specimen. For this purpose an 11 mm thick steel plate and an 8 mm thick aluminum plate were used. Only one plate was pressed against the steel block at a time. Each plate was pressed against the block using a water-based coupling agent to ensure acoustic transmission between the metal parts. Ultrasonic transducer arrays opposing each other were placed on the composite specimen and pressed against them creating pretension using the frame surrounding the specimen. The tension produced provided for both a fixed contact between the transducers and the composite specimens, and a strong pressing between the two metal parts. To ensure coupling between transducers and specimens the coupling agent was used as well. A sketch of the experimental setup is shown in Figure 1 (left). For steel a sound velocity of approximately 5,800 m/s can be assumed. Based on this value a signal would take approximately 12 µs to pass the steel block. For the plates pressed against the block additional transit time would add to this value. Assuming the same sound velocity for the steel plate as for the steel block and assuming a sound velocity of approximately 6,000 m/s for the aluminum plate, a transit time difference of approximately 590 ns would be expected.

For transit time measurements ultrasonic transducer arrays made of $LiNbO_3$ (36° Y-Cut) as piezoelectric material were manufactured. $LiNbO_3$ was chosen because the future application is at elevated temperatures. The $LiNbO_3$ was cut into 25 mm^2 squares by dicing. The chosen height of the piezoelectric squares was 500 µm. The body of the sensor system was fabricated by turning and milling and the material used was polyoxymethylene (POM). This material is the body material for the first prototype transducer arrays. Because it is not suitable for the future application at elevated temperatures for the final application another material has to be chosen.

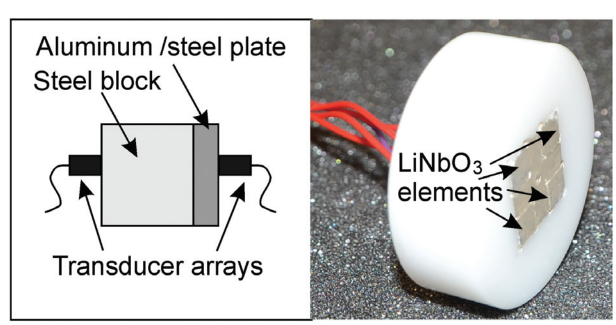

Figure 1: Test specimen (left); custom transducer ($LiNbO_3$).

Four 25 mm^2 pockets with a depth of 500 µm were milled into the flat top of the cylindrical POM body. In each pocket and in the center of the body a hole was drilled through the entire body part to guide connection wires. These wires were glued onto the backsides of the piezosquares using electro conductive glue. The piezosquares were placed inside the milled pockets and the gaps were sealed by superglue. The other sides of the piezos then were coated with silver lacquer establishing a common contact with the wire guided through the center drill hole. A front view of one of the transducer arrays is shown in Figure 1 (right). Voltages then were applied or measured using the wires.

Signal generation and measurement electronics (INOSON PCM 100; 100 Msamples sampling rate) were used for the experiments. For the measurements the transmitter arrays four piezoelements were excited in phase with a 1 MHz rectangular burst signal consisting of 3 bursts at 50% duty cycle. The four piezoelements at the receiver array were also connected. Coupling the piezoelements at both transducer arrays leads to higher signal amplitudes. For data acquisition 16,384 sample points at 100 MHz were sampled. The signal was filtered by a fifth-order bandpass filter having corner frequencies of 500 kHz and 1.5 MHz. For the measurements no averaging was performed.

$LiNbO_3$ Transducer Arrays

For the measurement of differences in sound velocity in order to determine differences in material composition ultrasonic transit time measurements are performed. For these measurements two custom transducer arrays have been manufactured. To characterize the transducer arrays the admittance Y_{el} and the intrinsic admittance Y_i were measured. For the measurements an impedance analyzer (HP 4192A) and an analog amplifier (NF HAS 4052) were used. Figure 2 shows the measurement results of Y_{el} for the transducer array which was used as transmitting array. Measurements for all four transmitting piezoelements are shown and are denoted by P1–P4.

The four piezoelements of the transmitting array show similar admittance over the measured frequency range. For the driving frequency of 1 MHz all four piezoelements have similar admittance and phase values. Measurement of the four piezoelements of the receiving array showed more varying results.

The intrinsic admittance Y_i of the transducer arrays was measured using a fiberoptic laser vibrometer (Polytec

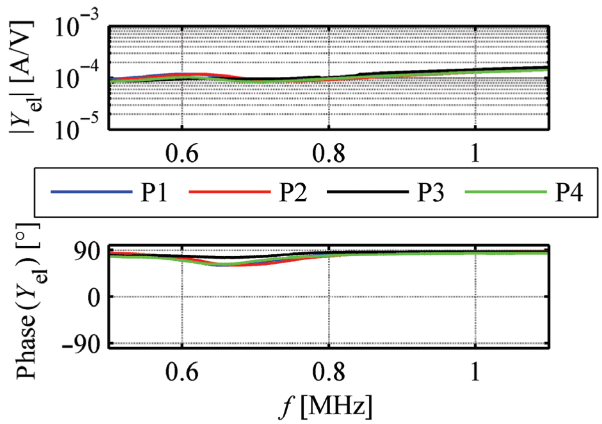

Figure 2: Admittance and phase measurement of four $LiNbO_3$ piezoelements of the transmitting transducer array; P1–P4 correspond to the individual piezoelements.

OFV-5000 with decoder VD-09 and OFV 552 fiberoptic sensor head) to measure the piezoelements' out of plain velocity. Measurement results for the transducer array used as transmitting array are shown in Figure 3.

In contrast to the measured admittance Y_{el} the measurement of the intrinsic admittance Y_i shows more differences for the individual piezoelements for the measured frequency range. For 1 MHz, the frequency used for signal generation, differences in magnitude and phase can be observed especially for piezoelement P2. This piezoelement shows the largest deviation compared to the other three elements. The measurement results for the receiving transducer array also shows deviations between the individual piezoelements. The differences between the individual piezoelements of the transmitting and the receiving array are compensated by

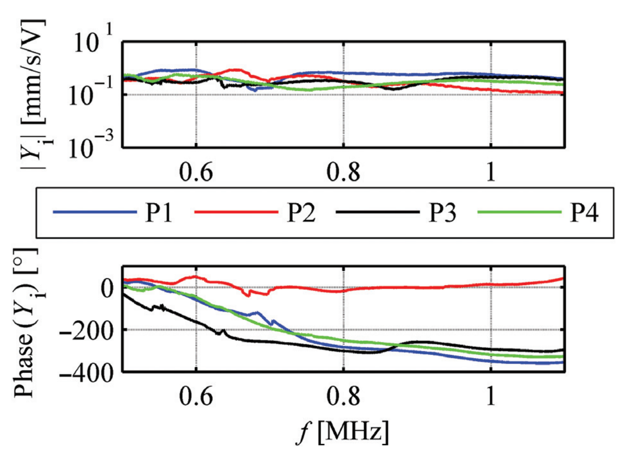

Figure 3: Measurement of intrinsic admittance and phase of four $LiNbO_3$ piezoelements of the transmitting transducer array; P1–P4 correspond to the individual piezoelements.

exciting the transmitters piezoelements in Phase and using the sum of the receivers piezoelements for evaluation.

Transit Time Measurements

To determine differences in material distribution, transit time measurements were conducted using the experimental setup described above. Transmitter and receiver arrays were pressed against composite specimens consisting of a steel block and a steel or aluminum plate. Measurements were conducted with two transducer arrays opposing each other. Figure 4 shows the signal over time at the receiver array for the specimen consisting of steel and aluminum. High voltage directly at the beginning of the measurement can be seen. This signal component is crosstalk of the signal generation electronics and is also present if no transducer array is connected to the electronics.

The signal reaches the receiver array after approximately 13 µs. This value agrees well with the considerations made earlier. After the first occurrence of the signal, no further delayed occurrences are clearly visible. Such further occurrences would be due to reflections inside the composite body. The transmitted signal is reflected at the interfaces between the transducers and the specimen and also at the interface inside the specimen.

In order to determine the transit time difference for the two different composite specimens a detailed view of the signals detected at the receiver array is shown (Figure 5). Here the detected signals for measurements on both composites are plotted in different colors. The blue curve shows the signal detected for the steel block and the steel plate, while the red curve shows the signal for the steel block with the aluminum plate. In order to determine the transit time difference of the burst signals, the average time difference of the first three distinct consecutive sine waves shown in Figure 5 was calculated. Considering the time values corresponding to the three maxima, an average time difference of 746.67 ns can be determined.

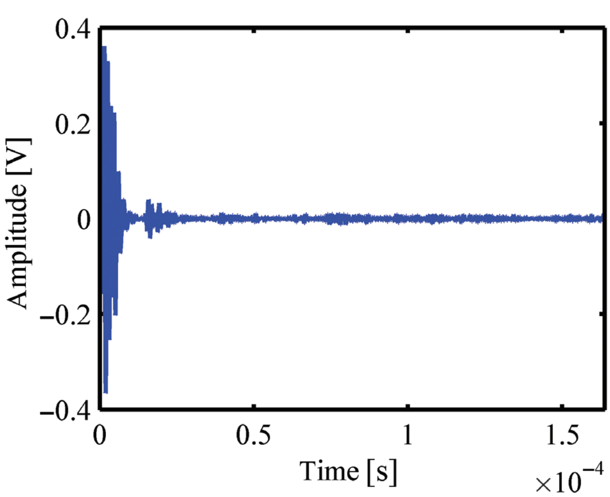

Figure 4: Signal of the receiving transducer array on composite specimen consisting of steel and aluminum.

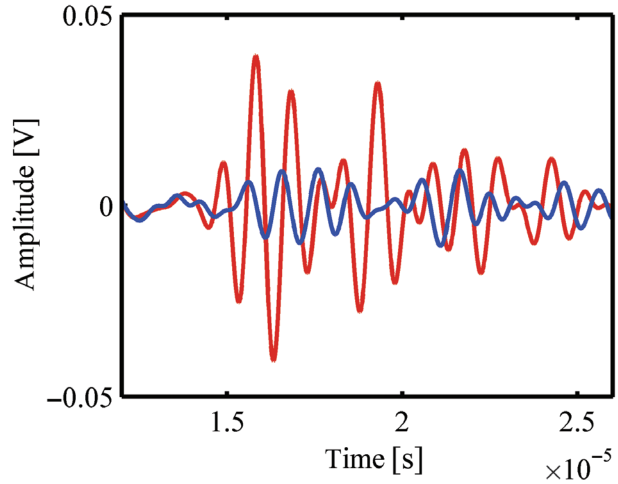

Figure 5: Details of receiver array signals: blue – steel–steel; red – steel–aluminum; $\Delta t = 746.67$ ns.

Besides the difference in transit time also differences in attenuation of the received signals can be seen in Figure 5. The signal for the measurement for the steel–steel composite shows a higher attenuation than the measurement for the steel–aluminum composite.

Conclusion

Transit time measurements with custom transducer arrays have been conducted. For different material compositions a difference in transit time has been measured. For two different composite specimens, steel–steel and steel–aluminum, an average difference in transit time of 746.67 ns could be determined. This measured value differs from the value calculated in Section "Experimental Setup" (590 ns). The explanation for this difference can be the approximate calculation of the difference in transit time. The values of sound velocity in the different materials have been chosen very roughly for calculation. This calculation can only be a rough guide to check the plausibility of the measurement results.

An additional factor which influences measurement results is the use of a coupling agent. Although the coupling agent ensures contact between the interfaces it also generates differences in impedance and is an additional material that is sonicated. Though the coupling agent film is thin its influence on measurement results should not be neglected.

The differences in attenuation between the steel–steel and the steel–aluminum measurement are also caused by impedance changes.

Further reflections of the transmitted signal which occur on the interfaces of the metal parts are not clearly recognizable in the measurements due to low transmitted and received amplitudes.

The measurements show that the custom-made transducer arrays can be used for transit time measurement. For the future application at elevated temperatures another body material has to be chosen. Also the individual piezoelements could be better matched to show more uniform intrinsic admittance.

For this investigation the layers of materials with different sound velocities were quite large. Workpieces with differences in material distribution or differences within the single materials, due to heat treatment, will have quite thin layers on the micrometer scale which show differences in sound velocity. In order to determine transit time differences of such materials, a higher time resolution is needed.

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