Single-Sided Contact-Free Ultrasonic Testing – A New Air-Coupled Inspection Technology for Weld and Bond Testing

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Abstract

The automotive industry profits of many fully automated processes during its fabrication stages. Most of the processes are performed by robots just like all typical welding processes. To achieve quality requirements testing is necessary. It is recommended that a radiation and contact-free nondestructive testing method is applicable. This ensures a maximum testing speed and a minimum of necessary safety provisions, preparations or post-processing of the test objects. Two special testing scenarios will be discussed using single-sided air-coupled ultrasonic testing. A main advantage is the contactless measurement without the application of any oil or water using high-power ultrasonic pulses. In addition to common transmission mode testing, we present a pitch-catch-technique using Lamb-waves. The influence of geometry effects and the importance of high bandwidth will be discussed. The first test specimen are edge-to-edge laser-welded metal sheets as used for instance in automotive production processes. The goal of a better quality assurance is the immediate control of the welding process. Accordingly, for future testing systems it is recommended to implement the work tool and the testing sensor into the welding robot. The aim of the testing is to monitor the complete performance of the welding and to record interruptions of the weld seam or any reduction of the laser energy. Any discontinuity within the sound path leads to changes of the ultrasonic signal. Due to the fact that the non-welded plates should have no defects, changes of the signal indicate directly a change of the weld seam. The second test samples are adhesive bonds found in composite material structures such as combinations of metal sheets and carbon fiber reinforced plastics (CFRP). The mechanical stability, lifetime and performance of such composite structures strongly depends on the quality of the bond. Air-coupled ultrasonic testing is a promising nondestructive method for the characterization of these bonds. In transmission mode the absence of glue acts as an additional interface within the test object which strongly reduces the transmitted ultrasound wave. Glue application errors can be detected easily.

Keywords: Ultrasonic Testing (UT), Air-coupled, Contact-free, Bond, Weld, Composites

1 Introduction

The automotive industry profits of many fully automated processes during its fabrication stages. Most of the processes are performed by robots just like all typical welding processes. To achieve quality requirements testing is necessary. This is normally done using nondestructive techniques at the finished pre-product. The goal of a better quality assurance is the immediate control of the welding process. Thus, for future testing systems it is recommended to join the work tool and the testing sensor at the welding robot. The aim of the testing is to monitor the complete performance of the welding and to keep records of interruptions of the welding seam. A special welding process is the laser assisted edge-to-edge welding of steel plates. Here it is important to recognize and report any disruption the welding material or the any reduction of the laser energy.

With respect to an industrial application three aspects had to be fulfilled. The method should be nondestructive, should be contactless, should be single-sided applicable and should allow 100% testing. The first two points are intrinsically fulfilled in air-coupled ultrasonic testing. The ultrasonic waves are transmitted and received through the coupling medium air. This method is normally used in through transmission mode, i.e. the transmitting and receiving transducer is located at both sides of the sample. Due to the difference of the acoustic impedances between air and typical samples (plastics, metals, adhesion, composite materials etc.) most of the ultrasonic wave intensity is reflected at the interfaces and only a small fraction reaches the receiver. Therefore high power transducers for transmitting enough signal and highly sensitive receivers and amplifiers are necessary. Typical intensity losses through different samples are in the order of 60 – 90 dB.

The third point of the above mentioned technical requirements, i.e. the single-sided approach is not easy to realize with air-coupled ultrasonic testing. The fact that most of the signal is reflected at the surface of the sample prevents to detect any signal because it is totally hidden within the front surface echo. One possibility is to excite Lamb waves. This allows to separate the two signals in a practical way. Often an additional shielding is used to suppress the signal of the front echo.

In this paper we present a simple method for air-coupled ultrasonic testing of welding seams between thin steel plates. A single-sided approach has been realized in a well-known pitch-catch configuration. Due to the special geometry no additional shielding of the front echo is necessary.

2. Method

The measurements of the present work were performed using the multichannel ultrasonic system SONOAIR of the company SONOTEC (Halle, Germany). The key component of the system is a 4-channel transmitter and a 4-channel receiver unit, respectively. The high-power digital amplifier provides an output with voltages up to 800 V in the frequency range of 50 kHz up to 3 MHz. The receiver unit is able to detect signals in the same frequency range with a gain between 0 dB and 120 dB using low-noise preamplifier and amplifier. An x-y-scanning system is available with different mounts for the ultrasonic transducers. Different drivers of controllers for positioning systems like scanners or robots are included in the software package. Ultrasonic transmitters and receivers are available in different frequencies between 50 kHz and 400 kHz. The measuring software allows the adaptive control of the measuring process such as scanning control, gate set-up, time delays for each transmitter and receiver channel and user defined filter for combining the signals. Moreover, an interface for more complex data processing is available.

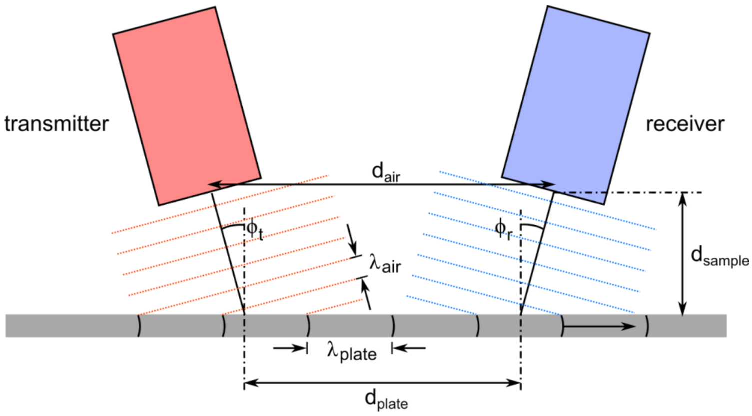

Figure 1: Working principal for single-sided air-coupled ultrasonic testing of lamb waves.

The basic principle of the testing method is shown Fig. 1. Above the sample the transmitter and receiver is placed with a certain angle ϕ_t and ϕ_r with respect to the surface normal. The transmitter emits an acoustic wave with a frequency of 200 kHz which is depicted as dotted lines. This regular air pressure wave hits the surface of the plate and induces an ultrasound wave in the plate. By adjusting the angle of incidence it is possible to tune the distance of the pressure oscillations to the corresponding wave length of the lamb wave in the sample (see Fig. 1). The now excited lamb wave propagates within the sample and leads to pressure oscillations at the interface as well. Therefore ultrasonic waves are reemitted again at the whole path length of the propagating lamb wave. As depicted in the cartoon the receiver detect these reemitted waves.

For the angle ϕ the following relation applies:

$$\sin\phi = \frac{\lambda_{air}}{\lambda_{plate}} = \frac{c_{air}}{c_{plate}} \quad (1)$$

To determine the optimum angle of the transducers it is possible to measure the reemitted wave at different distances d_{air} of both transducers. As the result one gets a B-scan of this measurement as shown in Fig. 2. The positive values of the ultrasonic signal are shown in red and the negative signals in blue color. With an increasing distance d_{air} the distance d_{plate} (see Fig. 1) increases as well. The signal leads to a pattern with a linear slope as depicted in Fig. 2(b). This slope corresponds to the inverse speed of the lamb wave. For the two different plates of 0.8 mm and 1.6 mm thickness velocities of 2100 m/s and 1600 m/s where found, respectively. This nicely fits to the expected behavior that the velocity of a lamb wave strongly depends on the material thickness [1]. Due to the decreasing of sound velocity with increasing thickness of plate a symmetric mode s0 is observed in this case. The asymmetric mode a0 is to slow and disappears in the much louder signal of the direct air wave. According to equation 1 the corresponding optimum angles of incident can be calculated to 9.3° and 12.3°, respectively.

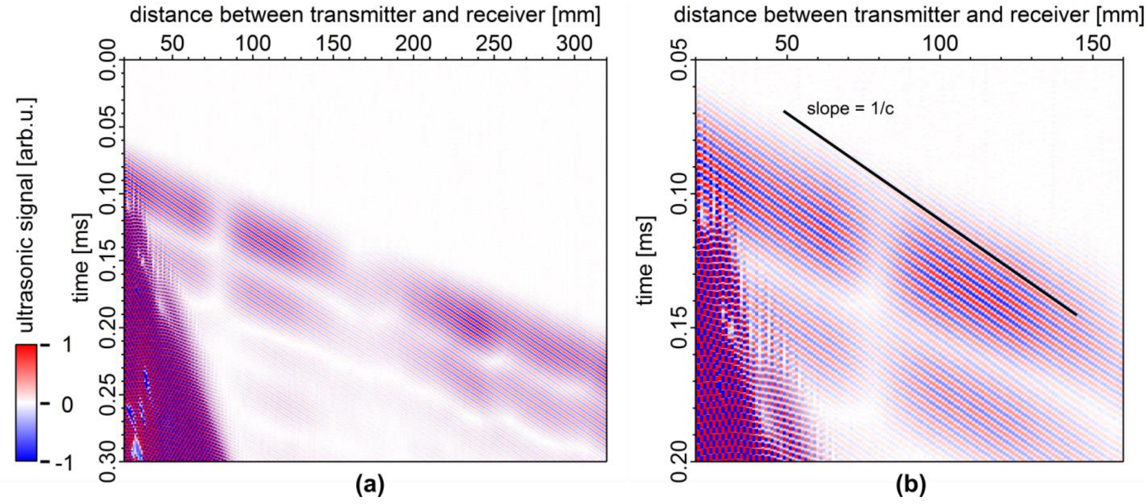

Figure 2: Determination of the sound velocity of the lamb wave within a 0.8 mm thin steel plate (a) and a detailed view (b).

Note that for this measurement it is not necessary to adjust the angle of incidence to the optimum value. Moreover this measurement helps to determine this angle in an easy way without any considering any other experimental boundary conditions for signal optimization. Contrary to a single mode excitation [2] the transmitter is placed within the near field length to the sample to excite even a multi-mode signal.

3. Results

For the characterization of the welding seam the setup as shown in Fig. 3 was used. The ultrasonic transducers with a frequency of 200 kHz have a distance d_{air} of approx. 45 mm to each other. To enable a totally contactless method no additional shielding was applied. It is expected to detect in general two main signals, i.e. the direct sound wave through air between the two transducers and the reemitted lamb wave signal.

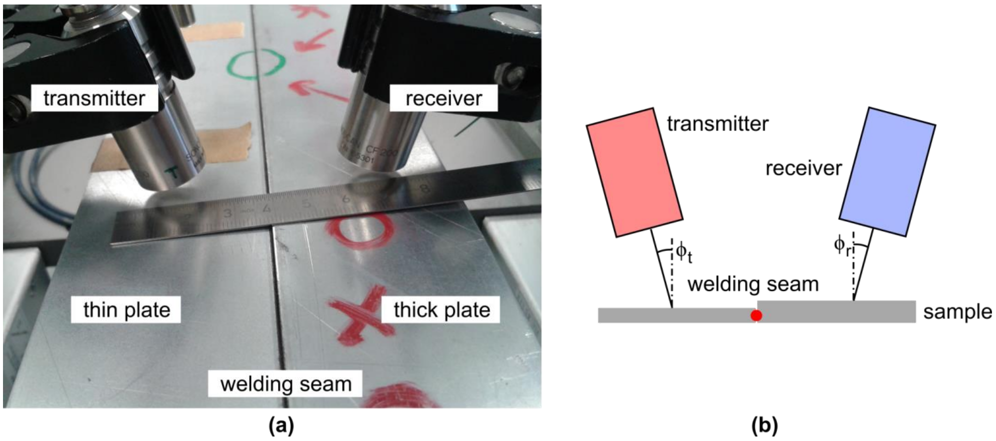

Figure 3: Experimental setup for the welding seam inspection (a) and (b). Tape measure shows mm units.

To separate both from each other it is necessary to adjust the distances in a proper way. Therefore the times of flight of both signals have to be compared. According to Fig. 1 the following equations apply:

$$t_{air} = \frac{d_{air}}{c_{air}} \tag{2}$$

$$t_{sample} = 2\frac{d_{sample}}{c_{air}} + \frac{d_{plate}}{c_{plate}}. \tag{3}$$

To reach the separation the following condition has to be fulfilled:

$$t_{air} > t_{sample} + t_{pulse} \tag{4}$$

Note that the fulfillment of equation (4) requires an important experimental condition. As already visible in Fig. 3(a) the distance between the transducer and the sample (d_{sample}) should be as small as possible to get the smallest time t_{sample}. Therefore one normally has to adjust the sample within the nearfield length of the transducers. This normally leads to artifacts in traditional scanning methods but seems to be no problem in this special configuration from our point of view. One additional argument is the given geometry of the investigated samples. The only defect should occur within the welding seam. Therefore the direct shape of the ultrasonic wave at the entrance of the plate is less important because the path through the plates is always the same and no additional change of the ultrasonic signal is expected.

In Fig. 4(a) the results of the A-scans at the defect-free and defective region of the sample are shown. At larger times above 0.17 ms the signal through air is visible. Note that the latter one has a much higher intensity because no intensity losses at the sample-air interface occur and normally saturates at this level of signal amplification. At smaller time of flights between 0.08 and 0.15 ms the signal through the sample is recorded and nicely separated from the direct air signal. Comparing the signals at those different sample positions a change of the intensity is observed. The signal is smaller at defective regions. Additionally to the drop of the signal intensity a shift of the signal phase is observed as well as indicated by the dotted line. The whole measurement is shown as a B-scan in Fig. 4(b). Here an additional change of the intensity and phase behavior at time of flights around 0.15 ms becomes nicely visible. The lateral extension of both patterns (around 0.1 and 0.15 ms) is different and might help to characterize and distinguish between different defect types. However, the B-scan patterns observed in air-coupled ultrasonic testing using lamb waves are comparable with those found in traditional coupled TOFD analysis.

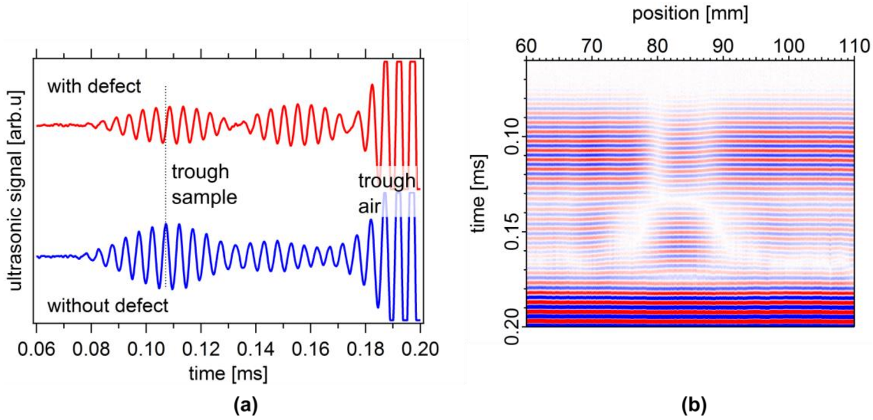

Figure 4: A-scans of defect-free and defective regions of the sample (a). B-scan the whole defective region (b).

For a closer analysis the data of Fig. 4(b) are analyzed in more detail. The results are shown in Fig. 5. The standard intensity analysis is shown on large scale of the position coordinate in Fig. 5(a) and in more detail around the defect in Fig. 5(b). Between 75 and 90 mm an intensity drop is observed. In the center of this feature a small increase of the intensity occurs. For a better comparison of the length scale the black bar indicates the distance of 10 mm which is equivalent to the present defect length. Before and after the defect additional intensity fluctuations are observed. However, those show an increase of the intensity and are most likely due to interference effects of the ultrasonic waves within the sample in the vicinity of the defect. In Fig. 5(c) and (d) the time of flight (ToF) data are shown on the same position scales. As already mentioned above the defect leads to a shift of the signal phase which leads to an increase of the time of flight. Again the black bar indicates the defect length.

Comparing those two analysis methods different conclusions are possible. At first the signal to noise ratio is better for the intensity method. But the results of the ToF measurements are far away from any noise limitations. For an easy characterization of the defect length the ToF is more reliable. The signal change occurs only within the defective region. Note that the small change of the ToF at positions larger than 100 mm is due to the geometry of the sample which is not perfectly flat which changes the distance between the transducer and the sample. However, the additional fluctuations of the intensity data may contain additional information of the defective region and might be used to perform further characterizations of the seam or its defects.

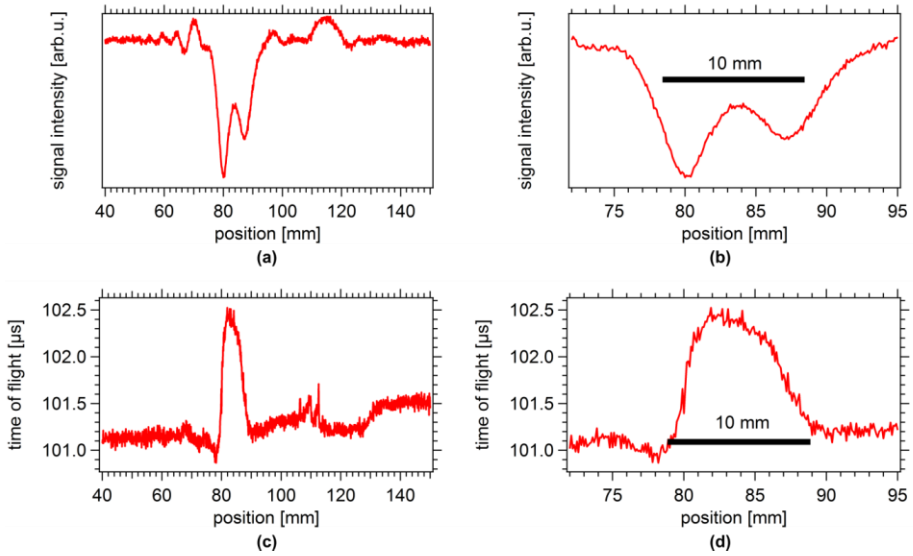

Figure 5: Intensity (a and b) and time of flight analysis (c and d) of the data of Fig. 4(b).

To check the influence of the setup to the signal different arrangements were tested as shown in Fig. 6(a-c). The distance between both transducers are fixed due to the requirement of equation (4). Only the relative position of the welding seam was changed. In configuration (a) the seam is close to the receiver, (b) in the middle of both and in (c) the seam is close to the transmitter. The results of the intensity and ToF analysis are summarized in Fig. 6(d) and (e), respectively. The obtained curves do not show any influence to the exact position of the welding seam. Only the ToF signatures for the asymmetric configurations (blue and green curves) are slightly narrower but in both cases in a similar way.

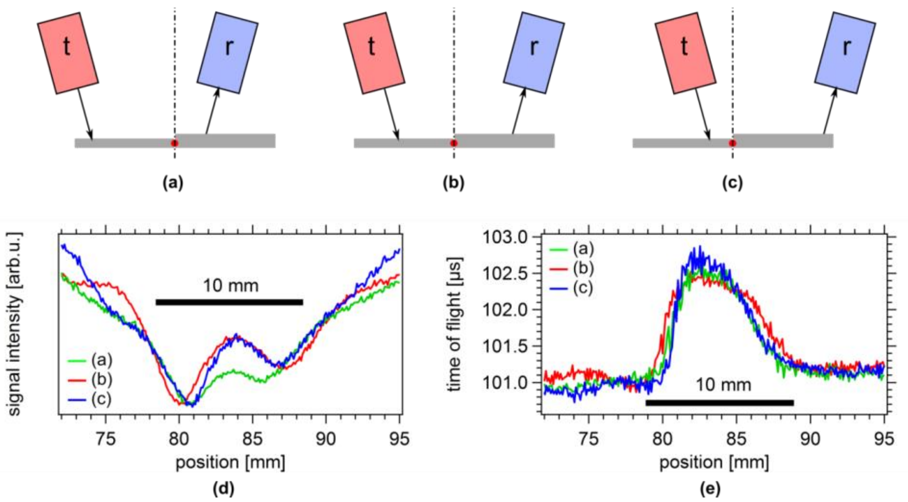

Figure 5: Intensity (d) and time of flight analysis € using different setups (a-c).

4 Summary and outlook

We presented a new approach for the characterization of laser assisted edge-to-edge welding seams. The method is based on single-sided air-coupled ultrasonic testing and based on excitation and detection of lamb waves. The given geometry of the investigated welding seam and the transducer setup allows to measure totally contactless without any shading support.

The obtained ultrasonic data are sensitive to defects of the seam in the signal intensity as well as the time of flight. Both signals allow to characterize the condition of the seam. The dimension of the defect size can be evaluated. The method is independent of an exact configuration of the transducers with respect to seam which allows an easy implementation of this method into automated systems. The applied data analysis has been developed in post-processing but can be fully implemented into online analysis with direct output of the result.

References

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