High temperature (> 500°C) wall thickness monitoring using dry coupled ultrasonic waveguide transducers

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Abstract

Conventional ultrasonic transducers cannot withstand high temperatures for two major reasons: the piezoelectric elements within them depolarise, and differential thermal expansion of the different materials within a transducer causes them to fail. In this paper the design of a high temperature ultrasonic thickness gauge that bypasses these problems is described. The system uses a waveguide to isolate the vulnerable transducer and piezoelectric elements from the high temperature measurement zone. Use of thin and long waveguides of rectangular cross section allows large temperature gradients to be sustained over short distances without the need for additional cooling equipment. The main problems that had to be addressed were the transmission and reception of ultrasonic waves into and from the testpiece that the waveguides are coupled to, and optimisation of the wave propagation along the waveguide itself. It was found that anti-plane shear loading performs best at transmitting and receiving from the surface of a component that is to be inspected. Therefore a non-dispersive guided wave mode in large aspect ratio rectangular strips was employed to transmit the anti-plane shear loading from the transducer to the measurement zone. Different joining methods to attach the waveguides to the component were investigated and experiments showed that clamping the waveguides to the component surface gave the best results. The thickness of different plate samples was consistently measured to within less than 0.1mm. Performance at high temperatures was tested in a furnace at 730°C for 4 weeks without signal degradation. Thicknesses in the range of $3 - 25$mm could be monitored using Hanning windowed tonebursts with 2 MHz centre frequency.

I INTRODUCTION

In the petro-chemical industry there is a need to monitor pipe wall thicknesses at high temperatures. Crude oil, the base material for any petro-chemical process, is a cocktail of many compounds that has to be processed at elevated temperatures in refining plants. Many of the compounds in the crude oil are chemically active and can attack the pipe work leading to wall loss which can ultimately lead to leakage. The rates of attack are usually exacerbated at elevated temperatures [1]. Wall loss and potential leakage present substantial safety and financial risks (potential loss of life, plant and production). Plant operators usually try to mitigate these risks by regular wall thickness measurements at predefined thickness monitoring locations in a plant.

Ultrasonic thickness gauging is the most commonly used non-destructive testing technique for wall thickness measurements. However, current commonly available ultrasonic transducers cannot withstand high temperatures ($> 250°$C). It is therefore necessary to carry out manual measurements at plant shut downs. The current procedure thus has a number of disadvantages: inspections have to be performed at shut downs with the possible consequences of prolonging down time and increasing production losses, insulation has to be removed and reinstated for each manual measurement, and scaffolding has to be built to inaccessible areas within the plant, resulting in a considerable cost of the interventions. It has been suggested that a structural health monitoring (SHM)approach [2] with permanently installed ultrasonic thickness gauges could have substantial benefits over current practices. Permanent installation would allow more frequent measurements to be taken and remove errors introduced by re-coupling the probes thus resulting in higher fidelity data. It would also remove the need to disturb insulation and build scaffolding to inaccessible test points, resulting in a large reduction of the cost per measurement. The main challenge to be solved is the development of an ultrasonic transducer that can withstand elevated temperatures (500°C or more) so that permanent installation in a petrochemical plant is possible. This paper outlines the development of a waveguide based transducer that separates the high temperature measurement area from the ultrasonic transducer and processing electronics. Theory and implementation as well as experimental results are presented.

Knowledge of the financial consequences of prolonged shut downs, that can be of the order of millions of dollars per day, has aroused a strong interest in developing ultrasonic transducers that can operate at elevated temperatures in the past. One of the main reasons why conventional piezoelectric ultrasonic transducers cannot be used at high temperatures is because the piezo-ceramic becomes depolarised at temperature above the Curie temperature ($200 - 400$°C depending on type [3]) or because differential thermal expansion of the substrate, bonding layer and piezoelectric material cause failure. The development of piezo-materials that can sustain high temperatures and other harsh environments such as high radiation levels is being carried out by many researchers [4], [5], [6], [7], etc. Materials like bismuth titanate and lithium niobate can survive temperatures up to 550°C and 1000°C respectively, but lithium niobate decreases in sensitivity over time when left in an uncontrolled atmosphere at high temperature [8]. Kobayashi [9] and Wu [10] recently presented integrated piezo thick films that can be directly deposited onto structures and which can withstand high temperatures. However the attachment procedure for these transducers is intricate and time consuming, consisting of several deposition steps and subsequent poling. This is required to achieve robust attachment. Coupling and attachment issues are a major challenge for all high temperature piezoelectric materials since differences in material thermal expansion coefficients lead to the build up of large stresses. Progress is being made in the field, but to date there is no generally applicable solution for high temperature ultrasonic transducers that is easily applicable and widely commercially available.

Kazys et al. [11], [12] reported the development of a high temperature ultrasonic sensor for immersion in liquid Pb/Bi metal up to temperatures of 450°. They reported serious difficulties in finding a suitable joining method of the individual transducer components and developed sophisticated methods to overcome these problems. However, since they coupled into liquid metal they did not have to consider coupling the transducer into a solid material. Several authors have reported on the use of EMATS (electro-mechanical acoustic transducer) at elevated temperatures [13]. Dixon et al. [14] reported on the use of water cooled EMATs for wall thickness measurements at temperatures up to 450°C.

While there are also other very expensive techniques such as laser ultrasonics [15] that can be exploited at high temperatures, the most promising inexpensive method is the use of a buffer waveguide to isolate the sensitive transducer from the hot specimen. Such an implementation allows the use of commercially available standard piezo-crystals as transducers while a cheap and robust buffer waveguide (delay line) ensures that the temperature at the transducer itself is reduced to acceptable levels.

The buffer waveguide idea has already been pursued by previous researchers, mainly from the field of fluid flow measurement. The main problems to overcome are the dispersive nature of wave propagation in waveguides, and the transmission of energy into the specimen at the waveguide/specimen junction. Lynnworth and coworkers [16], [17], [18] have developed a series of wire bundle systems in order to produce marginally dispersive propagation of extensional waves along a waveguide system. They identified dispersion as the main problem and in order to minimise dispersion in the waveguide they excited the L(0,1) mode in very thin wires. The L(0,1) mode is the fundamental longitudinal wave mode that can propagate in a wire with a mode shape that exhibits uniform displacements across the section of the wire and polarisation along its axis. Due to the small diameter of the wires the waveguide operates at low frequency-thickness products where the phase velocity is almost frequency independent, i.e. non-dispersive (see standard texts on guided waves such as Rose [19] and Graff [20]). In order to obtain strong signals, many wires were put together in a bundle.

For the purpose of fluid flow metering Lynnworth [21] also patented a device that he called the 'hockey stick'. It uses shear waves that mode convert into pressure waves in the fluid that is contained within the pipe. The devices of Lynnworth et al. are designed for fluid flow metering applications. They work in the pitch catch mode (send on one probe and receive on another) in order to overcome high coupling losses and transmit across a fluid conduit. To couple enough energy into the fluid their cross sectional area is large (the width is about 30mm and the thickness of the order of the pipe wall thickness).

Heijnsdijk and van Klooster [22] have proposed a coiled foil waveguide as an alternative to a bundle of rods. The thickness of the foil is arranged to be much smaller than the smallest wavelength to be propagated; this ensures that the frequency thickness product of the foil is very low and therefore compressional pulses will propagate essentially non-dispersively along the foil. The foil is coiled around an axis parallel to the propagation direction and so if unwrapped would be very long in the direction parallel to propagation. This mimics a plane wave propagating along the foil where interference from edges is kept to a minimum.

Jen and co-workers [23], [24], [25], [26] have tried to limit the number of modes traveling in a thin bar by adding an attenuative cladding on the outside of the bar, the bar usually being tapered. This is essentially an attempt to remove the effects of the waveguide boundaries by reducing the amplitude of reflections from the surface. The number of trailing echoes is thus almost entirely removed; however the effects of dispersion are not entirely removed and the signal is slightly delayed, slightly distorted and strongly attenuated. This method is an improvement on older solutions that utilise uniformly and non-uniformly threaded bars as waveguides [27], [28]. Nevertheless the relatively high attenuation limits the propagation distance for this waveguide. At the same time, a longer waveguide is needed to isolate the transducer from high temperatures due to the large diameter of the waveguide (see figure 1). Furthermore, as for all other buffer waveguide methods, attaching these large waveguides with reliable coupling poses a major problem. Welding and brazing larger cross section waveguides to the structure without the introduction of defects is very difficult while conventional liquid coupling agents cannot be used at high temperatures, since they evaporate.

II The waveguide concept

Figure 1a) describes the waveguide concept. A transducer at one end excites an ultrasonic signal that travels along the waveguide, is coupled into the material under test and then a second waveguide is used to pick up the signal from the test piece and conduct the signal back to a receiving transducer. In order for this principle to work there are three different aspects that need to be considered in detail: the temperature distribution along a waveguide coupled to a hot body at constant temperature; the ultrasonic source characteristics of different waveguide geometries on a metal substrate; the ultrasonic wave propagation in the waveguide. The following sections will discuss each of these topics.

A Temperature isolation

The main purpose of the waveguide is to isolate the fragile piezoelectric transducer element from the high temperature environment that it cannot withstand. Figure 1b) illustrates this by plotting the temperature distribution along waveguides of different cross sections attached to a constant high temperature source (600°C) and surrounded by air ($k = 1W/m/K$) at ambient temperature (25°C). Calculations were performed as described by Mills [29]. The figure shows that a thin ($0.5mm$ radius wire or 1 by $15mm$ strip), poorly heat conducting, stainless steel (thermal conductivity $k = 15W/m/K$) waveguide can sustain a temperature drop from 600°C to 50°C over a distance of $0.2 - 0.3m$ under natural convection cooling, while a larger radius waveguide ($10mm$ radius) needs to be substantially longer ($\sim 1m$) to sustain the same temperature drop.

B Source characteristics

In order to use waveguides as transmitters and receivers of ultrasonic waves on engineering specimens, knowledge of the waveguide's source characteristics is most important. This was developed by considering the specimen to be a half space and the stress field corresponding to the mode shape of the traveling mode in the waveguide was used as the loading function on the half space. In order to simplify the analysis the waveguide was assumed to be either a small circular source or an infinite line source whose characteristics could be approached by a waveguide of large width to thickness ratio (width $>> \lambda >$ thickness, where λ is the wavelength of the interrogating signal in the waveguide). It was thus possible to recall the results of studies on ultrasonic wave excitation by circular or line-loads on half spaces which have been described by many authors, e.g. [20], [30], [31], [32], [33].

A paper by Miller and Pursey [30] gives a very good account of the wave fields excited by different loading conditions on half spaces. They split the solution into two displacement wave fields: one for dilatational or compressional waves denoted by u_R and the other showing the directivity of shear waves denoted by u_θ. It is beyond the scope of this paper to discuss the solutions to each case in detail (see [34] for more detail) and only the outcome of the work will be summarized here.

The different loading conditions that were considered are shown in figure 2. For normal point loading, normal line loading and tangential line loading (cases a, c and d in figure 2), both longitudinal and shear waves are excited. Furthermore in all those cases a strong surface wave is excited. The surface wave does not penetrate into the material and therefore in thickness gauging applications the energy that it contains can be considered as wasted. Miller and Pursey [31] showed that the energy radiated by the surface wave is about 67% of the total source energy of a point source, while the shear and compressional waves only radiate 26% and 7% of the source energy respectively. However, in the cases of circular torsional loading and anti-plane shear loading (cases b and e in figure 2), only shear waves are excited. For maximum signal strength it is desirable that all the energy is transmitted into one type of wave and therefore circular torsional and anti-plane shear sources exhibit the most desirable characteristics.

The directivity of the excited waves is also important. Ideally the source radiates equally strongly in all directions or emits a narrow beam in the normal direction (angled beams would require the separation between emitter and receiver to vary depending on the component thickness that is to be monitored). Figure 3 shows the source directivities for the different loading conditions. For normal point and line sources the results are similar (only line source results are shown in figure 3a) and a relatively broad beam ($60°$ wide) of longitudinal waves is excited in the direction normal to the surface. However this beam is weaker than the excited shear waves that travel in a narrower beam ($15 - 30°$ wide) at an angle of $30 - 45°$ to the normal of the surface. For the tangential line source (figure 3b) , again the shear wave is much stronger than the longitudinal wave. The shear wave travels normal to the surface over a range of about $60°$ with a distinct peak at about $57°$. The much weaker longitudinal wave travels in a relatively narrow beam ($15°$ wide) at a shallow angle of $30°$ to the horizontal. The directivity of the torsional circular disc (figure 3c) has two hemispherical lobes without coverage of the normal direction, while the anti-plane shear source (figure 3d) radiates equally strongly in all directions. Therefore the anti-plane shear source again shows the most desirable characteristics for thickness gauging applications and it is important to transmit these anti-plane shear loads from the transducer via the waveguide to the specimen surface.

C Wave propagation in a strip

The main task of the waveguide is the transmission of ultrasonic signals (stress waves) from the transducer to the specimen and back again. In general the signal transmission should be as strong as possible and with as little distortion as possible, i.e. non-dispersive. The previous section showed that for optimal operation of the system the waveguide should transmit anti-plane shear line loading onto the surface of the specimen. This can be achieved with shear horizontal (SH0) wave propagation along a strip waveguide. However, it is important to ensure that a mode similar to the shear horizontal (SH0) mode in an infinite plate can be obtained in the finite width strip waveguide.

In standard textbooks (e.g. Rose [19] and Graff [20]) analytical solutions to wave propagation in infinite plates and perfectly cylindrical waveguides are usually presented, but solutions to waveguides of rectangular cross sections are more complex and are not presented. Solutions for rectangular cross section (strip) waveguides can be found using a semi analytical finite element technique (sometimes referred to as 'SAFE' [35]). The analysis is beyond the scope of this paper and was presented in a separate publication [36], but the main findings will be recalled here.

It was found that a shear horizontal type guided wave mode that is very similar to the shear horizontal (SH0) mode in infinite plates exists in strips of large aspect ratio (width >> thickness) rectangular cross section. The mode was called the SH* mode (the * differentiating it from the SH mode of an infinite plate and reminding the reader that it is a strip mode). Figure 4 shows the phase velocity dispersion curve of the SH* mode in a 1mm thick and 15mm wide steel strip ($\rho = 7932 kg/m^3$, $E = 216.9 GPa$, $\nu = 0.2865$) and the corresponding shear stress (σ_{yz}) mode shape of the SH* mode at 2 MHz ($\lambda \sim 1.5$mm). It can be seen that the SH* mode has a cut off at about 120kHz and asymptotically approaches the bulk shear velocity (c_s) in the high frequency limit. The phase velocity difference between the SH* mode and the bulk velocity is less than 1% above 1MHz and it can therefore be assumed that high frequency SH* mode signals travel virtually non-dispersively (without distortion) along the waveguide.

The mode shape in figure 4 c) clearly illustrates the distribution of shear stresses across the width of the waveguide. Shear stresses are strongest at the centre and decay in a parabolic fashion towards the edges. From figure 4 c) it can be seen that the energy of the guided wave mode is concentrated at the centre of the strips with marginal contributions from the edges. Thus the SH* mode is insensitive to disturbances such as clamp attachments to the edge of the strip which has the practical advantage of being able to attach features to the edges of the strip without influencing the signal. When coupled to another component the transmitted shear stress profile is many wavelengths ($> 7\lambda$) wide and less than one wavelength ($< 1\lambda$) thick. The waveguide source thus emits SH waves that spread as if radiated from a point source in the thickness direction and collimated (as if excited by a very large transducer) in the width direction. At the central plane the waveguide source very closely approximates a line source of SH waves.

In [36] it was shown that the SH* strip mode can be selectively excited with signal to noise ratios of 30dB and better. Since it is non-dispersive for signals with frequency content above 1MHz and transmits anti-plane shear loads, the mode is an ideal candidate to transmit and receive ultrasonic signals from a remote piezoelectric transducer to a specimen. Therefore the next step was to implement this practically.

III Experimental Tests

In conclusion from the theoretical investigation it was found that a large aspect ratio rectangular strip is the best waveguide geometry for transmitting ultrasonic waves along a waveguide and coupling them into a solid component under test. The large aspect ratio rectangular section allows the excitation of a non-dispersive SH mode which allows the transmission of short, broadband pulses from the transducers to the test component and at the same time has the source characteristics that allow strong coupling into a bulk SH wave that spreads in a cylindrical fashion into the test piece. A range of experiments were conducted to experimentally investigate the feasibility of testing at high temperatures.

A Attachment

In practice it is required to permanently attach the waveguide to the test piece in order to allow thickness monitoring. Monitoring locations are hardly ever known a priori so a reliable attachment technique that results in high signal fidelity had to be found. Two attachment methods were investigated: welding/brazing and clamping. Twelve 300mm long, 15mm wide and 1mm deep stainless steel (SS304) strips were welded or brazed to a 6mm thick, 100 x 50mm mild steel plate by tungsten inert gas (TIG) welding while brazing was done by silver soldering the strips to the plate. Once samples were prepared, a 1/2 inch ultrasonic shear transducer (Panametrics/Olympus NDT V154) was coupled to the far end of the waveguide (stainless steel strip) to excite the SH* mode. The transducer was the same for all the experiments; it was coupled by shear couplant (honey) with its face onto the cross section (1x15mm) of the strip and held in place by a purpose made clamp. It was ensured that the polarisation direction of the transducer was parallel to the width of the strip and that the SH* mode was excited strongly (SNR 30dB). A detailed description of the transducer clamp construction can be found in [34]. All signals were 5 cycle, 2MHz Hanning windowed tonebursts. They were generated by a purpose built function generator receiver unit (Wavemaker Duet, Macro Design Ltd.) and signals were recorded by an oscilloscope (LeCroy 9400A) before being transferred to a PC for subsequent signal processing.

It was very difficult to weld the thin strips onto a thick plate reliably.

The main problems were burning through the strip, burning off the edges of the strip or build up of excessive flash around the weld. The best pulse echo measurement of all the welded samples is shown in figure 5. Figure 5a) shows the pulse echo signal in the strip, i.e. the signal that was reflected from the waveguide end, before it was welded to the plate. Figure 5b) shows the pulse echo signal that was received after welding. The returning signal amplitude is reduced compared to an unattached strip and many more wave packet arrivals can be seen. Note the change in scale between figure 5a) and figure 5b). The strongest arrival occurs at the same time as the end reflection in an unattached strip and there are reverberations within the plate. Vertical lines indicate the expected arrival time from backwall echoes in the 6mm thick plate. There are no arrivals that correspond with the expected times. This is due to the effect of strong signals caused by the presence of the weld fillet which mask and interfere with backwall signals. Therefore thickness gauging using these signals is impossible. In all of the 12 samples the weld/braze fillet signals were as strong or even stronger than in the time trace shown in Figure 5. For these reasons attachment via welding/brazing was deemed not feasible.

Next attachment by dry clamping was investigated. A clamp that could attach two parallel waveguides with a separation of 1mm to the plate was manufactured (see figure 6). The clamp only made contact with the waveguide edges, where the wave amplitude is practically zero, see figure 4; it therefore did not influence the signal. Using this clamp it was possible to test the waveguides in pulse echo mode (send and receive on the same strip) and pitch-catch mode (send on one strip and receive on the other). Figure

7a shows the pulse echo signal collected from a strip waveguide clamped to the plate specimen. The signal is dominated by the end reflection signal, followed by a long train of low amplitude signals. Coupling through the clamped junction is poor and therefore signals from features within the plate specimen are very weak and are hidden within the arrival of low amplitude strip modes that are present due to imperfections in the transduction system or the waveguide/plate junction.

Figure 7b shows the signal received in pitch-catch mode on the strip clamped adjacent to the sending waveguide as shown in figure 6. While the signal amplitude is much reduced (note the difference in scale in 7a and b) the signal arrivals are much better defined. This is because the receiving strip only receives signals that have been transmitted into the plate specimen which reduces their amplitude but avoids pollution from unwanted strip modes that are excited upon reflection from the strip end. It can therefore be noted that signal clarity and transmission through the joint without considerable distortion is much more important than the transmitted amplitude. Therefore dry clamped joints are much preferable to welded joints.

Figure 8 shows the signal path that the wave travels once transmitted into the plate. The anti-plane shear source emits shear waves almost equally strongly in all directions, therefore the first arrival is a signal that traveled the direct path between sending and receiving waveguide via the plate surface. Since the two waveguide centres are separated by $\sim$ 2mm, the first arrival is only slightly delayed with respect to the end reflection signal collected in pulse echo mode (figure 7a). Subsequent arrivals have traveled once or multiple times to the backwall and returned to the receiving strip. The delay between consecutive echoes is proportional to the plate thickness and can be used to calculate it if the shear velocity of the plate material is known.

The studs to attach the clamp to the specimen were welded on using simple commercially available stud welding equipment. This process is very practical, reliable and takes less than a second (a few minutes including setup time). The minimum clamping force that is required to obtain strong signals is around 500N. The signal amplitude increases slightly when increasing the clamping force however this has no effect on the arrival time of the signals and $500 - 2000$N is a good operating range. The temporal features of the signals are very repeatable on reclamping however the amplitude does change with each reclamp. Tests on curved surfaces such as measurements on pipes have shown that the curvature does not have a detrimental effect as long as it is large compared to the thickness.

B Thickness measurements

Once the repeatability of the clamped coupling mechanism was established, the method was used to clamp the waveguide system to a stepped wedge of different thicknesses ($4, 5, 6, 8, 10mm$) in order to verify the thickness measurement capabilities of the system. Time traces recorded by the SH* mode waveguide system clamped to the different steps are displayed in figure 9.

The first arrival stays constant for all plate thicknesses, while the second and later arrivals are delayed in proportion to the thickness of the block. This is expected since the first signal corresponds to the signal travelling from the sending waveguide along the surface of the block to the receiving waveguide, and so the first signal is independent of the thickness of the plate. Later arrivals are echoes from the other side of the plate and depend on the plate thickness.

The time difference between the second and third arrivals was determined from the peak of the Hilbert envelope of the signal and then used to calculate the thickness of the specimen. The Hilbert envelope was chosen over more advanced signal processing techniques because it is very simple to implement this on an onboard processor without the need for much processing power. The necessary bulk shear velocity was determined by a reference measurement on the thickest part. Figure 10 shows thicknesses evaluated by the SH* mode measurement plotted against the thicknesses determined by means of a caliper. The two measurements agree to within 0.05mm (average of errors).

C High temperature measurements

The system was then tested at high temperature. A pitch catch arrangement of two waveguides was employed. Two 1mm thick, 15mm wide and 500mm long stainless steel waveguides were clamped to a 6mm thick stainless steel plate. For temperature measurements a thermocouple was welded onto the steel plate at a location remote from the waveguide. The specimen was then placed in a furnace. A hole in the furnace allowed the waveguide strips to reach outside the furnace, creating a clearance distance of about 350mm between the oven and the transducer location. According to the predictions in figure 1 this clearance distance should be ample to allow for the temperature to drop from the furnace temperature at the specimen end of the waveguide to room temperature at the transducer end of the waveguide. When the furnace was heated to $500 - 600°C$ the transducer end could be comfortably held by hand, showing no noticeable increase in temperature.

During heating the temperature and ultrasonic signals were acquired by a PC. The temperature was logged every minute using a thermocouple logger (TC08) and the Picolog software (both from Pico Technologies Ltd.). Ultrasonic signals were sent and received using the desktop ultrasonic instrument (DUI) which is a combined arbitrary function generator and oscilloscope system produced by NDT Solutions Ltd. Signals were automatically recorded every 3 minutes during heating and every 5 minutes while cooling.

Figure 11 displays signals acquired during a typical heating cycle and a corresponding temperature curve is also shown. The arrival of the group of signals is delayed at higher temperatures due to the reduction of shear velocity in the waveguide at high temperatures. An increase in the separation between backwall echoes can also be identified; however because the propagation path in the plate is very much shorter compared to the path in the waveguide this effect is more subtle. Signal amplitudes remained strong, suggesting that there is no drastic change in attenuation over the temperature range used in the experiment.

The experiment was cycled several times and the recorded time traces were then used to evaluate the shear velocity in the plate specimen. The Hilbert envelope was used to evaluate the arrival time of a signal packet. The ultimate aim of the waveguide transducer is to monitor thicknesses at elevated temperatures. In this particular test the plate thickness was fixed and did not change. However, the ultrasonic velocity is a function of temperature and the temporal separation of the signal arrival times was used to calculate the shear velocity in the test plate. The shear velocity change can then be compared to expected values from the literature. In the above calculation the change in ultrasonic path length due to thermal expansion of the material was corrected for. For stainless steel Kaye and Laby [37] quote an expansion coefficient of $19.7 * 10^{-6}$/K at a temperature of 500°C. This value was used to correct for the thickness due to thermal expansion; the overall change to be expected over a temperature range of 600°C is thus about 1.2%.

Figure 12 shows the measured shear velocity from a heating and cooling cycle on a fine scale and a resulting linear curve fit. The standard error of the velocity measurement from the linear curve fit is 10m/s which corresponds to $\pm 0.3\%$ of the overall velocity. There is a linear decrease in velocity from $\sim$ 3100m/s at room temperature to $\sim$ 2800m/s at 550°C, which represents about 10% of the overall velocity. These results are in line with what is to be expected from data in the literature. For a different steel Papadakis et al.

[38] reported a drop of shear velocity from ~ 3200m/s at room temperature to ~ 2900m/s at 600°C. Compared to the measured 10% decrease in velocity the change in thickness due to thermal expansion of $\sim 1.2\%$ is negligible.

To demonstrate the long-term stability of the monitoring system, a different set of waveguides was clamped to a stainless steel plate and placed in the furnace. The furnace was switched on and kept running at a temperature of ~ 730°C for a period of 4 weeks. The temperature was monitored every hour to ensure continuity in temperature, and ultrasonic traces were recorded at regular intervals (every 20 minutes). The first and the last collected time traces are shown in figure 13. The signals remained relatively unchanged throughout the monitoring period (there was a slight drop in peak amplitude -1.4dB but the arrival time remained the same). The testing temperature of 730°C was chosen to be much higher than the intended maximum operating temperatures $500 - 550$°C of the waveguide thickness gauge in order to accelerate creep related degradation mechanisms in the clamp, which could result in a loss of coupling. It is well known that creep rate increases exponentially with temperature [39] and it was estimated that testing at 730°C for 4 weeks is equivalent to testing for 6.5 and 25 years at 550°C and 500°C respectively. The experimental results lead to the conclusion that long term monitoring at high temperatures with the proposed setup is possible.

D Corrosion measurements

Wall loss measurements by corrosion or erosion processes at elevated temperatures are the main intended application of the sensor. The waveguide sensor output in a simulated corrosion test was therefore experimentally verified. Two waveguides were attached as previously described to a $9.9mm$ (verified by micrometer measurement) thick mild steel plate by a purpose made clamp. The mild steel plate was then half immersed in a salt water bath so that the surface that the waveguides was attached to was above the water level and the opposite plate surface was immersed. An electrode (steel strip) was placed below the plate surface that was to be corroded and a current ($\sim 10A$) was applied across the mild steel plate and the electrode using a car battery charger. Before the current was turned on the acquisition system (same as previously described) was started and ultrasonic signals were collected every minute. The thickness was calculated from the collected ultrasonic signals. A schematic of the setup is shown in figure 14a) and the thickness measurement versus elapsed test time is shown in figure 14b). It can clearly be seen that after current switch on (about $70mins$) metal loss is detected until the current is switched off at about $500mins$ when the thickness measurement returns to a constant value. The standard deviation of the measurements after the current is switched off is roughly $0.01mm$. The plate surface (backwall) was flat before the corrosion process started. The actual surface roughness was not measured before the test but it was in a condition as supplied by the manufacturer without visible roughness to the eye and consistently $9.9mm$ thick as measured at several points by micrometer. After the corrosion test the surface had clearly corroded non-uniformly and this could be confirmed visually. The surface profile was analysed using a surface profilometer. The result is shown in figure 15. The approximate position of the probe and where the thickness measurements were made is also indicated. The figure shows that the thickness in the measurement region lies between 9.4 and 9.5mm which is in excellent agreement with the ultrasonically measured thickness. There was a variation of $0.1 - 0.2mm$ in wall thickness due to the non uniformity in corrosion in the region over the measurement area. This is small compared to the wavelength ($\sim 1.5mm$) of the ultrasonic wave and did not significantly influence the thickness measurement.

IV Conclusion

The design of a waveguide system for high temperature thickness gauging has been described. Thin flexible waveguides that can sustain a large temperature drop are used to isolate the vulnerable piezoelectric transducers from the high temperature measurement zone. The problem was split into two parts. The first considered the send and receive characteristics of different waveguide cross sections on a half-space, while the wave propagation in the waveguide was another challenge to overcome. It was found that anti-plane shear loading shows the best source characteristics. These anti-plane shear loads can be transmitted from one end of the waveguide to the component surface by employing the SH* mode of a large aspect ratio rectangular strip.

An experimental investigation of different waveguide to specimen attachment methods showed that the acoustic contact created by welding is strong, but causes severe signal degradation and poor repeatability which eliminate welding as a possible joining method. Clamping waveguides to the surface using a purpose built clamp proved more successful. The signal transmission across the dry clamped interface is too weak to allow operation in pulse echo mode, but clean and consistent signals can be collected in the pitch catch mode.

A clamp-on waveguide thickness gauging system was successfully implemented and thickness measurements on a stepped calibration wedge ($4 - 10$mm) were performed at 2MHz with an average error of less than 0.1mm. The waveguide system was placed in a furnace and cycled between room temperature and 550°C several times without deterioration of the signal strength and clarity. Signals recorded during the cycling were used to monitor the shear velocity of a stainless steel plate as a function of temperature. It is important to measure thicknesses at a constant temperature or to compensate for changes in ultrasonic velocity as the temperature changes. For a resolution of ± 0.1mm a local temperature sensor is not necessary if monitoring is carried out at reasonably stable process temperatures. However, if larger temperature swings ($\sim 30 - 50$°C) are to be expected over the monitoring period a sensor and compensation strategy is necessary. There may be the possibility of auto-calibration using the surface reflection but this has so far not been investigated. Signal clarity and amplitude was observed to remain constant with test time.

Long term tests at high temperatures (730°C) for over 4 weeks showed continued good performance of the waveguide thickness monitoring sensor, demonstrating its potential application as permanently installed plant integrity sensor even in harsh environments where conventional ultrasonic sensors would disintegrate.

Wall thickness loss due to corrosion could successfully be tracked using the waveguide sensor with a resolution better than $0.1mm$. The non-uniformity of the wall loss due to the corrosion encountered in the particular test experiment did not significantly affect the wall thickness measurement because the thickness variations were only a fraction of the ultrasonic wavelength. The signal strength remained strong throughout the test and a corrosion rate could easily be calculated from the acquired data.

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V Figures

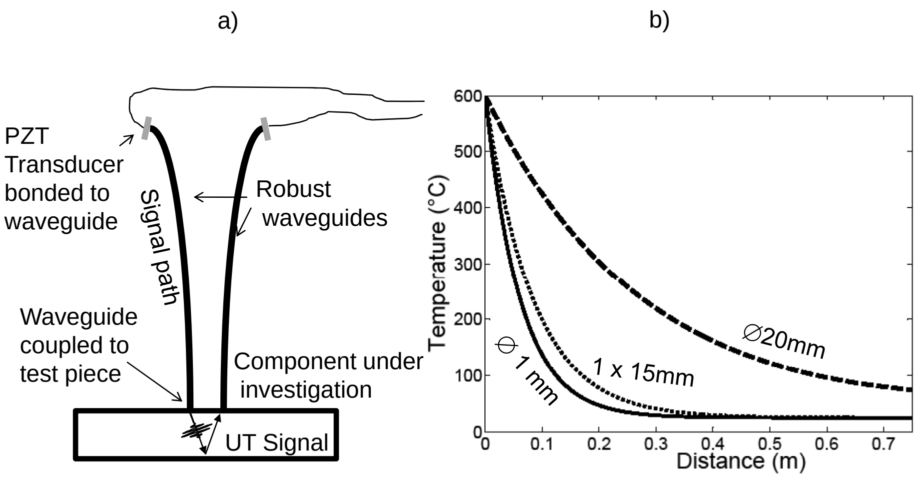

Figure 1: a) Waveguide thickness gauging concept showing one sending waveguide and one receiving waveguide. b)Temperature distribution along a (—) steel wire of 0.5mm radius, a (- - -) steel rod of 10mm radius and a (· · ·) rectangular steel strip (1 by 15mm). One end of each wire is maintained at 600°C while the air surrounding the waveguide is at 25°C. Calculation after Mills [29] with steel conductivity of k = 15 W/m/K and heat transfer coefficient of free convective air hc = 1W/m/K.

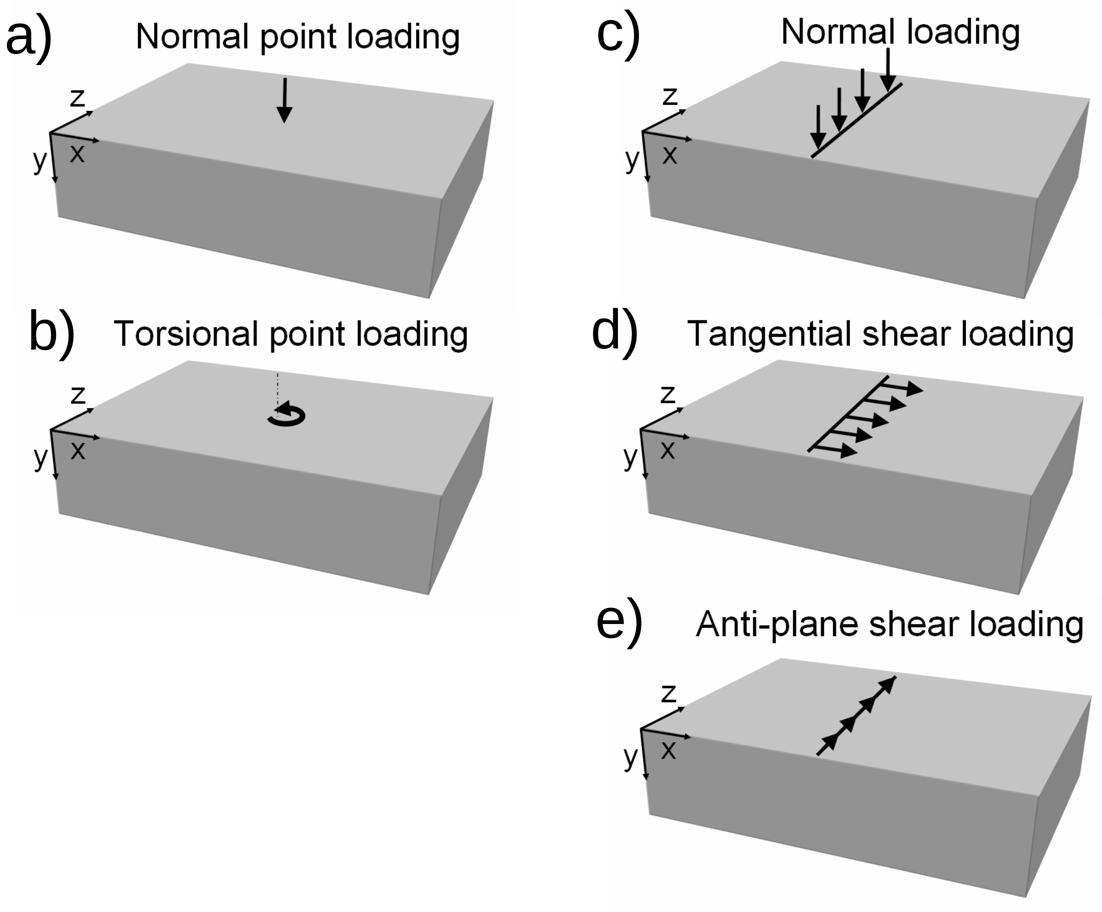

Figure 2: Schematics of the different loading conditions that were considered. For point sources: a) normal loading b) torsional loading and for line sources: c) normal line loading, d) tangential line loading and e) anti-plane shear line loading.

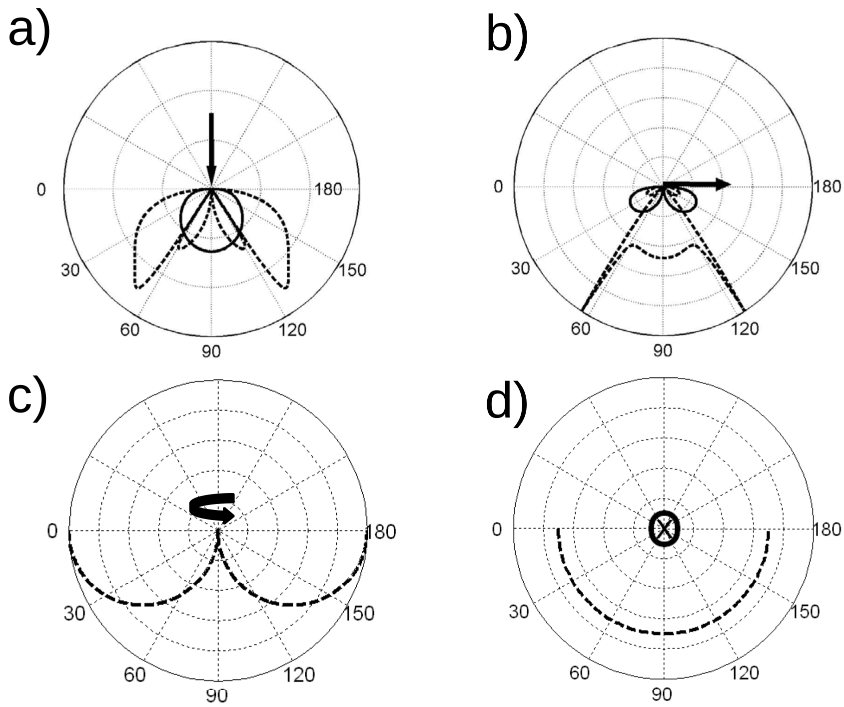

Figure 3: Directivity of the compressional (—) and shear (- - -) waves excited by different types of source loading conditions on a steel (C_L = 6000m/s, C_s = 3260m/s)) half-space for a) a normal line source, b) a tangential line source, c) torsional disc source (axi-symmetric) and d) anti-plane shear line loading. (at 2MHz and with characteristic dimensions of the line or disc smaller than the wavelength, calculations after Miller and Pursey [30])

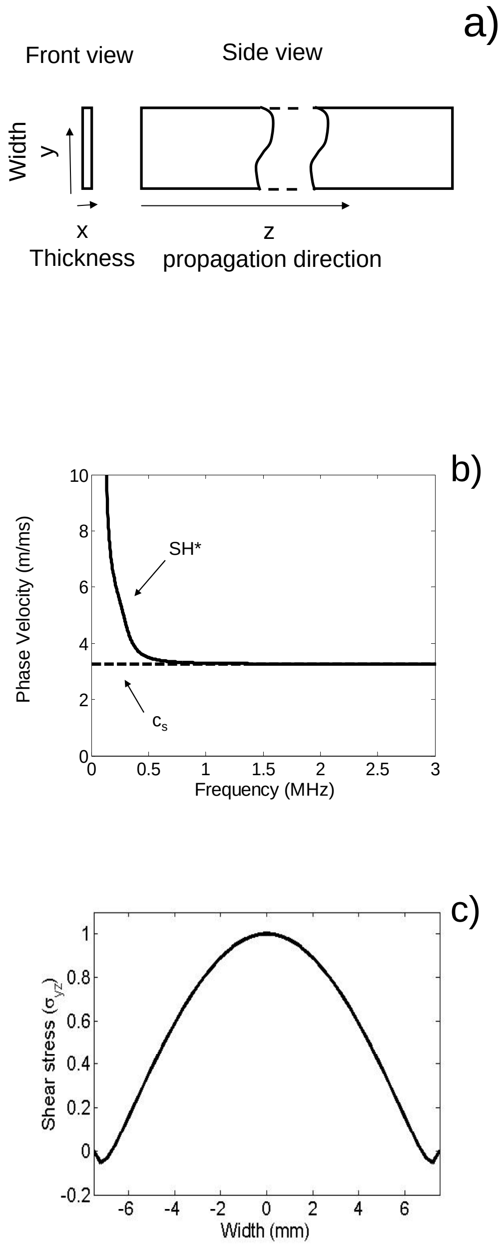

Figure 4: a) Sketch of the waveguide geometry, b) phase velocity dispersion curve of the SH* mode for a 1mm thick and 15mm wide steel strip and c) mode shape of the SH* mode at 2MHz.

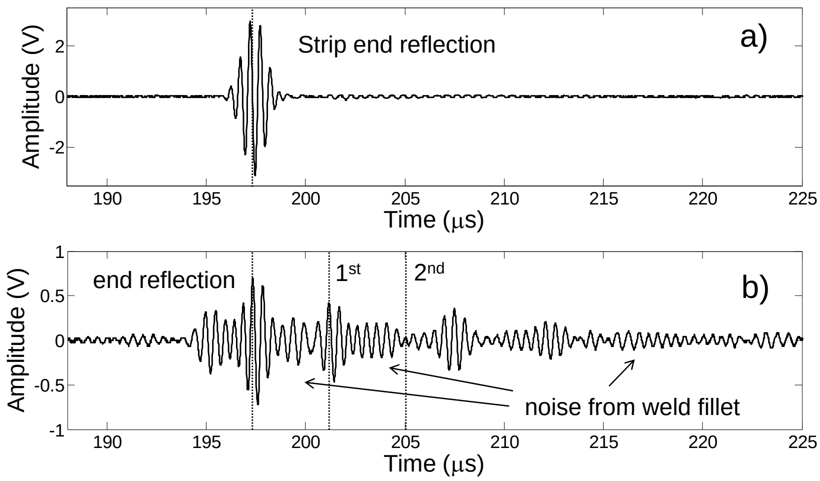

Figure 5: SH* mode pulse echo signal received through a 1mm thick and 15mm wide steel strip welded to a 6mm thick steel plate: a) signal before welding b) signal after welding. Vertical lines mark the expected arrival times of backwall echoes in the plate.

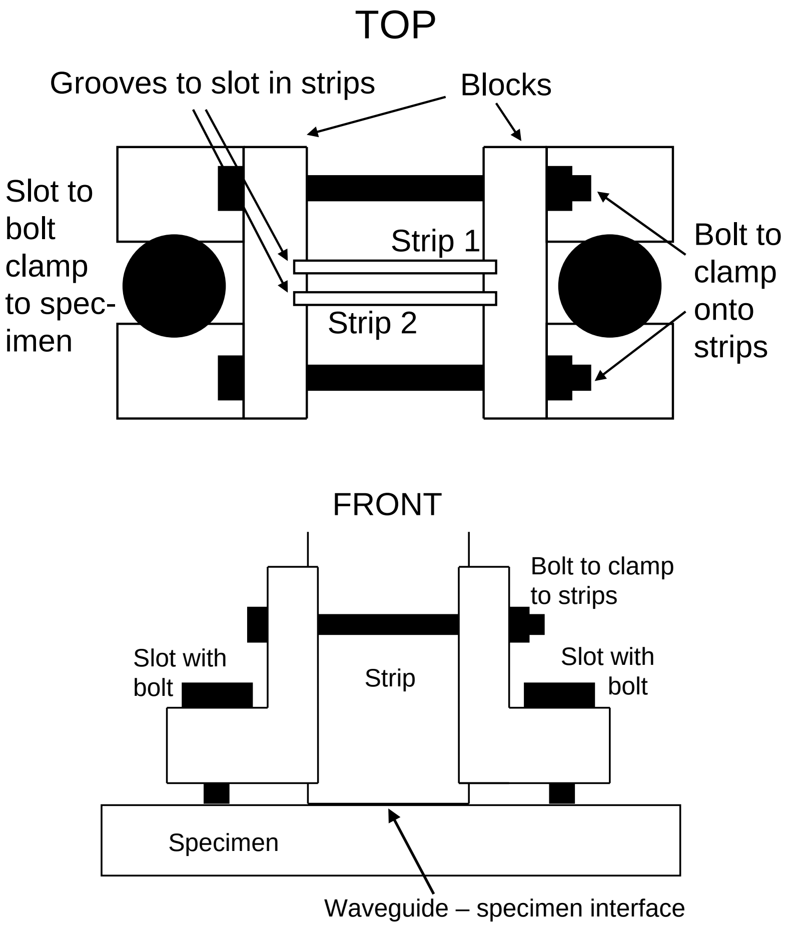

Figure 6: Top and front view of the clamp that was used to attach two strip waveguides to the sample plate.

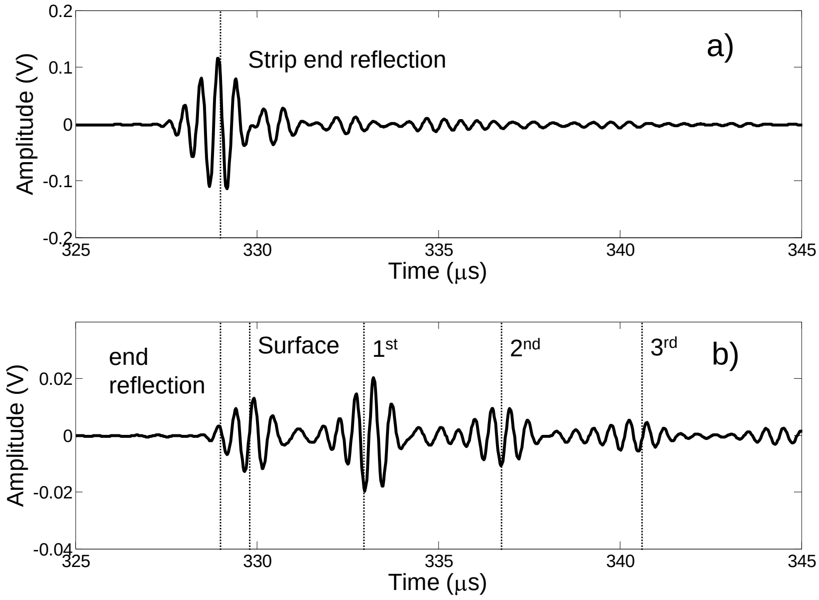

Figure 7: SH* mode signals sent and received through one or two 1mm thick and 15mm wide steel strips clamped to a 6mm thick steel plate: a) pulse echo signal on sending strip b) pitch catch signal received on second strip (signal already amplified by 17dB relative to a), strip separation 1mm).

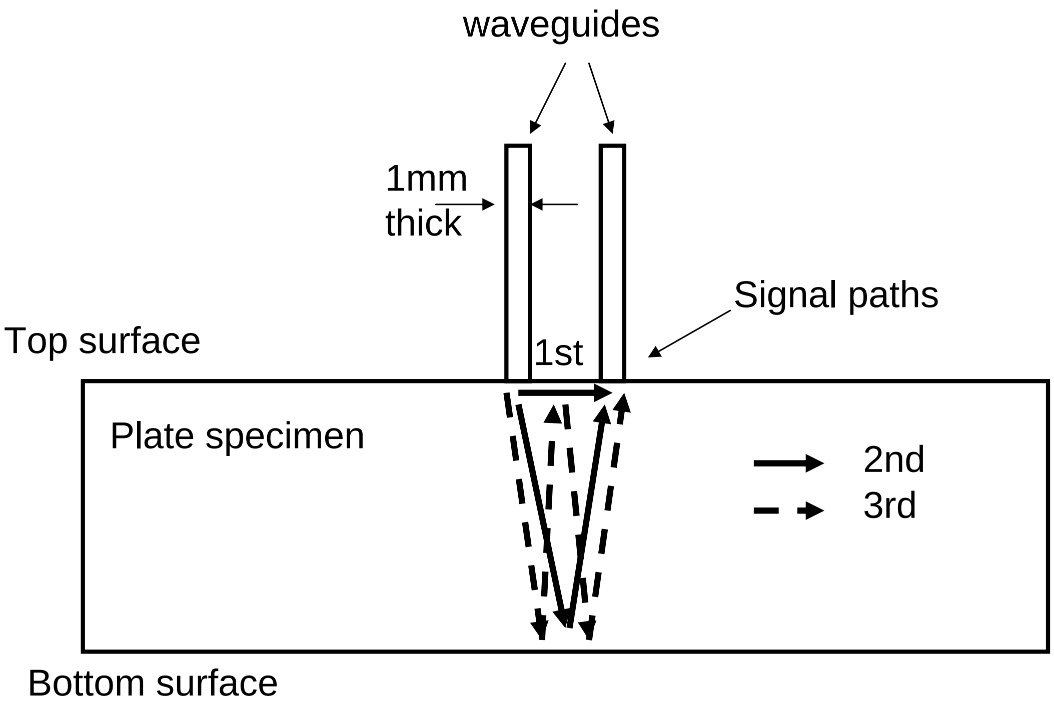

Figure 8: Signal paths that the SH waves travel in the plate specimen when the pitch catch mode is employed.

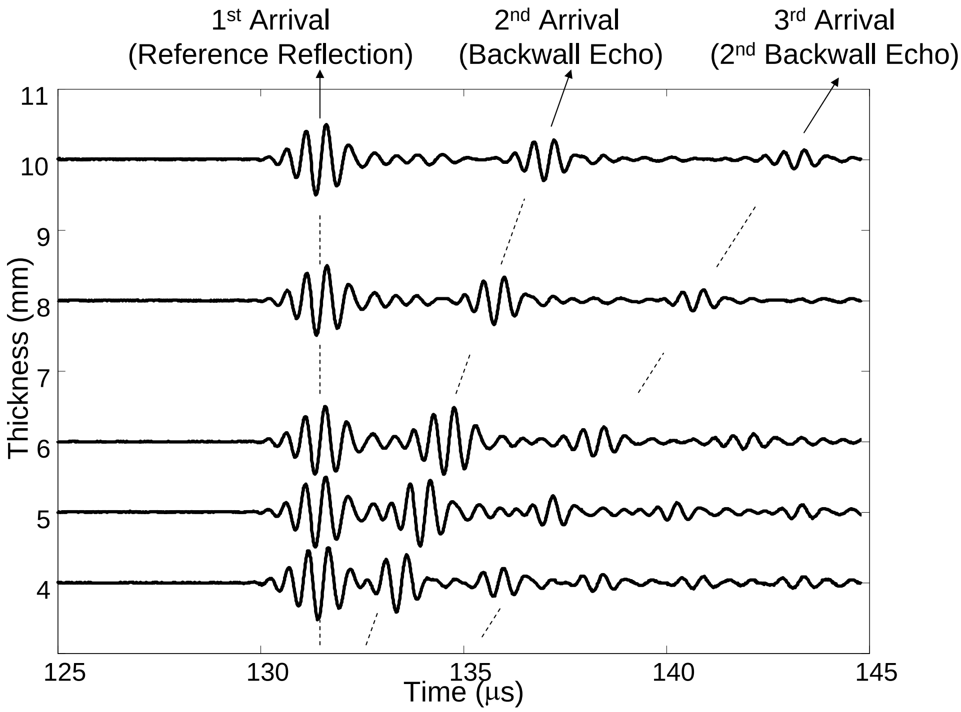

Figure 9: 5 cycle 2MHz Hanning windowed tonebursts sent and received by the SH* mode waveguide system coupled to a calibration sample of different thicknesses.

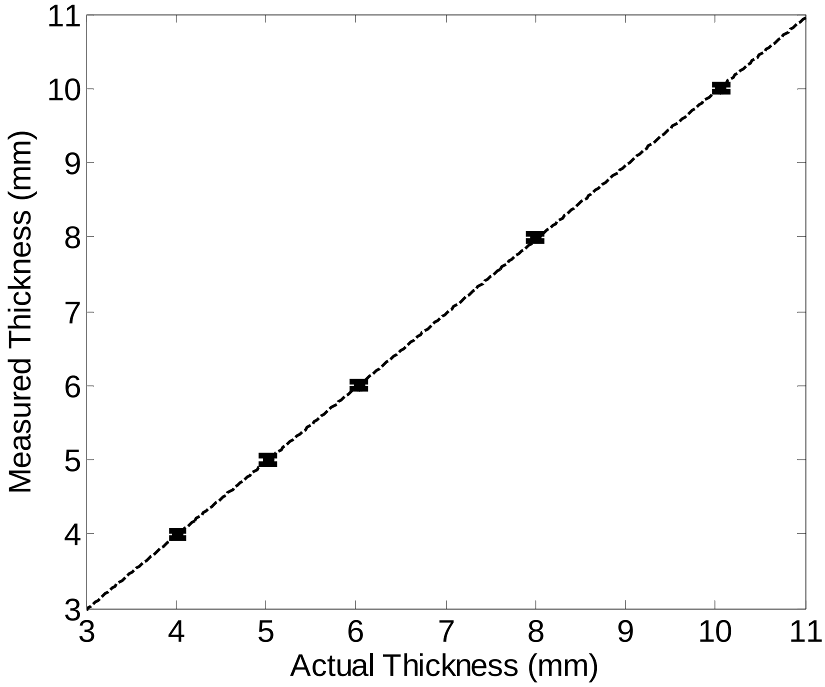

Figure 10: Mean thickness measured using the SH* mode waveguide thickness monitoring system (+ with ±0.05mm errorbars) plotted against the nominal thickness of the calibration sample (- - -).

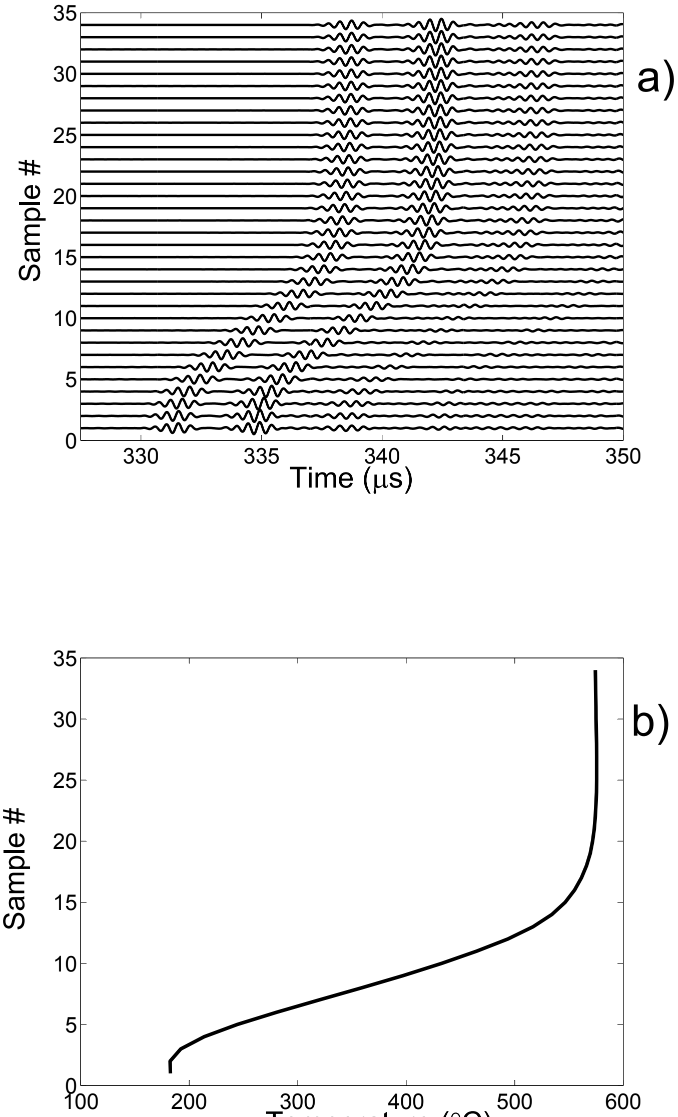

Figure 11: a) Signals and b) temperature recorded during a typical heating cycle. (Heating from 20°C to 550°C took about one hour.)

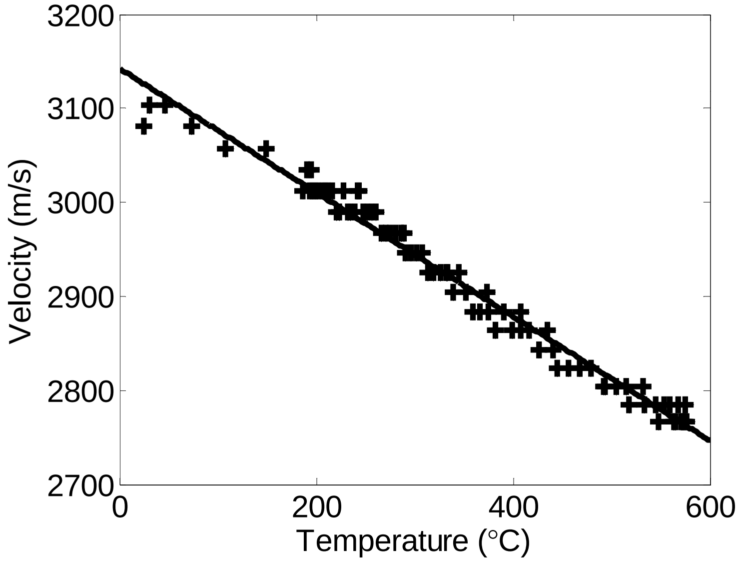

Figure 12: Shear velocity of the plate specimen as a function of temperature evaluated during different heating and cooling cycles (+) measurements, (—) linear fit.

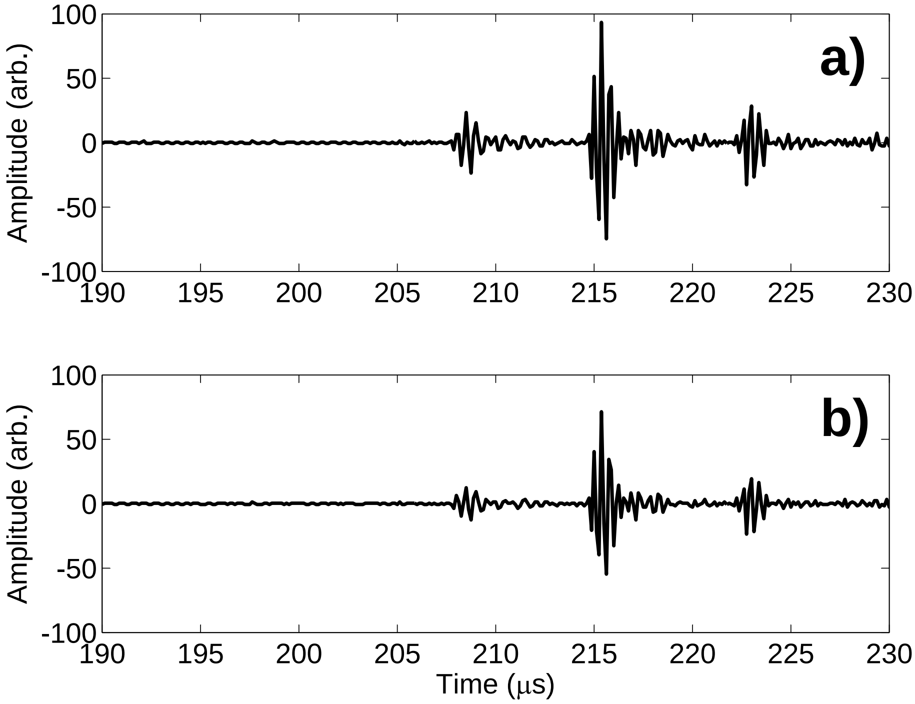

Figure 13: Waveguide remote monitoring system signal with sample at 730°C a) at start of experiment and b) after 4 weeks.

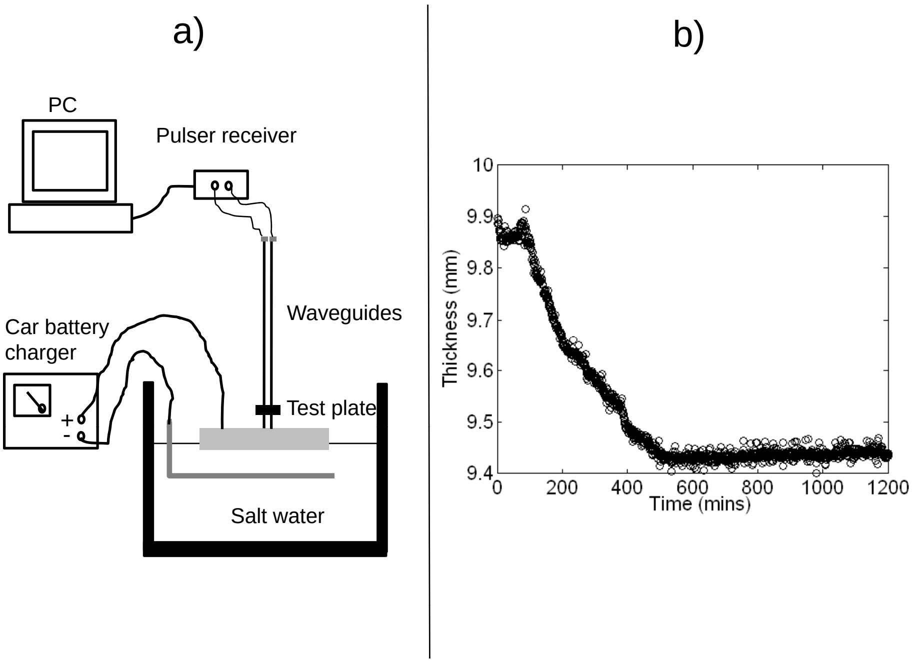

Figure 14: a) Sketch of the corrosion monitoring setup b) plate thickness vs time extracted from the ultrasonic measurements that were carried out at regular intervals during the corrosion test.

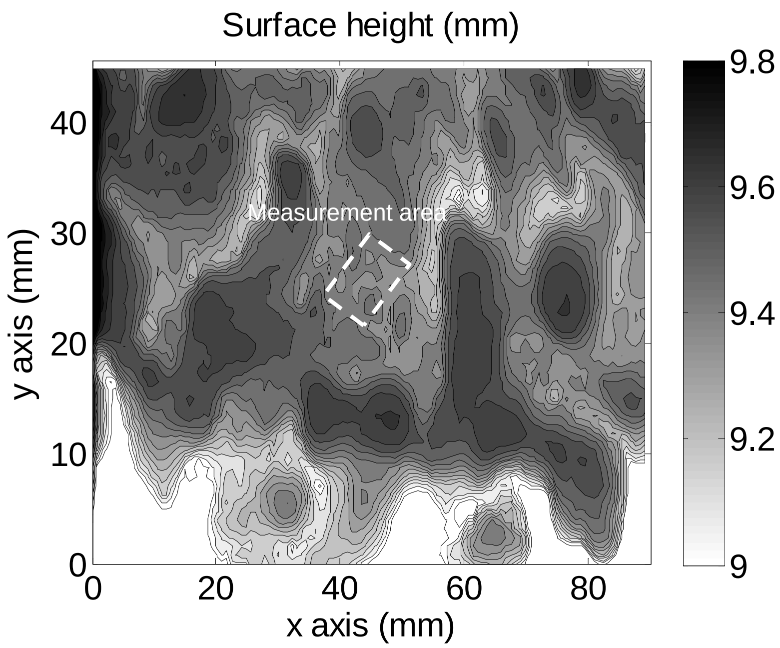

Figure 15: Contour plot of the surface of the corroded plate after the corrosion test was finished. The approximate area where the waveguide probes were attached (on the opposite surface) is also indicated.