

Research paper

Performance evaluation of a high-temperature ultrasonic transducer for in-situ defect detection in lead–bismuth eutectic alloy

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ABSTRACT

Non-destructive monitoring of reactor vessel walls in heavy-liquid-metal-cooled systems requires ultrasonic probes capable of continuous operation at elevated temperatures under challenging acoustic coupling conditions. In lead–bismuth eutectic (LBE)-cooled reactors, defect detectability is influenced by temperature gradients, oxide-layer formation, wetting behavior, and coupling-interface changes. This study evaluates a custom-developed high-temperature ultrasonic transducer for in-situ detection of notch-type defects in a stainless-steel reactor-vessel mock-up under laboratory and LBE conditions. The methodology combines cyclic laboratory testing in air, thermomechanical modeling of the mock-up during immersion in the Helios 3 LBE facility, in-situ ultrasonic measurements, and analytical/experimental assessment of coupling-layer thickness effects. Laboratory tests confirmed repeatable defect detection over multiple heating–cooling cycles up to 200 °C, with amplitude reduction during heating and near-complete recovery during cooling, indicating no irreversible transducer degradation. In the Helios 3 LBE facility, the defect remained detectable during two heating–cooling cycles, although the reflected amplitude recovered only partially after cooling. Probe inspection revealed no permanent degradation, suggesting that incomplete recovery was primarily caused by acoustic coupling changes rather than transducer failure. Analytical modeling and validation experiments demonstrated high sensitivity of reflected amplitude to coupling-layer thickness, with an 18 μm increase producing approximately –6 dB signal loss. These micrometer-scale coupling gap changes are sufficient to explain the observed amplitude variations. The results demonstrate that the developed transducer is suitable for high-temperature defect detection in representative LBE environments and that coupling-layer stability is critical for reliable ultrasonic monitoring of LBE-cooled reactor components.

1. Introduction

Nuclear power plants (NPP) should be monitored often due to the high hazard to humans and the environment. NPP are usually monitored using non-destructive testing (NDT) techniques, such as eddy current, ultrasonic testing, visual inspection, etc. Those NDT techniques allow the detection of defects in the wall of a power plant during continuous operation [1–4]. Nuclear power plants are usually cooled using various type of coolants: water, gases (helium, carbon dioxide, etc.), liquid metals (sodium, potassium, lead, etc.), liquid alloys (lead–bismuth, sodium–potassium, etc.), and other (salts, nanoparticles, organic coolants, etc.) [5–8]. Lead-based coolants are attractive for advanced reactor systems because of their thermal stability, high boiling point and

favorable safety-related properties, but their use requires strict chemistry and corrosion control. Lead–bismuth eutectic (LBE), to be used as coolant for the MYRRHA ADS [9] under development at the Belgian Nuclear research center (SCK CEN), is an alloy of 44.8 wt% lead and 55.2 wt% bismuth, has low melting point (123.5 °C), but high boiling point (1670 °C). LBE is known for its thermal and radiation stability, low chemical reactivity, and inertness with air and water minimize safety hazards, significantly improving safety of the reactor [6,8,10]. The corrosion behaviour of structural steels in LBE is strongly dependent on the concentration of dissolved oxygen. In the literature, “oxygen-free” LBE typically refers to dissolved-oxygen concentrations below approximately 10^{–8} wt%, under which protective oxide layers do not form and corrosion rates are highest. “Oxygen-containing” LBE denotes

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conditions where dissolved oxygen is intentionally maintained in the range of roughly 10^{-6} – 10^{-5} wt%, which is sufficient to promote formation of a protective oxide layer on steels while avoiding excessive oxide deposition [8,11]. There are also limitations of using LBE as a coolant: lead (Pb) toxicity, LBE causes corrosion and erosion of other metals, production of alpha-active polonium (^{210}Po) by irradiation, and the deficiency of bismuth in nature [6,8]. A corrosion rate of martensitic steel exposed to flowing LBE was calculated of 1 mm per year at 500 °C in an oxygen-free environment [8], corrosion of austenitic steels was observed after 288 h at 550 °C in an oxygen-containing LBE [12], while on the oxide dispersion strengthened steels it was noticed after 200 h at 535 °C [13].

Advanced nuclear reactor systems increasingly require measurement and monitoring techniques capable of operating under complex thermal-hydraulic and multiphase conditions. In such environments, conventional measurements can be affected by temperature gradients, fluid–structure interactions, phase interfaces, flow-induced fluctuations and limited accessibility to critical components. Recent developments in nuclear engineering have therefore focused on advanced experimental and computational techniques for characterizing multiphase flows and monitoring reactor systems, including advanced sensing and measurement approaches. These challenges are relevant for liquid-metal-cooled systems, where a combination of high temperatures, chemically active coolants, oxide formation, and complex acoustic or mechanical conditions can significantly affect the performance of in-situ measurement systems. In the case of reactors cooled by Heavy Liquid Metals (HLM), these challenges are further exaggerated by the high density of the coolant, its physical and chemical properties, oxide formation on material surfaces, and the need to ensure a reliable interface between the measurement system and the monitored component [14].

The application of ultrasonic methods in LBE-cooled systems brings significant challenges, including continuous transducer performance at high temperatures, acoustic contact and its quality in a liquid metal environment, as well as whether the defect wets the metal and how this affects the accuracy of the method and the ultrasonic response [15].

Furthermore, a notable deficiency exists in the availability of high-temperature contact ultrasonic transducers suitable for prolonged continuous measurements within the global market. Predominantly, existing ultrasonic transducers are engineered for brief contact durations with hot surfaces, limited to approximately 10 s [16,17]. Despite extensive scientific literature documenting ultrasonic transducers capable of functioning under extreme conditions, the authors express reservations regarding the thermal stability and efficacy of such transducers and coupling gels at elevated temperatures [18–20]. This shortfall highlights the imperative for developing advanced transducers capable of sustained, reliable operation in high-temperature environments, such as those encountered in molten metal processing.

The high-temperature ultrasonic transducer used in this study was developed and previously investigated by the authors [21]. However, that work focused only on laboratory characterization in air and did not address operation in liquid lead–bismuth eutectic. The main contribution of the present paper is the experimental validation of the transducer in a realistic LBE environment (Helios 3 facility), including thermal cycling, in-situ ultrasonic measurements, and numerical modelling of heat transfer during experimental measurements in LBE melting vessel. To address the critical deficiency in continuous high-temperature structural health monitoring, this paper demonstrates and evaluates the performance of a custom-developed ultrasonic transducer under highly representative in-situ conditions. Specifically engineered for defect detection in reactor vessel walls cooled by HLM, such as the Lead-Bismuth Eutectic (LBE) utilized in the advanced MYRRHA reactor, the designed probe generates shear waves at 2 MHz and is optimized for continuous operation at temperatures up to 220 °C. This is sufficient to use the sensor for NDT under MYRRHA maintenance conditions, foreseen for 200 °C. The transducer's performance was systematically evaluated on a thick-walled stainless-steel mock-up (AISI 316 L)

containing a calibrated notch defect, simulating a critical reactor vessel component in accordance with BPVC.V-2015 and BPVC.XI.1–2019 standards. To ensure robust validation, the experimental campaign was twofold: initial baseline assessments under controlled cyclic thermal loading in a laboratory environment, followed by rigorous in-situ testing within the state-of-the-art Helios 3 LBE melting facility at SCK CEN [11]. The experiments confirmed that the ultrasonic transducer successfully endured continuous measurements at temperatures as high as 200 °C, maintaining its ability to detect notch-type defects in the reactor wall even after multiple heating and cooling cycles. Notably, the LBE environment exerted no observable impact on the probe, instead transient changes in signal amplitude were traced to the acoustic couplant. To further elucidate this phenomenon, the study transcends standard performance validation by fundamentally investigating the mechanisms of signal attenuation during thermal cycling. Through analytical modelling and experimental verification, we quantitatively assess the impact of thermal deformation on the acoustic coupling layer. We demonstrate that transient signal variations are primarily governed by constructive and destructive interference within the couplant layer driven by micro-metric thermal expansions. Specifically, our results indicate that an increase in coupling layer thickness of merely 18 µm leads to a –6 dB loss in signal magnitude, suggesting that attenuation is also a function of coupling gap dynamics.

2. Materials and methods

2.1. High-Temperature ultrasonic probe

A high-temperature ultrasonic transducer, previously developed at Kaunas University of Technology [21], was employed in this study to evaluate its performance under both laboratory and in-situ conditions, with the aim of assessing its suitability for continuous defect detection at elevated temperatures. The probe was designed to withstand continuous operation up to 220 °C and was specifically developed for applications in the nuclear power industry, particularly for non-destructive testing and defect detection in reactor vessel walls cooled with Heavy Liquid Metals, such as Liquid Lead-Bismuth Eutectic. The probe is designed to enable continuous inspection of reactor vessel walls without significant degradation, thereby allowing more robust and more detailed inspection of HLM cooled reactors.

2.2. Mock-Up description

Probe performance was assessed using a thick-walled austenitic stainless-steel mock-up (AISI 316 L), representing a section of the MYRRHA reactor vessel wall, for which AISI 316 L is the reference structural material. The preliminary comparative measurements were also performed on a T91 ferritic–martensitic steel specimen. Owing to its coarser austenitic grain structure, the AISI 316 L material exhibits stronger grain scattering and hence a higher level of structural noise than the fine-grained tempered-martensitic T91 and was therefore selected for the present study as both the application-representative and the acoustically more challenging case. All results reported in this paper were obtained on the AISI 316 L mock-up. The mock-up thickness was set to 100 mm, corresponding to the actual wall thickness of the vessel. Lateral dimensions of 80 mm (width) and 240 mm (length) were selected to provide sufficient space for probe positioning and defect detection. A through-width notch defect, 2 mm in height and 4 mm in width, was introduced as the target reflector. The mock-up was used in the as-manufactured surface condition, with the native oxide layer on the stainless-steel surfaces left intact. Removal of the oxide layer to promote wetting by LBE was not performed, since deoxidation of a component of this size and thermal mass is not straightforward and an oxidized surface is representative of the in-service condition of a reactor vessel wall. Both the mock-up and the defect were fabricated in compliance with the American Society of Mechanical Engineers (ASME)

standards BPVC.V-2015 (Non-Destructive Testing for Non-Pipeline Calibration Units) and BPVC.XI.1-2019 (Operational Verification of Nuclear Reactor Equipment Components, Chapter 1, Rules for the Inspection and Testing of Light Water-Cooled Equipment Components for Boilers and Pressure Vessels). A schematic of the mock-up is shown in Fig. 1.

2.3. Ultrasonic inspection setup

To detect the target defect and assess its detectability under actual NPP operating conditions, a shear-wave inspection configuration was employed. The developed high-temperature probe was mounted on a 45° refraction-angle wedge made of plastic, enabling the generation and propagation of shear waves in the inspected material. The wedge generates shear waves by mode conversion of the longitudinal wave incident from the wedge onto the steel surface beyond the first critical angle. The resulting shear wave is vertically polarized (SV), with the polarization vector lying in the plane of incidence. The probe was oriented so that the plane of incidence was perpendicular to the length of the through-width notch, i.e., the beam propagated across the notch. In this arrangement the notch, together with the adjacent backwall, forms the standard corner reflector configuration used for surface-breaking planar defects in angle-beam inspection according to ASME BPVC.V practice. The exact absolute value of the reflection coefficient is not critical for this study, since all results are presented as amplitudes normalized to the initial value (U_s/U_{smax}) and the investigation concerns the stability of the response over thermal cycling rather than defect sizing.

Polybenzimidazole (PBI) and polyetheretherketone PEEK plastics were considered to produce the wedge. The specific wedge material was selected according to ultrasound attenuation in the plastic at elevated temperatures where the PBI plastic showed better performance than other high temperature plastics such as PEEK. Both of these plastics are known for their chemical inertness, but PBI is more suitable for this ultrasonic transducer due to its thermal stability, high glass transition temperature ($T_g = 410^\circ\text{C}$), whereas the T_g of PEEK is significantly lower (240°C), therefore, at 200°C the ultrasonic attenuation losses will be greater for PEEK than for PBI [22–24]. The probe was secured to the wedge with a spring-type holder to maintain uniform and continuous contact throughout the high-temperature measurement cycle. Acoustic coupling between the probe and wedge, as well as between the wedge and the sample, was ensured using viscosity standard S8000S (Paragon Scientific Ltd., UK) applied at the contact interfaces. This couplant was selected on the basis of a previous investigation of the acoustic properties of viscosity standards [25], which demonstrated that S8000S supports transmission of 2 MHz shear waves through thin layers with low losses and that its longitudinal and shear wave velocities decrease with temperature following the decrease of viscosity. It should be noted that both coupled interfaces are located on the top surface of the mock-up, which remained above the LBE at all times. The couplant was therefore never in contact with LBE. Reflections from the target defect were recorded with an ultrasonic flaw detector (M2M GEKKO, Eddyfi Technologies, USA).

2.4. The HELIOS3 LBE facility

HELIOS3 is a state-of-the-art stirred bubble column system designed to replicate the in-situ operating conditions of lead-bismuth eutectic (LBE) coolant in advanced nuclear reactors [11]. It is an isothermal LBE facility that consists of a melting vessel, a conditioning vessel for R&D on dissolved oxygen control and a storage vessel.

For the tests described in this paper, only the melting vessel was used. This vessel has a sufficiently large diameter (400 mm) to accommodate the US mock-up; LBE can be kept under vacuum conditions to minimize oxygen ingress and it has a movable lid to facilitate skimming of the surface to insert objects or remove oxides. While the lid is open, argon cover gas is blowing continuously across the LBE surface via a ring of holes near the lid, to minimize coolant oxidation. The temperature can be set up to 250°C and can be controlled within 1° . Although the melting vessel has no oxygen sensors, due to the presence of oxides on LBE ingots before melting and the unavoidable close contact with ambient atmosphere conditions, the typical oxygen content of the dissolved oxygen content in the LBE is close to the oxygen solubility limit at 200°C (2×10^{-7} wt%). This is used to our advantage for pre-cleaning the LBE. Typically, LBE is kept under vacuum at 150°C for a day to allow settling of oxides on the surface; these are then skimmed while blowing argon gas over the LBE. This procedure is repeated until we end up with a clean surface that only shows coolant oxidation on the surface when in contact with air.

2.5. Experimental campaigns

Two independent experiments were performed: (a) laboratory testing under controlled heating/cooling cycles in air at Kaunas University of Technology (Kaunas, Lithuania), and (b) in-situ testing in the Helios 3 LBE melting vessel at the SCK CEN research centre (Mol, Belgium).

3. Laboratory experiment

The laboratory experiment was conducted to assess probe performance during heating and cooling in air. The mock-up was placed inside a programmable oven (Binder GmbH, Tuttlingen, Germany), and measurements were carried out over a temperature range of $20\text{--}200^\circ\text{C}$. The surface temperature of the mock-up was monitored with a K-type thermocouple attached to the top surface, while oven temperature was measured with a reference thermometer (Fluke 1523, Fluke Corporation, Everett, USA). The experiment consisted of two phases:

1. **Heating phase** – the test object was heated in the oven to 200°C ;
2. **Cooling phase** – the sample was removed from the oven and cooled passively in ambient air ($23 \pm 2^\circ\text{C}$) for a fixed duration of 480 min. Since cooling was passive, the cycle was terminated after this fixed interval rather than at a prescribed temperature setpoint. The surface temperature of the mock-up at the end of the cooling phase was $\sim 55^\circ\text{C}$.

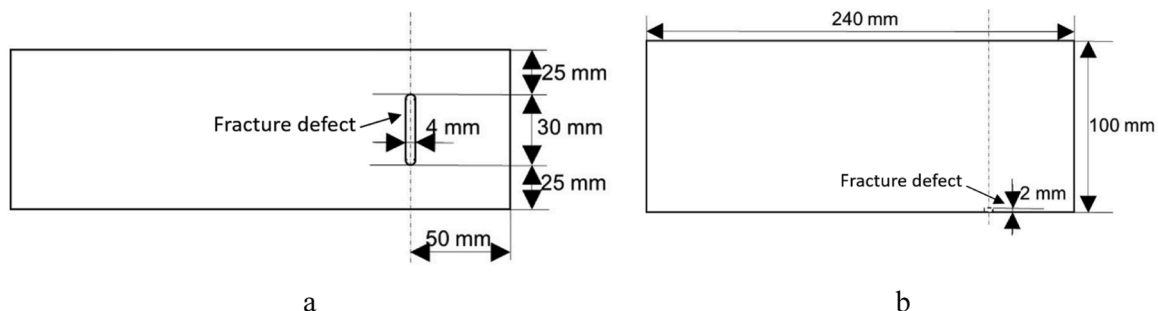


Fig. 1. Scheme of the sample: a – bottom view, b – side view.

The experimental setup for laboratory measurements is shown in Fig. 2.

4. LBE experiment

The second experiment was conducted in the melting vessel of the Helios 3 setup at SCK CEN [11]. For the tests, the LBE was cleaned according to the procedure described in section 1.4. The surface was skimmed, so the mock-up could be inserted in an oxide free surface. During the tests Argon is continuously flown across the LBE surface to minimize oxygen ingress. The LBE was kept at 200 °C under stagnant conditions. The mock-up was partially submerged in LBE to an immersion depth of approximately 20 mm (measured from the bottom surface of the block) using a dedicated rig that enabled controlled immersion and withdrawal. Seven K-type thermocouples were positioned at designated locations to monitor temperature distribution:

- TC2 and TC5 – bottom surface, directly immersed in LBE;
- TC3 and TC6 – embedded at mid-thickness;
- TC4 and TC7 – top surface;
- TC8 – near the probe to monitor the probe-mock-up contact interface.

Temperature data were recorded using a Data Acquisition/Switch Unit (Agilent 34972A, Keysight Technologies, USA). The arrangement of the probe and thermocouples is shown in Fig. 3a, and the mock-up immersed in LBE is shown in Fig. 3b.

As in the laboratory case, the experiment consisted of two phases:

1. **Heating phase** – the test object was submerged in LBE and heated to 200 °C;
2. **Cooling phase** – the sample was withdrawn from the LBE melt and cooled passively in ambient air. The cooling phase lasted 360 min in the first cycle and 300 min in the second cycle at the end of which the mock-up surface temperature was 32 °C and 39 °C, respectively.

A total of two complete heating/cooling cycles were performed. During both heating and cooling, ultrasonic signals were acquired every 30 s, while temperature data from the thermocouples were logged at 1-minute intervals. The complete experimental setup is shown in Fig. 4.

Numerical modelling of heat transfer during experimental measurements in LBE melting vessel.

Prior to the experimental measurements, numerical simulations of heat transfer in the mock-up submerged in LBE were performed to

estimate the duration of the heating cycle and the expected temperature at the top surface of the reactor vessel wall, where the ultrasonic probe was mounted. To reduce computational cost, only one-quarter of the structure was modeled, applying symmetrical boundary conditions, using COMSOL Multiphysics finite element software. A graphical representation of the simulation model is shown in Fig. 5. The simulations were carried out in stationary mode under the following assumptions:

- The outer boundary of the tank was ideally insulated (adiabatic boundary);
- The temperature of the LBE domain was constant at 200 °C, with the top and bottom boundaries of the LBE domain also fixed at 200 °C.

The resulting temperature distributions are presented in Fig. 6. Fig. 6a shows the temperature distribution across all domains of the structure, while Fig. 6b illustrates the temperature distribution with the air domain omitted, i.e., only within the solid regions.

Temperature distributions along gradient measurement lines 1 and 2 (see Fig. 5) are shown in Fig. 7a. To estimate the time required to reach thermal steady state, a time-dependent heat transfer simulation was performed over a duration of 6000 s. The temperature was monitored at the center of the top surface of the AISI 316 block, with the results presented in Fig. 7b. These results indicate that thermal steady state is reached after approximately 5000 s (≈ 1 h 23 min). Therefore, the chosen heating cycle of 2 h was considered sufficient to ensure thermal stabilization at the top surface of the mock-up. At steady state, the temperature at the top surface of the AISI 316 block, resulting from the thermal gradient, is expected to be approximately 185 °C.

These numerical simulations of heat transfer in the test object immersed in LBE provided the necessary thermal boundary conditions and confirmed the experimental protocol's validity for subsequent ultrasonic measurements.

The possible influence of this gradient on shear-wave propagation was estimated using temperature-dependent shear-modulus and density data for AISI 316 stainless steel [26]. Between 176 °C and 200 °C, the calculated shear-wave velocity decreases from approximately 3022 m/s to 2993 m/s, i.e., by approximately 0.93%. For an initial propagation angle of 45°, this velocity variation changes the local angle to approximately 44.47°. Assuming a linear velocity gradient across the 100 mm wall thickness, the corresponding lateral displacement of the beam center is approximately -0.92 mm. This small displacement, together with the finite width of the acoustic field generated by the 13 mm transducer, indicates that the temperature gradient has no significant effect on defect detectability under the investigated conditions.

The following chapter presents the experimental results obtained under these optimized conditions.

5. Experimental results

5.1. Laboratory experiment results

Prior to the experiments in LBE, the performance of the probe was investigated at the laboratory conditions at Kaunas University of Technology using a drying oven. The measurement of the reflected ultrasonic signal from the notch type defect in the sample was performed in the temperature range 20 °C – 200 °C. The entire heating/cooling phase lasted 480 min each. These heating/cooling phases were repeated six times to ensure reproducibility of the data, the average of which is shown in the graph below (Fig. 8). Representative A-scans recorded at the start of heating, during heating and at the maximum temperature are presented in Fig. 9 (a–c), displayed with identical receiver gain and time base. The notch echo remains clearly distinguishable from the structural noise at all temperatures and the amplitude reduction at elevated temperature affects the notch echo and the structural noise in a similar manner, while the peak amplitude follows the trend shown in Fig. 8. Cycle-to-cycle evaluation of the raw laboratory records yielded the

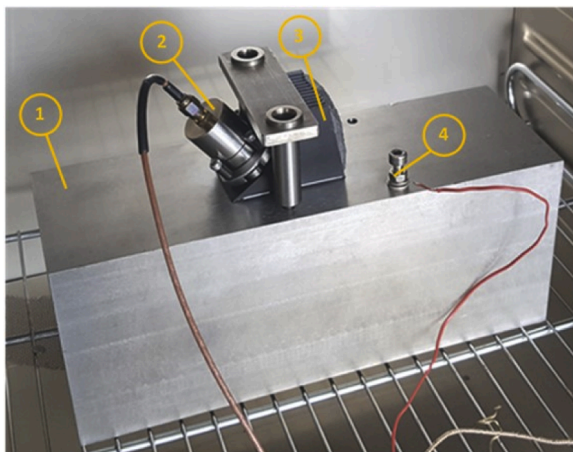


Fig. 2. Ultrasonic measurement in the temperature range 20 ÷ 200 °C in the heating oven: 1 - AISI 316 L steel calibration block; 2 - ultrasonic transducer; 3 - PBI wedge; 4 - temperature sensor.

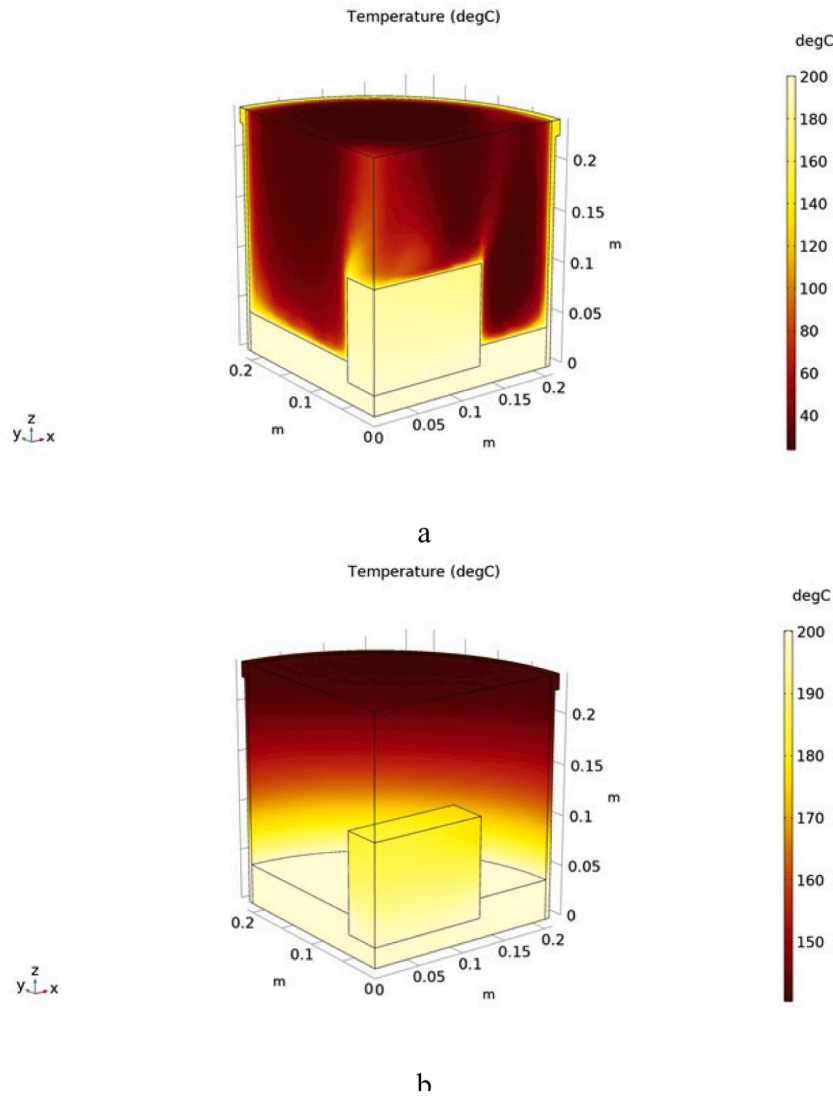


Fig. 6. Temperature distribution in modelled structure (a) and in solid parts of the structure (b).

demonstrating that the notch echo remained detectable above the structural noise throughout and that upon cooling the echo recovered in amplitude without change of shape or arrival structure, consistent with a coupling-related rather than degradation-related origin of the partial recovery.

In the first heating/cooling cycle (Fig. 11a) full duration of heating-cooling cycle was 480 min long: the heating lasted for 120 min, while the cooling for 360 min. As was expected, with a sudden increase in temperature, the value of U_s/U_{smax} decreased sharply. After ~ 34 min of heating U_s/U_{smax} value was at its lowest point ($\sim 0,07$), while the temperature was 197°C . When the temperature was constant ($197\text{--}198^\circ\text{C}$), after 34–120 min of heating, U_s/U_{smax} values ranged between 0,07–0,13. After 120 min, the heating part of this cycle was completed, and the cooling part started. After 137 min of this cycle the temperature slowly decreased with an increase of the U_s/U_{smax} . The sharpest increase in amplitude was observed during the cooling period (138–163 min of measurements), when the amplitude rose from 0.18 to 0.35 within 25 min. After 6 h of cooling, the U_s/U_{smax} value did not return to its initial value, but only reached 0.47, even though the temperature had dropped to 32°C .

Before proceeding with the 2nd heating/cooling cycle all the contact surfaces between probe and the wedge and between the wedge and the mock-up were wiped and again coupled with the same coupling gel. This

time the heating-cooling cycle was shorter than the previous (420 minutes long): the heating lasted for 120 min and the cooling for 300 min. The same tendency as in Fig. 11a was noticed in Fig. 11b: the U_s/U_{smax} amplitude decreased as the temperature rose and after the cooling neither the temperature nor the U_s/U_{smax} amplitude has returned to its initial value. This time U_s/U_{smax} value was at its lowest point ($\sim 0,2$), when the temperature reached 197°C after ~ 48 min of heating the sample. When the heating part of this experiment was over and the cooling of the sample had started, the temperature remained stable for 9 min. At that time, U_s/U_{smax} value increased from 0.23 (the 120th minute of measurements) to 0.3 (the 129th minute of measurements). As the sample was cooling down from 134°C to 129°C , the amplitude of U_s/U_{smax} had dropped again (from 0.36 to 0.24). After this transient decrease in amplitude, the value of U_s/U_{smax} gradually increased. Closer inspection of Fig. 11 shows that this transient decrease is not unique to the second cycle: a corresponding feature is present in the first cycle as well, where after 178.5 min the amplitude decreased from 0.337 to 0.270 (n.u.) at a mock-up temperature of 133.8°C , before resuming its rise (red circles in Fig. 11). In the second cycle the corresponding decrease (0.36 to 0.24) occurred after 168 min at 134.1°C . Although the elapsed times differ, the temperatures at which the feature occurs coincide within 0.3°C , indicating that the amplitude follows a deterministic function of the thermal state of the measurement stack rather

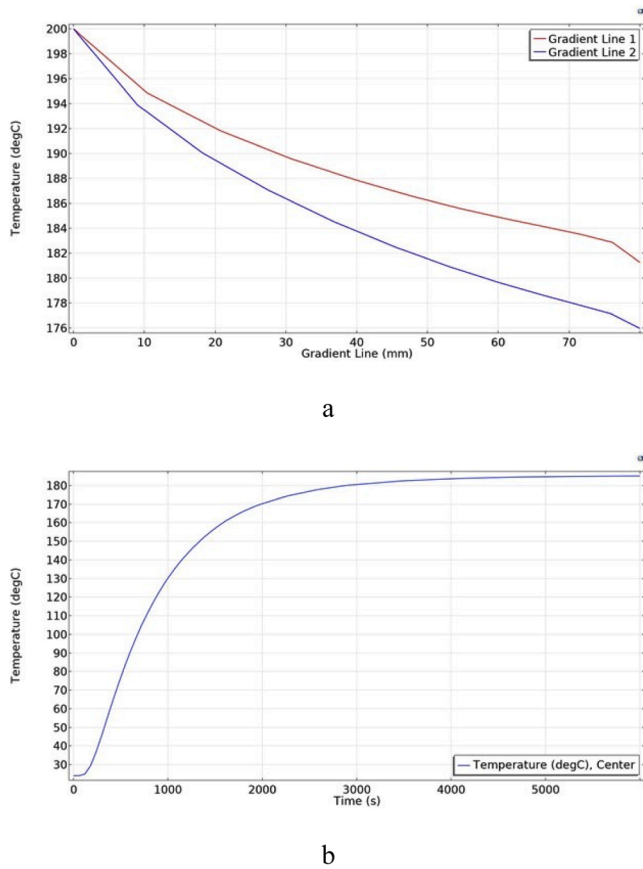


Fig. 7. Temperature distributions along gradient measurement lines (a) and temperature on the centre of top surface of AISI 316 block vs time (b).

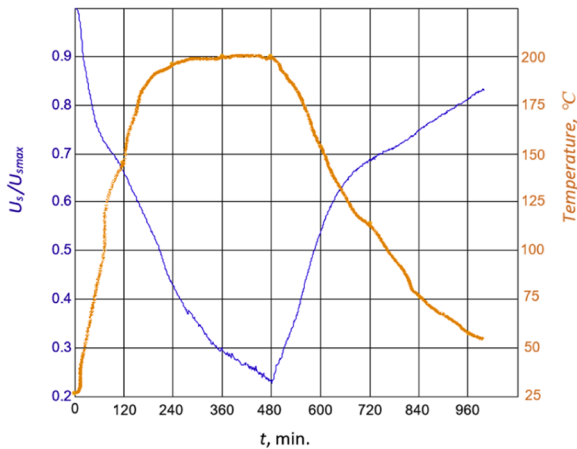


Fig. 8. Normalised amplitude U_s/U_{smax} of reflected signal and temperature T of the test block dependence on time.

than of time and excluding a random fixture event as the origin. Notably, the time-of-flight of the notch echo decreased smoothly and monotonically through this interval, following the temperature-dependent wave velocity, with no discontinuity accompanying the amplitude event. This rules out probe displacement or a change of the bulk propagation path and confines the origin of the fluctuation to an interface layer thin enough not to affect the measured propagation time. Such behaviour is consistent with the coupling-layer interference mechanism analysed in Section 4: transmission through a thin layer alternates between constructive and destructive conditions as its thickness passes

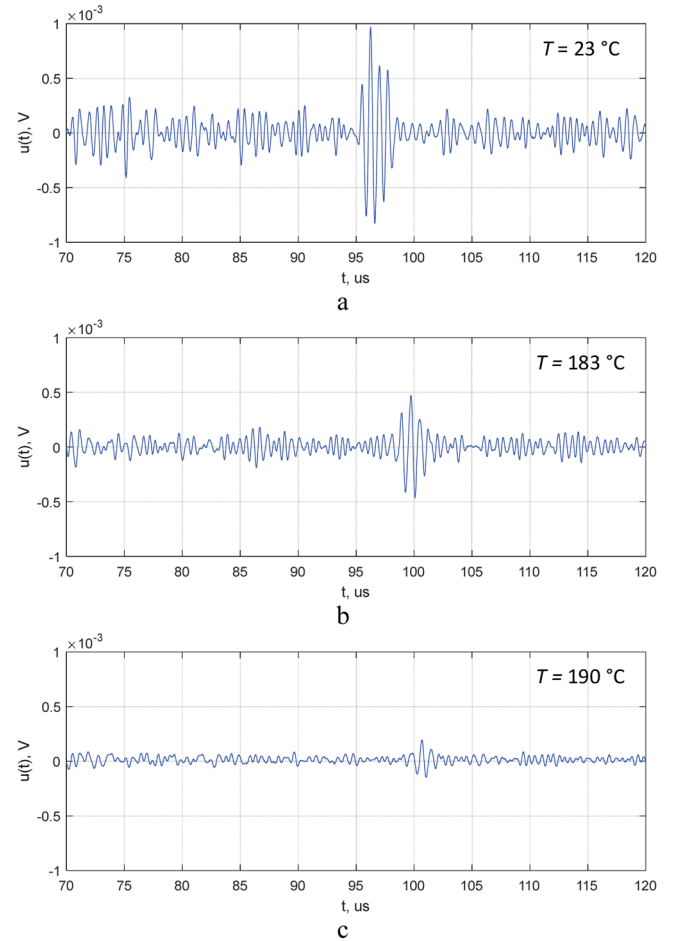


Fig. 9. Representative A-scans of the notch reflection, displayed with identical receiver gain and time base within each row: a – laboratory experiment at 23°C at the start of heating, b – 183°C during heating and c – 190°C at the maximum temperature.

through multiples of a quarter wavelength, so a monotonic contraction of the coupling gap during cooling can produce a locally non-monotonic amplitude evolution, recurring at similar temperatures in successive cycles because thermal contraction is itself a deterministic function of temperature. A definitive attribution would nevertheless require direct monitoring of the coupling interface, which is identified as a subject of future work. After this cycle the sample was cooled down to 39°C and the U_s/U_{smax} value reached 0.47. It is worth noting that both cycles, despite the interfaces having been wiped and freshly re-coupled between them, terminated at the same recovered amplitude of $U_s/U_{smax} = 0.47$ (at 32°C and 39°C , respectively). Since the two cycles constitute independent realizations with renewed coupling layers rather than strict repetitions, the coincidence of both the amplitude trajectories and the final recovery values indicates that the observed behaviour is a reproducible property of the transducer-wedge-couplant-mock-up system under the given thermal cycle, rather than a random outcome of a particular coupling realization.

A similar amplitude changes (Fig. 11) were observed during measurements in the laboratory (Fig. 8). Although Fig. 8 shows that the largest amplitude drop was observed after the maximum temperature was reached and remained stable for 2 h, Fig. 11 shows that this occurred immediately after reaching 200°C . In both cases there was a similar drop in amplitude (in laboratory experiment to ~ 0.25 , in Fig. 11a to ~ 0.07 , in Fig. 11b to ~ 0.2), which could be explained as the effect of LBE on the transducer was similar to that of hot air (in the laboratory experiment) due to oxide layers formed on the surface of the test object.

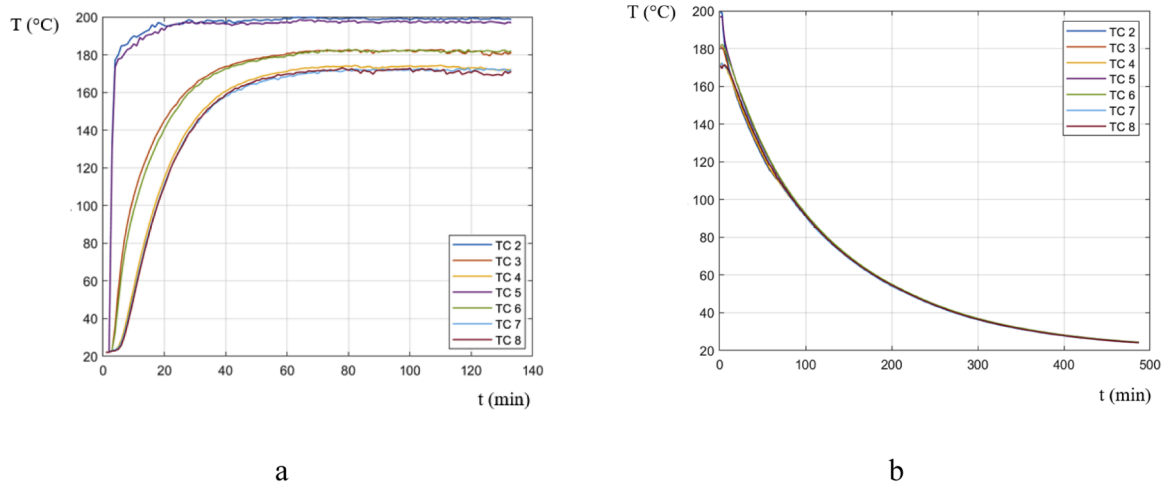


Fig. 10. Temperature variation of the test object during: a – heating, b –cooling.

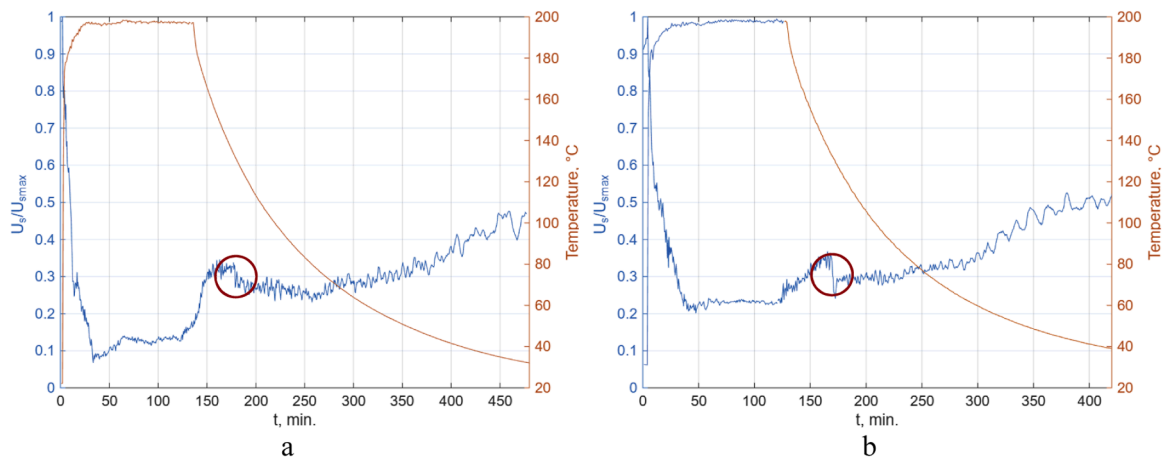


Fig. 11. Normalized reflection from the notch amplitude dependence on time and temperature during the heating and cooling cycle: a – 1st heating/cooling cycle, b – 2nd heating/cooling cycle. Red circles mark the reproducible transient amplitude decrease during cooling, discussed in Section 3.2.

Although the laboratory experiments demonstrated full recovery of the reflection magnitude across six consecutive heating/cooling cycles, the experiments conducted in the LBE vessel showed only partial recovery. Specifically, at a mock-up surface temperature of 30–40 °C, the normalized amplitude (U_s/U_{smax}) reached only about half of its initial value. A detailed inspection of the probe prior to the second heating/cooling cycle in LBE revealed no evidence of irreversible probe degradation. It should also be noted that during the cooling phases the mock-up temperature fell well below the LBE melting point (123.5 °C), so that any LBE remaining on the bottom surface after withdrawal solidified. However, liquid LBE does not wet oxide-covered steel surfaces [13–15], and since the native oxide layer of the mock-up was left intact, wetting of the bottom surface and of the notch was not achieved during the experimental campaign. This was confirmed by post-test inspection: the solidified LBE residues were only loosely attached to the surface and could be removed easily, indicating the absence of a metallurgical bond. An unbonded solid residue resting on a non-wetted interface cannot transmit shear stresses across the contact and therefore does not appreciably alter the acoustic boundary condition at the backwall or at the notch, at most, it introduces a minor local mechanical loading. The solidification of residual LBE during cooling is therefore not considered a significant contributor to the incomplete amplitude recovery. A dedicated acoustic characterization of S8000S couplant is available up to 40 °C [25] and shows that its shear and longitudinal wave velocities decrease with temperature in proportion to the decreasing viscosity.

Extrapolating this trend, the shear stiffness of the couplant layer is expected to decrease substantially towards 200 °C, reversibly weakening shear-wave transmission across the coupled interfaces during heating and recovering upon cooling. This is consistent with the reversible amplitude behaviour observed in the laboratory campaign. Although no decomposition or volatilization data for S8000S at 200 °C are available, the couplant remained functional throughout six 16-hour laboratory cycles and two LBE cycles and re-coupling of the wiped interfaces before the second LBE cycle restored the signal, indicating that the observed amplitude history is governed by the state of the couplant layer rather than by degradation of the probe.

Therefore, the observed changes are attributed to the state of the coupling layers rather than to the transducer itself. Since the probe was held against the wedge by a spring-type holder maintaining the contact force, the probe-wedge interface was mechanically compensated. The magnitude of the expected thermal mismatch can be estimated as follows. The difference in thermal expansion coefficients between PBI and AISI 316 L is $\Delta\alpha \approx 7 \mu\text{m}/(\text{m}\cdot\text{K})$. For a wedge contact length of $L \approx 50 \text{ mm}$ and a temperature excursion of $\Delta T \approx 170 \text{ K}$, the resulting differential expansion is $\Delta L = \Delta\alpha \cdot L \cdot \Delta T \approx 60 \mu\text{m}$. Deformations of this order, acting on the wedge-mock-up interface, can distort the flatness of the contact and locally change the thickness of the couplant layer by tens of micrometers. Direct measurement of the coupling-gap thickness was not performed in this campaign. Therefore, in order to establish whether a gap change of this magnitude is sufficient to produce the observed signal

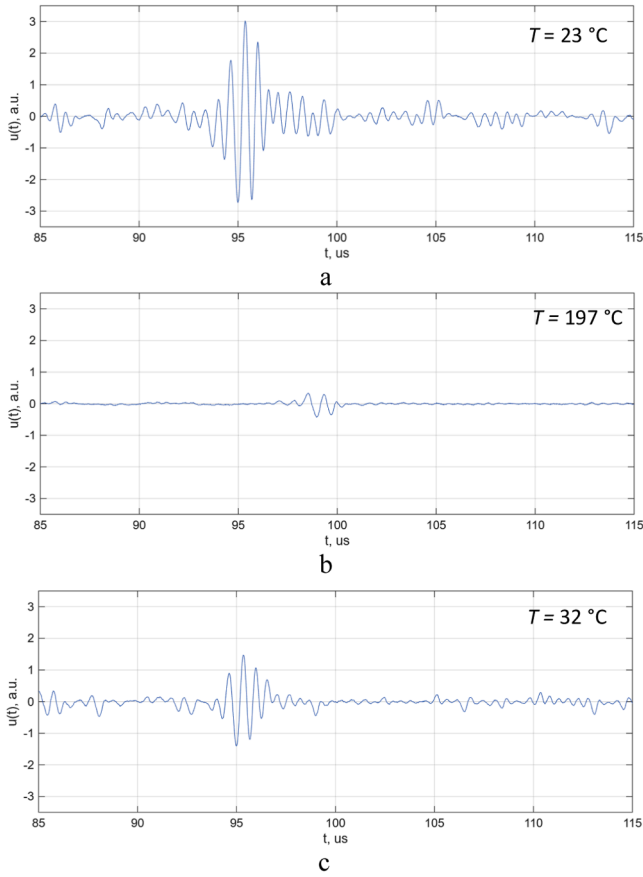


Fig. 12. Representative A-scans of the notch reflection, displayed with identical receiver gain and time base: a – LBE experiment, first cycle, before immersion (23 °C), b – at the temperature plateau (197 °C) and c – at the end of the cooling phase (32 °C).

loss, a dedicated investigation of the amplitude sensitivity to the coupling-layer thickness was carried out, as described in the following section.

Investigation of the measured ultrasonic signal's amplitude dependence on the thickness of coupling liquid gap.

In this section, the dependence of ultrasonic signal amplitude on the thickness of the coupling liquid layer was investigated through analytical modelling and experimental validation. It was assumed that the dominant mechanism responsible for signal attenuation is destructive interference within the coupling medium, arising as the effective layer thickness increases due to thermal deformation. When the coupling layer thickness corresponds to an integer multiple of half the acoustic wavelength, constructive interference occurs, enhancing transmission into the test object. Conversely, when the thickness approaches an odd multiple of a quarter wavelength, destructive interference dominates, reducing the transmitted amplitude. The following subsections present the analytical model, experimental setup, and corresponding results.

The purpose of this investigation is to establish the sensitivity of the transmitted and reflected signal amplitude to micrometer-scale changes of a thin coupling layer, rather than to reproduce quantitatively the full inspection configuration. A simplified reference configuration was therefore adopted: a PZT → water coupling → stainless steel stack under normal incidence with longitudinal waves, which permits both a tractable analytical description and a precise experimental realization in which the layer thickness can be controlled with micrometer accuracy. The actual inspection system (PZT–couplant–PBI wedge–couplant–steel, with oblique incidence and mode conversion to shear waves) differs from this reference configuration while the implications of these differences are discussed at the end of this section. More generally, we

consider the stack of M homogeneous, isotropic layers indexed $i = 1, \dots, M$, each characterized by density ρ_i , longitudinal wave velocity c_i and acoustic impedance Z_i . All interfaces are assumed planar and parallel, and the thickness of i^{th} layer is denoted d_i . The PZT is modelled as a transmitter launching a prescribed scalar source waveform $s(t)$ into layer 1 at time $t = 0$. The scalar acoustic pressure $p(r, t)$ in each layer satisfies the wave equation:

$$\nabla^2 p_i(r, t) - \frac{1}{c_i^2} \frac{\partial^2 p_i(r, t)}{\partial t^2} = 0, \quad (1)$$

with continuity of pressure and normal particle velocity at each interface:

$$\begin{cases} p_i = p_{i+1} \\ \frac{1}{\rho_i c_i^2} \frac{\partial p_i}{\partial t} = \frac{1}{\rho_{i+1} c_{i+1}^2} \frac{\partial p_{i+1}}{\partial t} \end{cases} \quad (2)$$

For plane-wave incidence at normal incidence ($\theta_i = 0$) the transmission and reflection coefficients at the boundary between layers i and $i + 1$, are given as:

$$T_{i \rightarrow i+1} = \frac{2Z_{i+1}}{Z_i + Z_{i+1}}, \quad (3)$$

$$R_{i \rightarrow i+1} = \frac{Z_{i+1} - Z_i}{Z_i + Z_{i+1}}, \quad (4)$$

where $Z_i = \rho_i c_i$ is the acoustic impedance of layer i . A set of possible ray paths P is then constructed from sequences of reflections and transmissions across interfaces. Each path $p \in P$ consists of straight segments j propagating in layers $i(j)$ with lengths of L_{pj} . The corresponding propagation time-of-flight τ_p and amplitude A_p are expressed as:

$$\tau_p = \sum_j \frac{L_{pj}}{c_{i(j)}}, \quad (5)$$

$$A_p = A_0 \prod_k \gamma_k, \quad (6)$$

where τ_p is time of flight, A_p is the magnitude, A_0 is the source scaling factor (or reflection from the PZT–first layer boundary), $\gamma_k \in \{T_{i \rightarrow i+1}, R_{i \rightarrow i+1}\}$ are the transmission or reflection coefficients encountered along the path. The impulse response of the system at the transducer, in pulse–echo mode, is then given by the superposition of all valid paths:

$$h(t) = \sum_{p \in P} A_p \delta(t - \tau_p). \quad (7)$$

The received ultrasonic signal is obtained as the convolution of the impulse response with the source waveform:

$$u(t) = (h * s)(t), \quad (8)$$

where $s(t)$ is the reference or source signal. This model was used to predict the reduction in normalized backwall reflection amplitude as a function of the water coupling gap thickness, varied from 0 μm to 100 μm .

In addition to analytical modelling, experimental measurements were conducted using a specially developed measurement chamber (Fig. 13), which enabled precise control of the water column thickness during pulse–echo tests. The chamber comprised a probe holder, a water column, a reflector, and a micrometer-based water gap adjustment system, allowing highly accurate control of the coupling layer thickness. The experimental chamber was used to measure the magnitude of the reflected signal as a function of gap thickness replicating the simulation conditions. The comparison between the measurement and experimental results are presented in Fig. 14.

The results presented in Fig. 14 indicate that an increase in coupling layer thickness of only 18 μm leads to a –6 dB loss in signal magnitude. It



Fig. 13. Experimental chamber for assessment of water gap impact on the magnitude of reflected signal.

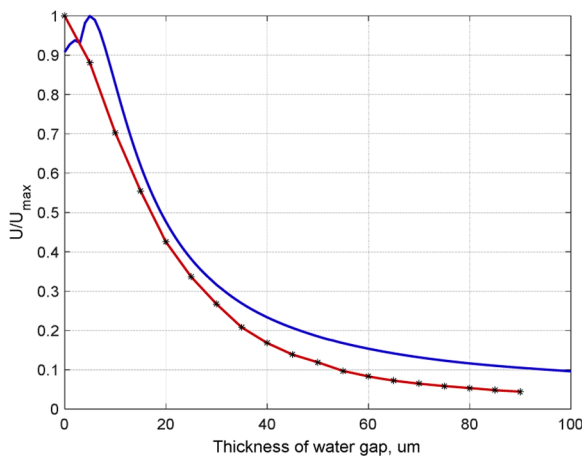


Fig. 14. Magnitude of the backwall reflected ultrasonic signal as a function of coupling layer thickness (blue – analytical modelling; red – experiments).

should be noted that within the investigated 0–100 μm range the response in Fig. 14 is monotonic, because for longitudinal waves in water at 2 MHz the first interference extremum lies near a quarter wavelength, i.e., at approximately 185 μm , outside the scanned range. In the actual inspection configuration, the conditions differ in two respects. First, the longitudinal wave velocity in the S8000S couplant is considerably lower than in water (approximately 920 m/s at 20 °C) and decreases further with temperature, so the corresponding wavelength and hence the layer thickness at which interference extrema occur is roughly halved relative to the water reference and decreases as the couplant heats. Second, during a cooling transient the interference condition is governed by two co-varying quantities: the layer thickness, which changes through thermomechanical deformation and the wavelength in the couplant, which changes through the temperature dependence of the couplant velocity. The transmission can therefore pass through constructive and destructive conditions even under a monotonic evolution of the gap and since both quantities are deterministic functions of temperature, such passages are expected to recur at similar temperatures in successive cycles which is consistent with the transient amplitude decreases observed at 133.8 °C and 134.1 °C during the cooling phases of the two LBE cycles (Section 3.2). This result should be read as a demonstration of sensitivity rather than as a direct measurement of the actual gap in the LBE experiments: it shows that a coupling-gap change of micrometre scale which is of the order expected from the differential thermal expansion estimated in Section 3.2 is sufficient to produce a

signal loss of the magnitude observed after the LBE cooling cycles. The incomplete amplitude recovery is therefore consistent with and most plausibly explained by a residual change of the coupling-layer state, although the gap evolution itself was not measured directly in this campaign. The transferability of this result to the actual inspection configuration follows from the physics of thin-layer transmission. The interference behaviour of a thin layer is governed by its phase thickness, i.e., the ratio of the layer thickness to the wavelength in the layer. Under oblique incidence the interference condition is modified only by a cosine factor of the refraction angle in the layer, while the strong, oscillatory dependence of the transmitted amplitude on micrometre-scale thickness changes is preserved. At the wedge–mock-up interface the wave crossing the couplant layer is longitudinal. However, the longitudinal velocity in the S8000S couplant (approximately 920 m/s at 20 °C [25], decreasing with temperature) is considerably lower than in the water of the reference configuration, so the wavelength in the layer and hence the thickness scale over which the interference conditions change is correspondingly smaller. In addition, a highly viscous couplant transfers shear stress across a sufficiently thin film, which further increases the sensitivity of the transmitted amplitude to the layer thickness. The simplified reference configuration therefore provides a conservative estimate of the thickness sensitivity. The model is accordingly used here to demonstrate the sensitivity scale of the mechanism, not as a quantitative prediction of the notch-echo attenuation.

6. Conclusions

1. The previously developed high-temperature ultrasonic transducer withstood repeated measurements at high temperatures (up to 200 °C) and remained capable of detecting a notch-type defect in the stainless-steel reactor-vessel mock-up after multiple heating–cooling cycles.
2. Laboratory tests showed repeatable amplitude reduction during heating and near recovery during cooling, indicating that the observed signal changes were not caused by irreversible degradation of the transducer.
3. In the representative Helios 3 LBE environment, the defect remained detectable during two heating–cooling cycles. No permanent probe damage was observed; however, the reflected amplitude recovered only partially after cooling, indicating that the coupling interface can significantly influence ultrasonic signal stability.
4. Analytical modelling and experimental validation confirmed that acoustic coupling is a dominant factor controlling signal amplitude. In the reference configuration, an increase of only 18 μm in coupling-layer thickness produced an approximately –6 dB signal loss, demonstrating that micrometre-scale gap changes which are of the magnitude expected from differential thermal expansion of the wedge-mock-up interface are sufficient to account for the incomplete amplitude recovery observed after LBE thermal cycling. Direct in-situ measurement of the coupling-gap evolution is identified as the subject of future work.
5. The results demonstrate the suitability of the previously developed transducer for high-temperature defect detection in representative LBE conditions, while also showing that future optimization should focus on coupling-layer stability and mechanical control of the probe–wedge–mock-up interface.

CRedit authorship contribution statement

Vaida Vaskeliene: Writing – original draft, Visualization, Methodology, Investigation. **Vykintas Samaitis:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation. **Egidijus Zukauskas:** Visualization, Formal analysis, Data curation. **Kriss Rosseel:** Writing – review & editing, Formal analysis. **Reimondas Sliteris:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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