Development of an assembly for the realization of a transducer able to operate at very high temperatures

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Abstract. Monitoring the operation of the latest-generation nuclear reactor requires ultrasonic transducers able to operate at very high temperatures ($> 600^{\circ}\text{C}$). To achieve this, CEA has requested from “Institut de Soudure” to help developing a new technology for these transducers compared to the one previously developed. This began with the development of a reliable assembly technique between a lithium niobate piezoelectric disc whose Curie temperature exceeds 1100°C and stainless steel discs. The chosen solution was to braze the niobate disc between two stainless steel discs. Parallel to this development, it was also necessary to develop a NDE procedure to verify the quality of the brazing assemblies. This development began with a simulation of immersion ultrasonic testing of the assemblies. The constraints were to be able to control the two brazed interfaces from the same access face, with the possibility of detecting and dimensioning defects with an equivalent diameter of 0.25 mm. This phase is important to define the optimal transducer with the associated operating conditions. The first assemblies validated the preliminary choices. To exploit the cartographies obtained, a signal processing procedure was developed. This enabled an automatic characterization of the indications observed. However, the analysis of the signals observed proved to be more complex than the one predicted by the simulation. Once the origin of the various observed signals was identified it was then possible to define windows allowing the construction of the cartographies to analyze. In case of a good quality assembly, it was possible to qualify the generated beam and to image it in the focal plane but with an observed signal having a very low damping. These first encouraging results, however, show that there is still some validation and development work to increase the sensitivity of the developed translator and its damping.

1 The problem

The CEA (Commissariat à l’Energie Atomique et aux Energies Alternatives) is developing a new generation of nuclear reactors in which the coolant is liquid sodium. To perform certain in-service inspection and control functions of these reactors, it is necessary to continuously measure any possible displacements of critical components. Sodium is opaque; it does not allow to perform optical measurements. One of the solutions is the use of ultrasound, liquid sodium having acoustic properties similar to that of water.

There is however an important constraint, it is the temperature at which the measurements will have to be made, at more than 600°C continuously for several years. It is therefore necessary to find an ultrasonic transmitter/receiver that can operate continuously at this temperature.

The CEA had already developed a translator that could operate at this temperature in the past (CEA patent FR 2977377[1]). In order to optimize the manufacturing process, as part of an R&D program, CEA asked the Institut de Soudure (The French Welding Institute, IS) to develop a new transducer assembly technology that can operate continuously at more than 600°C .

2 The technological principle retained

2.1 The piezoelectric element

There are few piezoelectric materials whose Curie temperature is above 600°C . Thus, the most commonly used material, PZT, has a Curie temperature below 350°C . In addition, in terms of tracking equipment over time, it is necessary that the piezoelectric properties of the material remain stable over time and at high temperature.

Table 1. Property of LiNbO₃ [2]

Density (kg/m ³)	4.647 x 10 ³
Curie Temperature (°C)	1210
Dielectric constant (ϵ_r)	29
Charge constant d_{33} (10 ⁻¹² C/N)	8
Coupling coefficient k_{33}	45

As a result, the choice of material is very limited. Based on the experience of the CEA, lithium niobate (LiNbO₃) was selected. This is in the form of a single crystal which can be cut along several crystallographic

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axes chosen according to the type of wave to be generated. The piezoelectric properties of this material are given in Table 1 in the case of the compression mode for the generation of longitudinal waves. It should be noted that according to the source, the Curie temperature is variable according to the crystal manufacture and the chemical composition (impurities). It is raised to 1133°C at a supplier of the material.

2.2 The translator's assembly

The objective is to realize a cylindrical transducer transmitting longitudinal waves with the central frequency of the piezoelectric disk of about 5 MHz. For this, the piezoelectric disk must have a thickness of less than 1 mm. It is therefore essential to assemble this disk on a rigid and liquid-resistant support that can be put in liquid sodium at 600°C. The choice of the CEA was the realization of a stainless steel case whose flat face will serve as the emitting face of ultrasound. It is therefore necessary to bind the disk to this housing, the connection must retain its properties of transmission of deformations to the operating temperature. One of the considered solutions is the brazing of the lithium niobate disk on this exit face.

The development of this brazing proved complex because of the difference in the thermal expansion coefficient between the retained stainless steel (AISI 304) and the fragility of the niobate disc. Indeed, this material does not have ductility.

The work done by the Institut de Soudure has led to the development of a brazing solution for the niobate disc on the front of the translator and the rear support for electrical contact. This work will not be detailed here.

3 Assemblies testing

3.1 The need for testing

In order to verify the quality of the brazed joint, it has proved necessary to be able to carry out non-destructive testing of the links made. Micrographic sections were also made to check the quality of the brazes. In the next phase of industrial manufacturing of sensors, it will be necessary to develop an adequate control procedure to ensure the quality of the assembly. This control will complement the ultrasonic qualification by drawing the generated beam. This will ensure that the linkage has the mechanical and acoustic energy transmission characteristics necessary for extended use at 600°C.

Fig. 1. Transducer assembly.

A non-destructive inspection procedure has been developed and adapted to this brazed assembly

constituted as indicated in Fig.1. The thickness ratio is not respected here, the niobate being thinner than the front face and, moreover, intermediate layers exist between niobate and steel. Given that the front face may have a radius of curvature to have a focused beam, the control can be made only from the rear face.

3.2 The stages of testing development

3.2.1 The choice of the technique

We have seen that the development of a control technique adapted to the assemblies that will be made seems to be necessary. The first question that arises is obviously the choice of this control technique.

The Institut de Soudure, as a technical centre for welding and related techniques, has a long history of developing brazing and non-destructive testing of brazes. For example, in the early 1990s the IS conducted an associative study on ceramic/metal brazing and associated controls [3, 4]. The IS has also been led to develop brazed assembly control between a copper tube and carbon tiles [5]. For these examples and other studies on braze control, it is the technique of ultrasonic immersion control using longitudinal waves at 0° which has proved to be the most efficient. This control technique was therefore chosen.

3.2.2 Testing simulation

Before starting the experimental development of the control, a parametric simulation study was carried out. The objectives of this simulation were multiple:

- Define the optimal translator.
- Define the experimental parameters (at least in part).
- Define the smallest detectable defect.

Since these parameters are not independent, an optimal combination has been sought. All the simulations were done with the CIVA software developed by the CEA.

Fig. 2. Simulation of the beam produced by the selected transducer showing the homogeneity of the focal spot at the brazed interfaces.

The starting-point was the definition of the smallest detectable defect. The selected value is a disc of 0.25 mm in diameter. It was then possible to define the

translator to use as well as some control parameters, the water column and the position of the acquisition windows.

For the definition of the translator, one constraint was to control the two brazed interfaces from a single access. The calculations results permit to define a 25 MHz translator, 10 mm in diameter with a focus at 50 mm (Fig.2).

It is then possible to detect a 0.25 mm defect with a water column of 38 mm, a pitch of 0.1 mm on each axis of displacement and an acquisition window ranging from 51 μ s to 54 μ s (Fig.3). At this level, the only control parameter remaining to be defined is the control sensitivity, which is done during the control on a reference piece representing an infinite brazing defect.

Fig. 3. Simulated mapping and calculated signal for a defect on the first brazed interface.

3.2.3 The method of exploitation of cartographies

Obtaining ultrasound mapping is only of interest if an operating methodology is defined:

- How is a defective area characterized?
- How to size this area?
- How to calculate the brazing rate?

To carry out these different processing steps, IS used the "Analysis" module of the CIVA software.

Fig. 4. Example of signal observed on a defective area with position of measurement windows.

The first point is directly related to the definition of control sensitivity. For these assemblies, we used as a definition technique the gain necessary to observe a 100% ultrasound echo on a defect of infinite dimension (very large in front of the focal spot of the translator) on the first brazed interface. It is then necessary to define a rating threshold. Normally, this is defined by comparing ultrasound control with micrographic sections. In the context of this development, the number of cuts being very small, it was only possible to give a first approximation of this threshold. The value retained is -

12 dB, a value consistent with the experience feedback from IS.

To make these measurements, it is necessary to define windows on the observed ultrasonic signal. An example is given in Fig.4.

The first point is that the signal observed experimentally is much more complex to analyse than the simulated signal (see Fig.3). However, it has been possible to define three measurement windows synchronized by a window on the interface (Fi):

- F1: measurement window on the first brazed interface,
- F2: measurement window on the second brazed interface,
- F3: window for measuring the background echo.

F1 and F2 allow the detection of braze defect type lack of wetting respectively on the first and on the second brazed interface. These windows operate by signal onset that will exceed the defined threshold. F3 is intended for the detection of other types of defects such as niobate cracking, which does not necessarily lead to the appearance of a specific signal but leads to the reduction of the transmission signal through the assembly. The measurement windows observe only the negative part of the signal to take into account the observed polarity and thus be more precise on the measurements.

The next step is to define a method for calculating the area of each indication above the defined threshold. The CIVA software segmentation tool calculates the number of pixels of an object. The surface of this object is then given by the surface of each pixel defined by the displacement step on each axis. The essential point here was to define, in addition to the threshold at -12 dB, the resolution parameters of the segmentation. The most important parameter is the distance resolution. Two objects will be considered separate if they are separated by more than 2 pixels.

It is then possible to calculate the brazing rate T_B . This is given in% by the equation

$$T_B = 100 * \left(1 - \frac{\sum_i n_i}{S_t} \right) \quad (1)$$

With n_i the number of pixels of each indication i and S_t the theoretical surface of the braze in mm^2 . This brazing rate is an overall rate for the two brazed interfaces. It can be calculated independently for the first interface brazed with the access considered taking into account only the defects detected with the window F1. The calculation on the second interface will be incorrect in case of a defect on the first interface.

4 Testing example

4.1 Description of the assembly

The proposed example concerns an assembly with a total thickness of 4.46 mm and a diameter of 15 mm.

4.2 Mapping obtained

The selected technique provides three mappings, one for each brazed interface and one for the background echo. The control was done respecting the parameters defined by simulation with a control gain of 25 dB defined on the reference defect. The maps in Fig.5 show a number of indications on the brazed interfaces. These indications are identified by the segmentation for the brazed interfaces (circled in red for the first interface and in white for the second). The analysis of the cartography with the echo of bottom does not reveal any other defective zone. It should be noted that a signal is observed on this map in the presence of an indication on the first interface. This signal corresponds to a second round of ultrasound between the indication and the access interface.

Fig. 5. Example of C-Scan obtain on a assembly.

4.3 Calculation of the brazing rate

The mappings obtained made it possible to calculate the brazing rate for each brazed interface by following equation (1).

For the first interface, the "defective" surface is 22.1 mm². This gives a brazing rate of 87.5%. For the second interface, the "defective" surface is 12.53 mm² or a brazing rate of 92.9%.

Due to the size and position of the unbrazed surface on the first interface, it is more than likely that the defective surface on the second interface is underestimated.

5 Perspective

The developments completed have shown:

- That the brazing procedure developed made it possible to obtain a crack-free assembly in the niobate and with a satisfactory brazing rate,
- That the control procedure with its interpretation aspect could be applied with satisfaction.

A new assembly has been tested as an ultrasonic transducer. Fig.6 gives the raw signal observed on a planar reflector at the focal length. This signal is of low amplitude and not amortized.

Improvements are still necessary in particular to optimize braze thicknesses and the NDT procedure, in particular the correlation of the mapping of the unbrazed surface with real defects. A new R&D program will soon be launched on these topics.

Before testing these assemblies at high temperatures, it is also necessary to increase the sensitivity of the sensor. This point is related to a loss of oxygen of lithium niobate at high temperature, known phenomenon.

A regeneration procedure has been put in place by the CEA. These translators being intended inter alia for distance measurements, it is also necessary to increase the damping of the realized translator. Due to the conditions of use of these translators (>600°C continuously), this requires a particular study that the CEA will launch soon.

Fig. 6. Example of optimal signal obtain with a good assembly.

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