ABSTRACT

Several components on the main primary system of the French pressurized water reactors (PWR) were realized in Inconel 600® and generally welded with a nickel-based alloy 82 or 182 (depending on the welding process). It was demonstrated that these components are potentially sensitive to the Stress Corrosion Cracking (SCC). So the inspection of these materials to detect and characterize potential cracks is a major challenge for the plant operator. As far as ultrasonic testing is concerned, alloy 182 welds may lead to disturbances of the ultrasonic propagation due to an elastic anisotropy of the material. It was thus necessary to conduct a preliminary work to study the effect of the weld structure on the ultrasonic controllability.

To perform this study, a welding mold in alloy 182 has been realized and characterized by metallurgical and ultrasonic analyses. These analyses allow determining the material characteristics which influence the ultrasonic propagation. In particular, the elastic anisotropy and the attenuation coefficients of the material were estimated. Moreover, artificial defects were manufactured in this mold and experimental tests in pulse-echo mode were performed to detect these defects. Several ultrasonic probes were tested and the influence of the wave characteristics was evaluated. A first quantification of the main ultrasonic disturbances, such as beam skewing and attenuation, was then determined.

Experimental results were then compared to modelling ones obtained with the FEM code ATHENA 2D developed by EDF. To describe the alloy 182 weld, we used a methodological approach previously developed for the austenitic stainless steel welds. The first stage of material characterization provided the modelling input data. Comparison between experimental and modelling results shows a good agreement and so validates the methodological approach which will be applied to industrial applications.

CONTEXT AND OBJECTIVES

Several components on the main primary system of the French pressurized water reactors (PWR) were realized in Inconel 600® and welded with a nickel-based alloy 82 or 182 (depending on the welding process). It was demonstrated that these components are potentially sensitive to the Stress Corrosion Cracking (SCC). So the inspection of these materials to detect and characterize potential cracks is a major challenge for the plant operator.

It was demonstrated in previous studies that austenitic welds disturb ultrasonic propagation because of their anisotropic and heterogeneous structure [1-2]. Electricité de France (EDF) developed an approach, based on modelling, to study the influence of the structure of austenitic stainless steel welds [3-4]. The objective of the present study is to apply this approach to alloy 182 welds and to analyse the effect of the weld structure on the ultrasonic controllability.

A welding mold was especially realized to achieve this aim. Firstly, this weld must be characterized to provide input data to modelling tools. Secondly, the main disturbances of the ultrasonic beam (skewing and attenuation) in this type of weld must be quantified. Then, comparisons between experiment and modelling with a finite elements code (ATHENA 2D) are proposed. We focus on transducers with 2 MHz longitudinal waves, which are commonly used for the ultrasonic inspection of those welds.
WELDING MOLD CHARACTERISTICS

In accordance with industrial practices, the alloy 182 welding mold was realized with a manual arc welding process, in a flat position and with coated electrodes of 4 mm diameter. Around seven hundred runs were necessary to fill the mold. Macroographies of the weld are proposed on Figure 1. The mold geometry is not representative of industrial welds but the main objective of this preliminary study is to analyse ultrasonic beam disturbances after significant trajectories in the anisotropic alloy 182 material.

Because of the large dimension in the transverse direction and as the same order of runs was forced for each bead (from left to right on the Figure 1-a), the structure is strongly homogenous (weak variation of the columnar grain orientation in the full welding volume). We observe an 8° grain disorientation (compared with vertical direction) in the plane transverse to the welding direction. In the (VL) plane, the grain disorientation varies between -5° and +5° and we will consider that grains are vertical in this plane.

![Macrographies of the alloy 182 weld – a) In the transverse plane – b) along the welding direction.](image)

Figure 1 - Macrographies of the alloy 182 weld – a) In the transverse plane – b) along the welding direction.

Two blocks have been machined in this mock-up. The first one, reference number block 1, is defect free and is used for inspections in through-transmission mode (see paragraph 5). In the second one, reference number block 2 (Figure 2), four side drilled holes (SDH) of 2 mm diameter and one vertical notch of 10 mm height were machined to perform inspections in pulse-echo mode. A mock-up in forged isotropic austenitic stainless steel (AISI 316L) is used as reference block.

![Characteristics of block 2](image)

Figure 2 - Characteristics of block 2

ATHENA CODE CHARACTERISTICS AND MODELLING INPUT DATA

ATHENA is a finite element code that simulates wave propagation in all kind of elastic media such as heterogeneous and anisotropic structures [5-6]. The interaction between the beam and a defect is also
simulated thanks to the fictitious domain method. The mesh of the defect is then independent of the structured mesh of the calculation zone. It allows arbitrary shape and orientation defect modelling.

In ATHENA code, the equations are written in a mixed formulation in stress and velocity terms (marked \((\sigma, v)\)). A model was developed to take into account wave attenuation due to grain scattering [7]. The equations of this model read:

\[
\frac{\partial \sigma}{\partial t} + D \sigma = C \varepsilon(v) \tag{1}
\]

\[
\rho \frac{\partial v}{\partial t} - \text{div} \sigma = f \tag{2}
\]

where \(\varepsilon\) is the strain tensor, \(\rho\) the density, \(f\) a strength source. Equations without attenuation are found for \(D\) equal to 0, and \(C\) therefore refers to the material's elasticity tensor.

In this study, we use the 2D version of the ATHENA code. This simplification is possible for the case studied because the inspection plane (TV plane) is a symmetry plane of the material.

The heterogeneous weld is described in a set of anisotropic homogeneous mediums. Each of the "elementary" anisotropic homogeneous materials is characterized by a specific grain orientation and specific values of \(C\) and \(D\). The grain orientation mapping is achieved by an image processing software applied on macrography of Figure 1. Only sixteen mediums are necessary to describe the alloy 182 welding mold because of the strong homogeneity of the structure. Another option to obtain a weld description consists in using the MINA model (Modelling anisotropy from Notebook of Arc welding) based on information extracted from the welding notebook [8].

**DETERMINATION OF C AND D TENSORS**

Crystallographic analyses were performed on samples machined in the weld. EBSD (Electron Backscattering Diffraction) allows to determine local crystallographic orientation and to highlight grain boundaries. The grain width can be then estimated to about 300 microns (for several millimetres length). X-ray diffraction gives higher statistics on crystallographic orientations and the polycrystalline symmetry can be determined with this analysis. A \(\{200\}\) pole figure is presented on Figure 3. The material texture is clearly highlighted and is characteristic of an orthotropic symmetry with a \(<100>\) fibre axis slightly disoriented compared with V axis.

![Figure 3 - \(\{200\}\) pole figure for the alloy 182 weld](image)

Elastic constants of the polycrystalline material can also be estimated from X-Ray diffraction analysis. They are calculated from values of monocrystal elastic constants and three coefficients of the orientation distribution function [9]. The nine independent elastic constants of the alloy 182 weld are indicated on Table 1. These values are in agreement with literature data [10]. Ultrasonic propagation in the (TV) plane, which is a symmetry plane and the incidence plane in this study, depends on the four values indicated in bold.
Corresponding values of velocities of quasi-longitudinal waves and quasi-transversal waves with vertical polarisation, as a function of the angle of propagation, are indicated on Figure 4. The variations of velocity are slightly weaker than austenitic stainless steel ones. Complementary measurements of ultrasonic velocities have been performed with an immersion and through-transmission setup [11]. Results, indicated by the black squares on Figure 4, are in agreement with the X-Ray diffraction analysis.

As far as tensor D is concerned, attenuation coefficients for quasi-longitudinal waves and for a 2 MHz frequency as function of the angle between the direction of propagation and the grain orientation are indicated on Figure 5. They were estimated from attenuation measurements with a specific set-up on 316L weld samples [7], slightly adjusted from experimental data on SDH (see paragraph 0). Measurements for alloy 182 weld with the through-transmission setup are in progress. The constitutive equation is coherent with Ahmed’s theory which predicts a monotonous growth of attenuation of quasi-longitudinal waves [12].
RESULTS FOR DETECTION OF SIDE DRILLED HOLES

Analysis of beam attenuation

To determine the beam attenuation in the weld, two outputs are analysed:

- \( \Delta A1 \): Difference of amplitudes between SDH1 (20 mm depth) and SDH3 (40 mm depth) of block 1. A negative value stands for an attenuation for the deeper defect;
- \( \Delta A2 \): Difference of amplitudes between the reference mock-up and the alloy 182 weld for the 40 mm depth SDH. A negative value stands for an attenuation in the weld.

Black data on Figure 6 stand for the experimental values. A higher attenuation in the weld is clearly highlighted since \( \Delta A2 \) is negative for all probes. Echo amplitudes with the elastic model (grey data on Figure 6) are significantly overestimated which confirms the importance of taking into account grain scattering attenuation.

![Figure 6 - \( \Delta A1 \) and \( \Delta A2 \) for four angles of propagation of longitudinal waves](image)

A second series of calculation was started with the model with attenuation and values of Figure 5. Echo amplitudes are represented by line-pattern data (third column) on Figure 6. A good agreement is noted for all the cases.

Analysis of beam deviation

Inspections in through-transmission mode are very useful to reveal disturbances of the ultrasonic field. The experimental setup is presented on Figure 7. A cone-shaped probe is used as receiver to map the transmitted fields of L0, L45 and L60 waves through the weld.

Examples of results for L60 waves are presented on Figure 8 and compared to measurements in the isotropic reference block. Cscan presentations illustrate the phenomenon of beam distortion in the weld. Few beam divisions are observed because the structure is strongly homogeneous. On the other hand, beam deviation values (\( \Delta T \)) depend on the direction of inspection (D1 or D2). This phenomenon is due to dissymmetry of the structure (8° grain disorientation) which leads to different values of the angle of energy propagation for D1 and D2 (respectively 52° and 59.5° compared to 56° in the reference block).
The influence of the weld anisotropy on beam deviation is confirmed by the inspections in pulse-echo mode on block 2. In particular, values of deviation D for SDH3, as defined on Figure 9, depend on the angle of refraction. These values are well-predicted with Athena code if right characteristics of the structure and of the material are taken into account.

As far as the notch is concerned, classical diffraction and corner echoes are detected (Figure 10). Defect sizing based on the position of the diffraction echo and the hypothesis of an isotropic material conducts to significant errors (height estimation of 12 and 19 mm respectively with L45 and L60 waves instead of 10 mm). Correcting the angle of refraction and the velocity by taking into account the material anisotropy noticeably reduces these errors (height estimation of 10.5 and 13.5 mm respectively with L45 and L60 waves).
CONCLUSION

The work presented in this paper is a necessary preliminary step to study the ultrasonic controllability of an alloy 182 weld. The objective is to determine the main characteristics of the weld structure to simulate ultrasonic propagation. In this aim, a welding mold with a large volume and a regular series of runs was realized to obtain a relatively homogeneous structure.

The first phase of the study was devoted to the metallurgical and ultrasonic characterization of the welding mold. The orientation of columnar grains, the stiffness tensor and the coefficients of attenuation have been determined. This characterization underscores the material anisotropy and a dissymmetry of the structure related to the welding process.

Inspections with 2 MHz longitudinal waves in through-transmission mode on a flawless block and in pulse-echo mode on a block with calibrated defects reveal beam disturbances such as deviation and attenuation. Variations in results depending on the direction of control show the influence of the structure dissymmetry. Modelling with the finite element code ATHENA 2D, using the input data determined from characterization stage, is in good agreement with those experimental results.

In conclusion, the methodology previously developed for austenitic stainless steel welds can be applied to alloy 182 welds. It will be applied to address industrial applications such as inspections of reactor vessel clevis or steam generator divider plate.

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