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Austenitic and Bi Metallic Weld Inspection I

Ultrasonic Examination of a CVCS Weld

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ABSTRACT

The anisotropic, heterogeneous and coarse granular structures of austenitic stainless steel welds may lead to important disturbances of the ultrasonic propagation : beam skewing and splitting, attenuation, backscattering and spurious echoes. Numerous studies were undertaken by EDF R&D and CEA for a few years to study these disturbances and to improve the ultrasonic NDT in nuclear applications.

This paper presents a laboratory study on the ultrasonic examination of the branch pipe weld connecting the Chemical and Volume Control System (CVCS) and the primary coolant piping of PWR circuits. Both experimental and theoretical approaches are used in this work, which helped to set up the methodology for modelling ultrasonic inspection of an austenitic stainless steel weld, presented in this conference [1]. Two theoretical approaches are presented : a FEM code, ATHENA, developed by EDF, and a semi-analytical code integrated in the CIVA simulation platform, developed by CEA. These codes simulate the propagation of the ultrasonic beam in the weld and calculate the defect/beam interaction.

Experimental tests are performed on a plane mock-up representative of a CVCS weld in terms of material and welding process. The geometrical effect is not studied here. Experimental cartographies of the transmitted field through the weld were acquired for several orientations of the probe. These cartographies are compared to computed fields. The responses of defect embedded in the weld structure are also presented and compared to experimental measurements. In particular, the influence of the wave characteristics on the detection and on the characterization of the defects is evaluated.

1. CONTEXT AND OBJECTIVES

EDF R&D has launched in collaboration with CEA a consistent research program on ultrasonic inspection of austenitic stainless steel welds. This program deals with the comprehension of the structure effect on the NDT performances [2,3].

As far as structural effects are concerned, the main ultrasonic disturbances are:

- a strong anisotropy of the properties of elasticity which, coupled with the heterogeneity of the orientation of the grains, can produce significant deviation, splitting and distortion of the beam;
- an important scattering of the ultrasounds by the grains involving an attenuation and a structural noise.

This paper presents a laboratory study on the ultrasonic examination of the branch pipe weld connecting the Chemical and Volume Control System (CVCS) and the primary coolant piping of PWR circuits. The objectives are to demonstrate the ultrasonic controllability of a CVCS weld, to improve the understanding of the ultrasonic disturbing phenomena and to provide technical data in support of the development and the qualification of an NDT process.

This work is based on both experimental analyses on welded mock-ups and the use of modelling tools (ATHENA 2D code, CIVA software) which allow realistic simulation of the phenomena of propagation in complex mediums.

The modelling work is based on a methodological approach whose aim is to provide a realistic description of the austenitic weld. Details on this methodology can be found in an other paper of this conference [1].

2. CVCS WELD AND MOCK-UP

In this study, we focus on the particular case of the weld of a CVCS set-in branch pipe. Characteristics of this weld with a K chamfer (back welding) are given in Figure 1.

A plane mock-up is realized for this work. The 3D geometry of the component is not taken into account in order to separate the influent parameters (material and geometry). As a consequence, the study only treats the material aspect.

The multi-pass weld is realized in flat position by manual arc welding process with coated electrodes of 316L steel. A macrography of this weld in a transverse section with the direction of welding is visible on the Figure 2. In this plane, one distinguishes the austenitic columnar grains which grow in relation with the direction of the thermal gradient and whose orientation evolves according to the zone. The solidification structure is then anisotropic and heterogeneous.

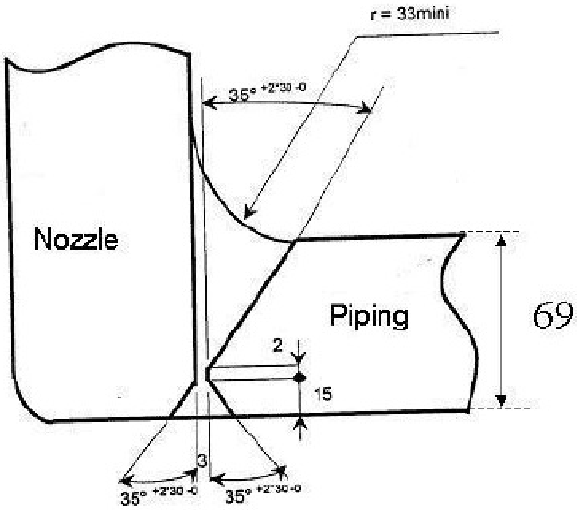


Figure 1 - Theoretical dimensions of the weld of a CVCS set-in branch pipe

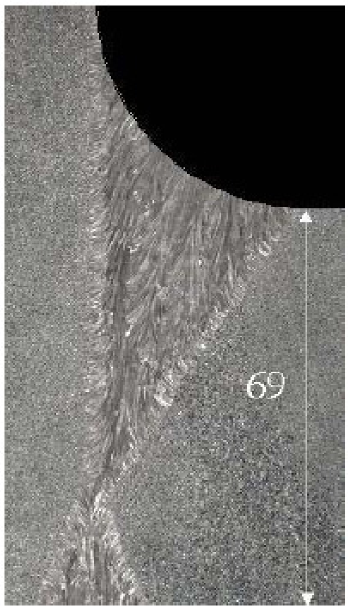


Figure 2 - Weld macrography

3. MODELLING CODES FOR ULTRASONIC PROPAGATION

For this study, we used two complementary approaches in modelling : ATHENA 2D code developed by EDF R&D and CIVA software developed by CEA. These codes simulate the propagation of the ultrasounds in anisotropic and heterogeneous complex mediums and the interactions of the beam with defects of complex geometry. A third code, coupling those two modelling approaches, will be integrated in CIVA_9.

ATHENA 2D solves the equations of elastodynamic expressed with the stresses and the velocities of the displacements by a finite element method [4]. The numerical methods in finite elements or finite differences approach the exact equations that represent the physical phenomena and give in particular quantitative information on the energy of the signals. The development of a 3D version of this code is in progress. Lastly, the phenomenon of attenuation due to the grain scattering was implemented in the code [4].

CIVA software is used to model 3D configurations with reasonable computation time [5]. The models are based on semi analytical kernels and numerical integration which allow computing beam propagation and flaw scattering in various cases including an anisotropic and heterogeneous 3D weld structure. CIVA enables to predict the performances of an inspection in realistic industrial configurations for complex specimen geometry, with standard or phased arrays transducers. Attenuation due to the grain scattering can also be taken into account.

As far as ultrasonic propagation in austenitic weld is concerned, validation of CIVA models is in progress.

In order to simulate the ultrasonic propagation in the weld, input data are required, in particular realistic descriptions of the weld. Indeed, too simplified weld descriptions could lead to erroneous results [6].

In previous publications, it has been demonstrated that the welds can be described by a finite number of homogeneous anisotropic domains in which the orientation of the grains must be determined. This type of description is obtain by image processing performed on the macrography presented on Figure 2.

An other approach uses the model MINA developed to describe the heterogeneity of a structure starting from the welding notebook of a multipass weld [7]. Modelling with MINA descriptions is not treated in this paper.

To complete the description, elastic constants representative of an orthotropic material are associated to each grain orientation [1].

In order to validate this modelling approach for the CVCS application, we present in the following sections some results for different inspection techniques. We compare more particularly experimental and modelling results.

4. ULTRASONIC TESTINGS ON THE CVCS MOCK-UP

Because of the weld and the depth of inspection, the industrial practices require contact transducers with longitudinal waves at a 2 MHz frequency. The experimental study was thus performed on the CVCS mock-up with 60° longitudinal waves transducers.

4.1 Inspections in Through-Transmission Mode

Inspections in through-transmission mode are very useful to reveal disturbances of the ultrasonic field. We present in this paragraph experimental and simulated mapping of the transmitted field propagated through the weld of the CVCS mock-up. Simulations were performed using CIVA -software. Several orientations of the inspection plane were studied in order to approach and evaluate some realistic configurations of inspection of the CVCS. For each measurement, the transmitter was positioned on the upper side of the mock-up and a receiver was scanned on the opposite surface. The experimental set up is presented on Figure 3.

Figure 4 present the mapping of the transmitted field through the weld for an inspection plane perpendicular to the weld axis. The experimental measurement is compared to the simulated ultrasonic field. Echodynamic curves indicate the amplitude of the signal versus the scanning axis. All the results are compared to propagation into the base metal.

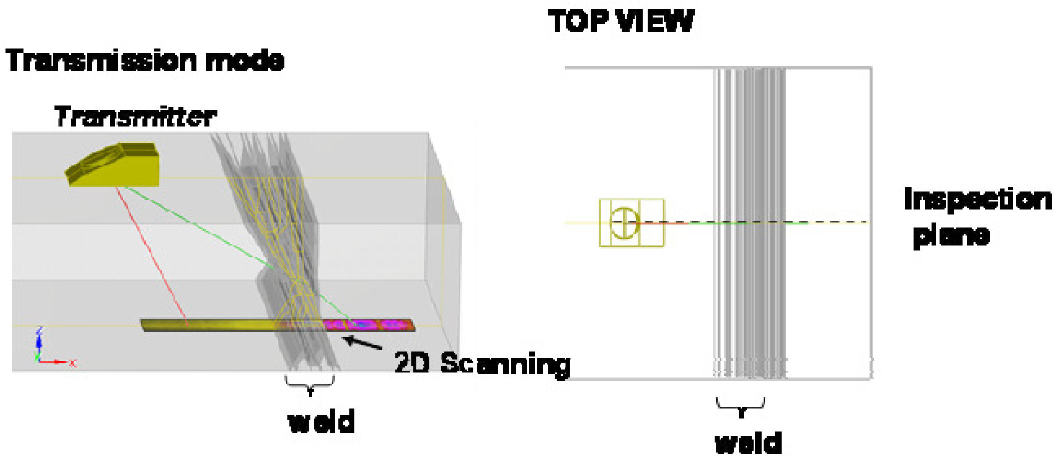


Figure 3 - Set-up of transmission measurements trough the CVCS mock up

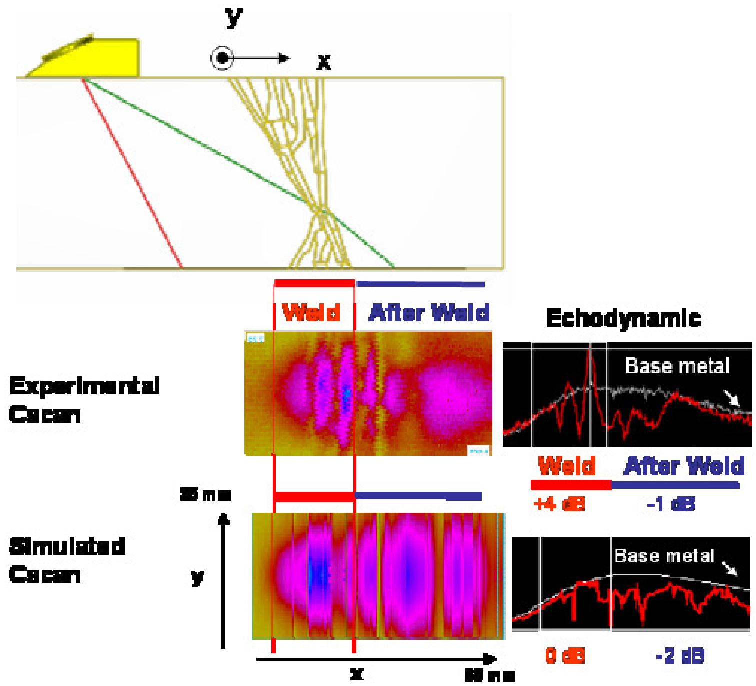


Figure 4 - Experimental and simulated results of transmission through the CVCS mock up

The experimental results show important fluctuations of the transmitted signal: the ultrasonic beam is disturbed and locally splitted inside and through the weld.

Inside the weld, local focussing of the energy leads to increased amplitude of the beam up to 4 dB referred to the base metal. The comparison of experimental and simulated fields shows a good prediction of the beam splitting of the transmitted field through the weld.

Average amplitudes are correctly predicted but complementary work must be undertaken to explain the difference between maximal amplitudes (4 dB less in modelling whereas calculations were launched without attenuation coefficient).

Figure 5 shows results obtained in through-transmission mode for an inspection plane oriented at 70° from the axis of the weld. The experimental measurement shows that there is no skewing of the ultrasonic beam out of the inspection plane. The simulation predicts the same beam direction as experiment. The propagation through the weld induces similar disturbances as observed at 90° : beam splitting and local focussing. These two phenomena are predicted with CIVA.

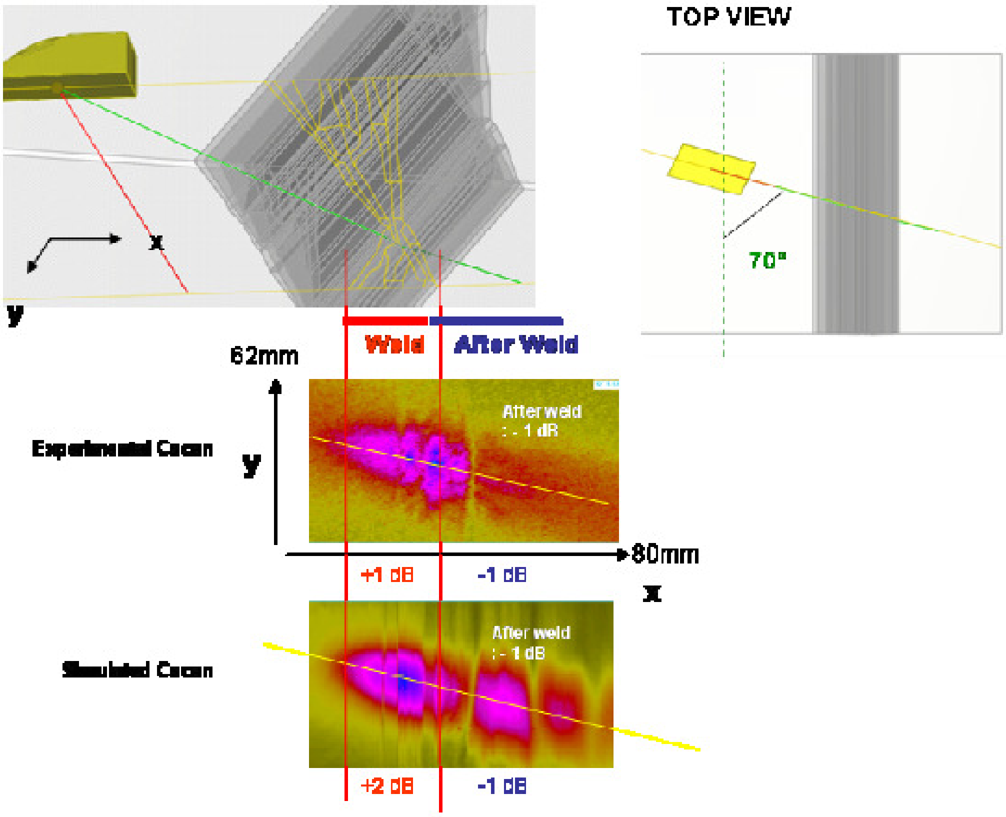


Figure 5 - Experimental and simulated results through the CVCS mock up for an inspection plane oriented at 70° from the weld axis

4.2 Inspections in Pulse-Echo Mode

4.2.1 Detection of a Side Drilled Hole

The aim is to study the interaction between the ultrasonic beam and a defect after a significant propagation across the weld. We are interested in the detection of a 2 mm side drilled hole located at a depth of 39 mm in the base metal of the nozzle part. The configuration of inspection is given in the Figure 6.

In experiments, the loss of amplitude ΔA of the specular echo on the side drilled hole detected through the weld is 11.5 dB compared to a propagation in the base metal. This high value is related to the significant propagation of the beam in the weld which involves as shown in the previous section various phenomena such as beam splitting, local deflection, scattering of the ultrasounds by the column-like grains. The computed fields in the inspection plane presented on Figure 7 illustrate the splitting and the local deflection of the ultrasonic beam.

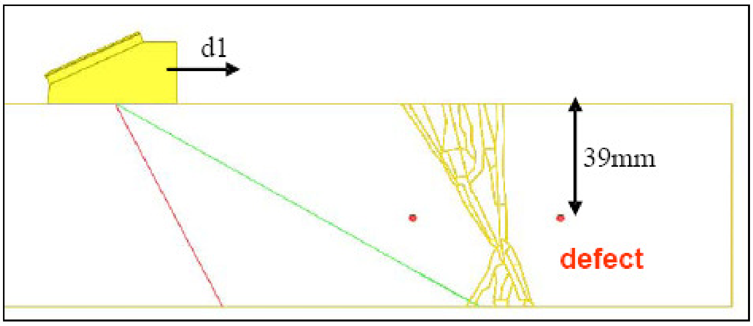
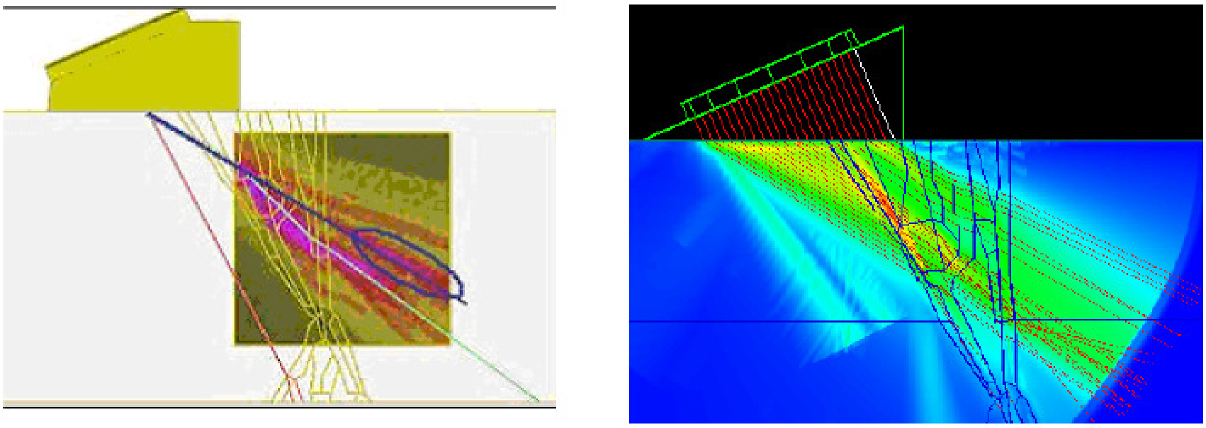


Figure 6 - Configuration of inspection of a side drilled hole located in the nozzle



a) b)

Figure 7 - Simulated field transmitted trough the CVCS mock up : a) CIVA model b) ATHENA 2D

If attenuation due to scattering effects is taken into account, modelling with ATHENA 2D highlights well this loss of amplitude (amplitude ΔA=9,5 dB). Without taking into account of the attenuation, the amplitude of the echo would have been over-estimated of 7 dB. It is also to note that in spite of this strong loss of amplitude, the defect is experimentally detected with a good signal to noise ratio (7 dB).

An inspection of the same defect using a dual element probes was simulated in 3D using CIVA. Figure 8 presents the reconstructed B-scan image of the computed side drilled hole response.

The result obtained without taking into account of the attenuation, confirms the overestimation of the defect amplitude. The side drilled hole is detected with a loss in amplitude of ΔA = 3.5 dB for an experimental value ΔA=11 dB. The reconstructed Bscan image obtained using isotropic material properties indicates a slight shift in the depth position of the defect according to the actual position (~ 2mm). The error in positioning results from the beam splitting and deflection through the weld.

Figure 8 - Simulated Bscan image for the detection of a side drilled hole (without attenuation)

4.2.2 Detection and Sizing of a Planar Defect

In this paragraph, we study the detection of notches emerging in the internal wall, located in the base metal and in the middle of the weld. The height of the defects varies between 5 and 20 mm. The configuration of inspection is given on the Figure 9.

For a notch in the base metal, Bscans are given on the Figure 10. We note the presences of a diffraction echo, a corner echo and a LLT mode conversion echo which are typical of such a defect. The signal to noise ratio is high (around 18 dB) and the notch is sized with a maximum error of 0.5 mm.

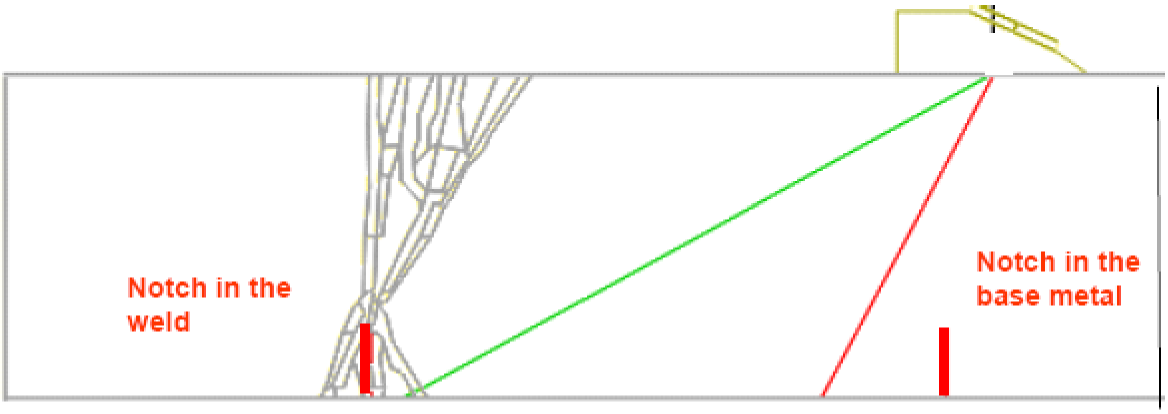
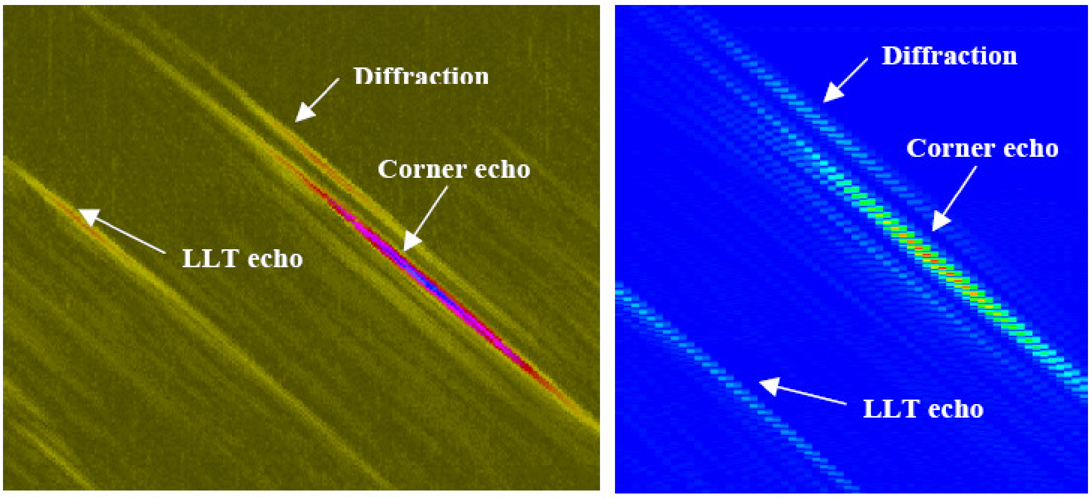


Figure 9 - Configuration of inspection of a notch located in the weld



a) b)

Figure 10 - Bscan for a notch (10 mm height) located in the base metal
a) experience – b) modelling with ATHENA 2D

For a notch in the weld, Bscans are given on the Figure 11. We note the appearance of additional echoes between the corner and the tip diffraction, whose origins may result from mode conversions, at the different interfaces on the beam path.

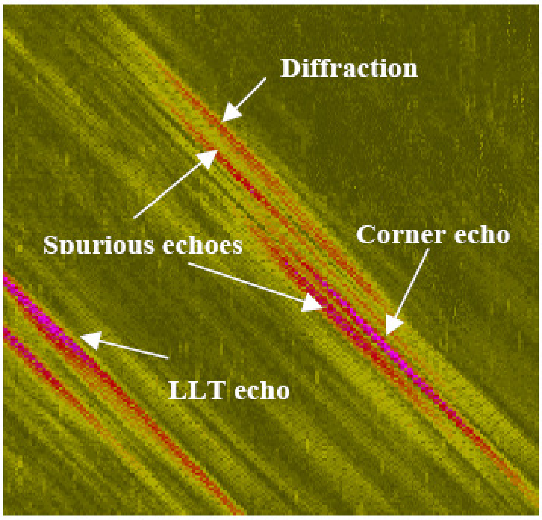
In term of detection, the signal to noise ratio of the corner echo is between +5 and +10 dB according to the notch. The amplitude of the corner echo of the "weld" defect is 10 dB less than the "base metal" defect one. Furthermore, significant experimental variations can be observed between two close Bscans.

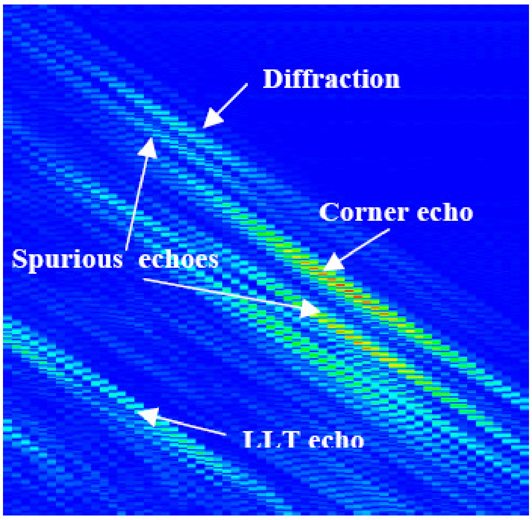
In term of sizing, according to the notch and to the sizing method, errors on the defect heights are estimated between 1 and 4 mm if one assumes that the material is isotropic.

The LLT mode conversion echo becomes significant for notch height greater than 15 mm. This echo can be helpful for defect characterization as its amplitude increases with the notch height.

Modelling with ATHENA 2D reproduces correctly the experimental results, especially the presence of spurious echoes, the amplitudes of the various echoes and the sizing errors.

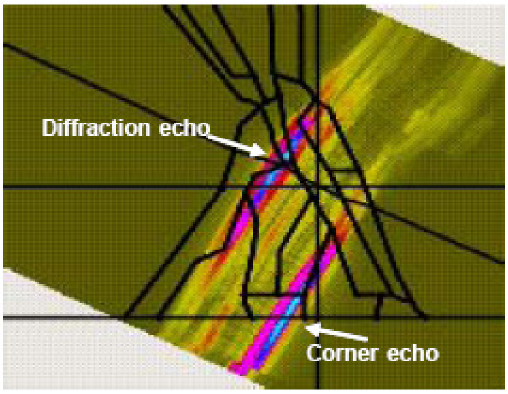
Notches responses were also predicted using CIVA. A good agreement, in term of amplitude, was obtained on corner and diffraction echoes in the weld. These results are presented on Figure 12 . Grain scattering is not taken into account but, as the beam path in the weld is weak (especially for the diffraction echo), this parameter is less influent than for the side drilled hole inspection. On the other hand, mode conversion through the chamfer and the interfaces of the weld structure (possibly at the origin of spurious echoes) are not simulated in the present version of CIVA.





a) b)

Figure 11 - Bscan for a notch (15 mm height) located in the weld
a) experience – b) modelling with ATHENA 2D.



	15mm Notch in the weld	
	Corner echo	Diffraction echo
Experiment	-7 dB	-10 dB
CIVA Simulation	-8 dB	-9 db

Figure 12 - Reconstructed Bscan for a 15 mm notch located in the weld (CIVA modelling).

5. CONCLUSION

The ultrasonic testing of a CVCS weld was studied in through-transmission mode and pulse echo techniques. The interaction of longitudinal waves with two types of defects (side drilled holes and notches) was analysed. All the defects inspected were detected but significant disturbances of the ultrasonic beam were highlighted. In particular, spurious echoes and beam deflection due to the anisotropic and heterogeneous structure of the weld can lead to difficulties in characterizing the defect.

Modelling, with two complementary approaches, allows to explain the origins of these disturbances. The testing configurations studied validate the methodology developed to provide a realistic description of the weld for modelling. Lastly, this study shows that it is necessary to take into account the ultrasonic attenuation due to grain scattering in order to obtain quantitative measurements.

Validations of the models will be carried on and some works are in progress to study the influence of variations of the weld structure on the performances of the ultrasonic testing. Moreover, this study shows the need to take into account the actual direction of the beam into the weld in order to improve the sizing of the defect.

6. REFERENCES

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