Assessment of Ultrasonic Techniques for Characterization of Stress Corrosion Cracks in SG Partition Stubs

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Abstract. Studies by EDF and AREVA NP on Inconel zones have identified the Inconel 600 partition stubs of steam generators as potential areas of SCC, on the hot leg side. Decision was made to perform an expert assessment using ultrasonic testing (UT) techniques to be applied on the whole area of the stub showing penetrant testing (PT) techniques indications. UT techniques, probes and tools were then developed for that purpose. The aim is to size shallow defects, sizing capacity being maintained for defects propagated to a half-thickness.

Although no formal qualification was required, the development was performed in view of a performance demonstration. Three mock-ups were manufactured by AREVA NP: two welded mock-ups with machined defects, surface condition and geometry representative of the "envelope" of situations likely to be found on the SG; one mock-up, with representative corrosion cracks

Development was carried out in two phases: development of techniques and specification of probes and tooling, then development of tools, industrialization of probes, development of procedures, personnel training and performance demonstration.

The basic inspection relied on TOFDT, with a contact probe; frequencies, PCS and dimensions were optimised using the results from the mock-ups. Three sets of transducers were defined: a HF transducer for flaw sizes close to the critical size, another HF transducer, with lower PCS for smaller defects, both transducers for material whose permeability was equivalent to that of the mock-ups; anticipating less permeable materials, a MF probe was added.

Tests having shown that these transducers did not cover the whole plate thickness, a back-up phased-array probe was selected to scan the plate beyond half-thickness. For a better access under the TSP, a focused transducer was also added to complete the previous set. All of these transducers were operated in immersion, with the same tool: a COBRA type arm which positioned the probes on the whole area to inspect while providing positioning accuracy. Probes were assembled in order to cover the largest surface.

Performance demonstration tests have validated the inspection strategy and provided evidence that the developed techniques were adapted to the case considered in terms of inspected volume and sizing accuracy. The capability of the manipulator to cover the whole area, to perform the inspection in the requested time frame with an acceptable positioning accuracy was also demonstrated.

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1. Introduction

EDF entrusted to AREVA NP the development of an in-service inspection method dedicated to potential SCC cracks detection and characterization in the 900 MW steam generator stub. The divider plate (DP) ensemble consists in two welded 2 m long and 32 mm thick Inconel 600 rolled plates, the so-called stub being 70 mm wide and located between the tubesheet (TS) and the DP (c.f. Figure 1). Junctions between the stub and the TS and between the stub and the DP are insured by Inconel 182 electrode welds.

Whereas EDF's specifications include expectations concerning the method development as well as its industrialization, this paper only describes the first phase up to the performance demonstration tests. Besides, these specifications define the zone to be inspected, i.e. the zone delimited by the two above mentioned welds, extending over a length of two meters centred on the SG axis. Inspection should detect and characterize flaws with an accuracy of 10 % for 2 to 10 mm deep cracks, and 1 mm for 10 to 20 mm deep cracks. For the remaining defect depths (20-34 mm), only detection is required.

Moreover, it is asked to develop a technique able to detect potential SCC cracks (surface-breaking defects) whose length could reach 13 mm, that could be skewed by more than 20°, tilted and that could be arranged in clusters. As stub or welds parameters such as surface conditions, material permeability, weld profiles, presence of repairs…, could vary, it is intended to include their influence on the developed technique performances.

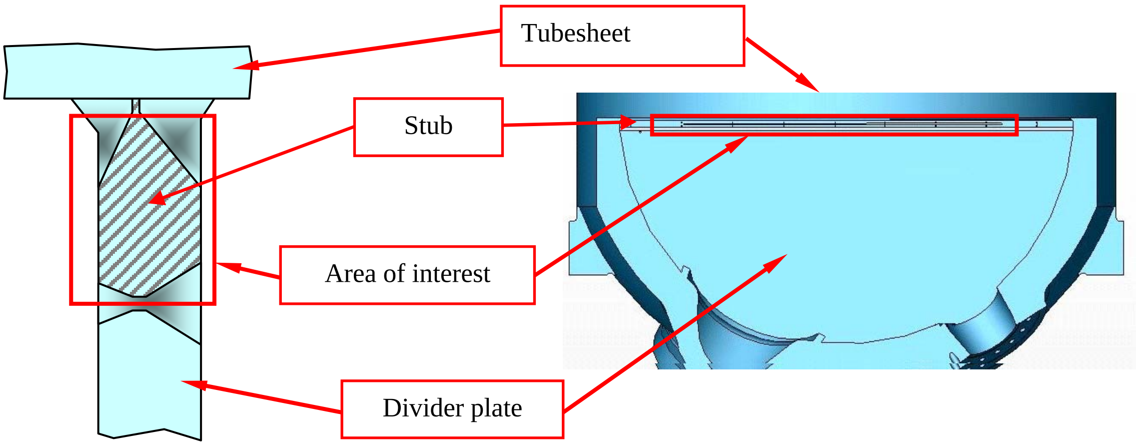

Figure 1 – SG DP ensemble as well as area concerned by the inspection

2. Development methodology

2.1 Methodology and experimental equipment

2.1.1 Perturbing parameters identification

The methodology consisted in an identification of the parameters that may potentially reduce the performances of the UT methods.

Four kinds of perturbing parameters were then identified and evaluated: geometrical parameters, material related parameters (base metal and molten material), defect related parameters and at last surface conditions parameters. In all, the influence of 13 parameters was analysed during this project. In details, these parameters are:

Geometrical parameters

First, the TS/stub knuckle could potentially be a limit for inspecting the upper area of the stub and was then identified as a perturbing parameter.

Data from the workshop enable us to quantify potential welding induced DP/stub misfits that could induce loss of coupling of contact transducers and/or loss of shape of the beam of contact transducers as well as with immersion methods.

Material related parameters

Each of the DP/stub assembly is potentially anisotropic (rolling, heat treatment, weld runs, stresses …). Because tested methods, and particularly the phased array ones, have a wide angle range it was necessary to have information about the isotropic state of the base metal.

It appeared during the inquiry of manufacturing that there are repaired zones on the DP. Even if the assessments by EDF did not put in evidence defects in the weld DP/stub, it is not possible to exclude that defects may appear in the border line or in the molten metal of a repair.

Surface condition parameters

The conditions of surface finish are indeed determining for this inspection. Thus, it was not possible to restrict the assessment, to the values specified by manufacturing procedures. The influence of this parameter was therefore studied on realistic surface finishes determined according to a replica made on-site and the notices of the operators.

The ripples on the surface (called grinding marks) were also taken into account after evaluation on the same bases.

Crack related parameters

Despite the information supplied by EDF's specifications, crack morphology was not known. Therefore the robustness of the methods and/or their limits over the specified ranges had to be demonstrated.

- The main parameter to study was crack depth, but study has to focus on short cracks so the diffracting length has kept a special attention keeping in mind that inspected area could be as large as several meters.
- Some PT inspections having put in evidence skewed cracks, the effect of the skew of cracks was also studied.
- Crack tilt couldn't be specified due to the fact that cracks were supposed to be SCC ones. So crack tilt effect has been quantified while testing.
- Crack clusters could blind transducers and should be considered in the evaluation.
- Finally, crack morphology could significantly decrease the energy of the echoes.

Once all these perturbing parameters have been identified and organized hierarchically, a test program has been built including numerical modelling where possible. Due to the tight schedule and the limited quantity of material available, it was essential to limit the number of tests. On one hand, computerised modelling with CIVA software enabled to quantify the influence of tilt; on the other hand, the experience of AREVA NP acquired in ISI of Inconel BMI using TOFD technique added to the experience of Intercontrôle in the use of FISSCOR on undercladding defect type indications enabled the quantification of the transfer coefficient between notches and cracks.

2.1.2 Input data

ISI and replica

Some data were available thanks to the PT inspections of a reference set of SG and to a replica made on the stub of a SG in a French PWR plant. It has to be stressed that grain size known from the analysis of the replica fitted well with the grain size known from manufacturing feedback and with the grain size of the mock-ups. Therefore it was demonstrated a fair confidence of the representativeness of the mock-ups specially the AREVA NP ones with their built-in perturbing parameters.

Manufacturing data

To tighten the range of the perturbing parameters as much as possible, an inquiry was led to identify exactly the batches of sheet metal and the manufacturing process of the concerned SGs. In our case it led to go back up to the manufacturing of SGs concerned to specify the most representative mock-ups for adjustment tests and those for performance demonstration.

2.1.3 Mock-ups

EDF owned some mock-ups without weld, with EDM notches ranging from less than 1 mm to through wall and some welded mock-ups having EDM notches machined at various distances from the molten metal. These mock-ups have been used to set up the standard performances regarding detection and depth, when excluding any other perturbing parameter. Those including EDM notches located inside the molten metal were also used, but not as a technique selection tool.

Figure 2 – Welded stub/DP mock-up

In addition, AREVA NP designed and manufactured 3 new mock-ups: 2 welded mock-ups (see figure 2) made of an Inconel 600 DP, a stub plate and a TS have been designed and built up at the Technical Centre’s welding department. The goal of these mock-ups was to fill up or to complete the range of the perturbing parameters potential variation, especially in dealing with surface condition, molten metal, geometry of the scanned area and cracks in some extent. These 2 mock-ups have been designed and welded in accordance to the manufacturing procedures, to the welding operating procedures and to the inspection procedures of AREVA NP Saint-Marcel workshop. A third mock-up was completed by Technical Centre chemistry and corrosion department including induced SCC cracks. The design depth of those cracks was determined considering defects mechanical stability criteria.

Fifteen EDM notches have been machined in the first welded mock-up. Three notches 2, 4 and 10 mm deep were located close to the knuckle, i.e. 20 mm far from the TS. These notches have been designed to evaluate the covered zone under the TS. The 4 next notches, 2 and 4 mm deep, aimed to understand methods behaviour over cracks in clusters. The 3 next notches having the same depth as the 3 first notches have been machined in the stub/DP weld so that diffracting geometry was close to the molten metal and could provide welding influence quantification. In such a position, half of the ultrasound path of TOFD methods goes through the welded metal but it is realistic condition regarding the input information. Considering asymmetric methods shooting up through the weld and down out of the weld gave us information about molten metal parameters. A 4 mm deep EDM notch was machined close to the stub/DP weld in the neighbouring of the repaired weld to simulate cracks located near a repair. At last, three 4 mm deep notches of different length were machined in the DP to study the diffracting length influence.

Ten EDM notches have been machined in the second welded mock-up. As in the first mock-up, 3 notches (2, 4 and 10 mm deep) were located close to the knuckle, 20 mm far from the TS. The other notches of this mock-up were machined inside or close to the stub/DP weld. This weld was realised to create a hard surface scanning environment including hard grinding and plate misfit. Four notches (2, 4, 10 and 20 mm deep) were machined in such a position that the diffracting geometry was close to the stub/DP weld and the next 3 notches were implemented inside the welding metal. All the notches are intended to quantify the molten metal parameter and the grinding parameters including scratches and wavy surface. Finally, a 20 mm deep notch was implemented relatively close to the stub/DP weld, although being at the boundary of the sizing range specifications.

In addition to the required manufacturing inspections, macrographs and sizing have been performed on the mock-ups. In particular, it was shown that EDF and AREAVA NP mock-ups base metal were equivalent, showing a grain size 5 to 7, homogeneous along all the stub thickness with some rare large grain under the plate’s surface. These data allowed to consider that the available mock-ups were very similar to actual in-service stubs.

Ultrasonic L wave velocity and damping were also measured at four frequencies: 2, 4, 7 and 10 MHz and at four angles: 0, 30, 45 and 90 degrees shooting up, down, right and left in a cut Inconel plate specimen. With these data, we have shown that the base metal was isotropic considering velocity, non dispersive, but that it was slightly anisotropic considering damping in the frequency range of our transducers. The same tests were carried out with EDF’s mock-ups including tests in the welds though considering only 0 degree waves. In the end, the difference between the highest and the lowest base metal L wave velocity is less than 6% of the average velocity. In that sense, that difference should be considered when sizing precision is evaluated.

2.2 Methods

To deal with these conditions, AREVA NP proposed and tested 4 kinds of TOFD methods detailed hereafter. Whereas all of these methods are to be used from the SG hot leg, all of the meaningful configurations were also tested in a cold leg configuration (i.e. from the surface of the mock-ups opposite to the notches) in order to evaluate any performance discrepancy between diffraction echoes arising from the tip on the crack breaking surface or opposite surface.

2.2.1 TOFD forward (figure 3)

Nine TOFD transducers arranged in up to 14 configurations with frequencies ranging from 2.25 to 7 MHz, angles from 30 to 60° and PCS from 9 to 35 mm were tested and optimized considering wedge footprint. These transducers were tested because of their sizing capability, their manufacturing simplicity, their potential reduced footprint and their short delivery time.

2.2.2 Phased array TOFD (forward)

Three phased array forward TOFD transducers (2, 4 and 7 MHz) were tested with focal laws from 35 to 70°. These transducers were proposed because of their ability to go through a wide depth range of stub wall thanks to the numerous focal laws, because an improved S/N ratio was expected in the molten metal resulting from focalisation and in addition because of their versatility in an expert appraisal context. Due to the sizing difficulty arising from the lack of morphological evidence and the lack of lateral wave (time reference) and despite a higher S/N ratio than single crystal transducer this method was not retained and will not be described.

2.2.3 Phased array TOFD (backward SE)

Three phased array backward TOFD transducers (2, 4 and 7 MHz) were evaluated with focal laws ranging from 35 to 70°. Tested configurations were SE, i.e. transducers in a transmit/receive set-up, inclined both with a wedge and roof angle. The stub/DP weld knuckle and the potential grinding-induced wavy surface of this knuckle limited probe accessibility to the upper portion of the stub at the border of the weld. This backward TOFD was thought as a by-pass to overcome scanning limitation of standard TOFD. In addition as the forward phased array TOFD did, the 8 focal laws of these transducers could be set to inspect a wide thickness range of the stub. This method can be used shooting up and shooting down.

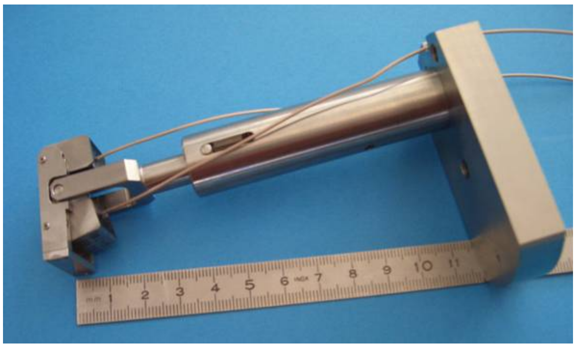

Figure 3 –Forward TOFD

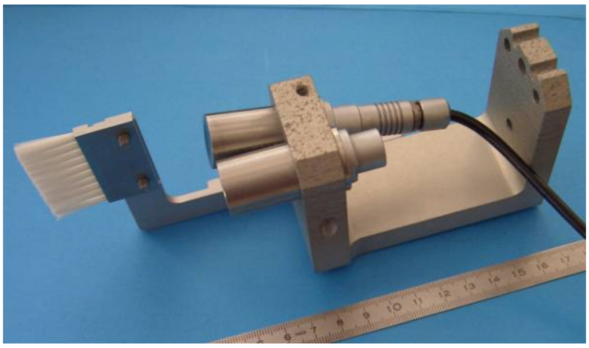

Figure 4 –FISSCOR tool

2.2.4Focalised

Two focalised probes have been tested. DSR 2 MHz, 63° L wave and FISSCOR 8 MHz, 45° L wave (c.f. figure 4) as a complementary method that was planned to exhibit the widest thickness range potential below the stub/DP weld knuckle. Let us point out that FISSCOR exhibit the highest S/N in the base metal. Focalised methods were also selected because of their on-site advantage lying in the risk limitation to collide with a cleat. As the backward TOFD, FISSCOR can be used shooting up and shooting down.

3. Sizing principle

Sizing process is that usually deployed with AREVA NP. Calibrating TOFD Forward method, the function between EDM size and the difference between the time of flight of the lateral wave and that of the diffracted echo is determined with other methods, absolute time of flight is considered. Using phased array, every focal law is calibrated according to the same principle. The standard block includes EDM notches ranging over the whole sheet, this standard block being free from perturbing parameter. This methodology takes benefit of experimental compensation of all the transducers related parameters that may bias a purely geometrical calibration.

4. Results

As mentioned above, results were obtained in two phases, the first one being obtained in the base metal on the mock-ups having no other influent parameters than the EDM notches depths (some of the EDF mock-ups), the second in the welds and base metal of the AREVA NP mock-ups including the identified perturbing parameters.

4.1 Performances in the base metal

Results obtained led to the selection of the techniques for the second series of tests.

- 3 TOFD Forward configurations, ranging from 4 to 7 MHz in frequency, 14 to 25 mm in PCS and 35 to 55° in incidence angle, leading to an acceptable SNR (> 6 dB in the base metal) and adequate dimensioning for 2 to 15 mm deep notches.
- FISSCOR leading to a SNR larger than 9 dB and adequate sizing for 2 to 20 mm deep notches
- One of the phased array based TOFD Backward configurations, leading to a SNR larger than 9 dB for notches whose depth was ranging from 10 to 34 mm. It is important to notice that this configuration was only retained for detection and not for sizing because of the difficulty to work on extended diffraction echoes.

For these configurations, the obtained performances were used in the second series of tests as a reference measurement, yielding the evaluation of the influence of each parameter on both SNR and sizing depth range.

Although these techniques appear as redundant, they were chosen at this stage of the development in prediction of the eventual uneven perturbing parameter-induced performance degradation. They were also selected in trying to maximize the covered inspected area.

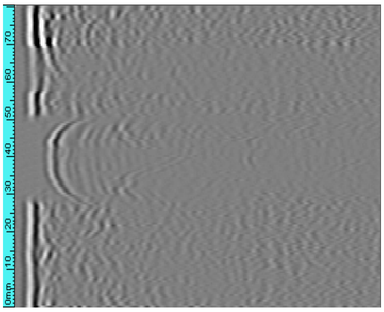

Figure 5a: EDM 4 mm in base metal

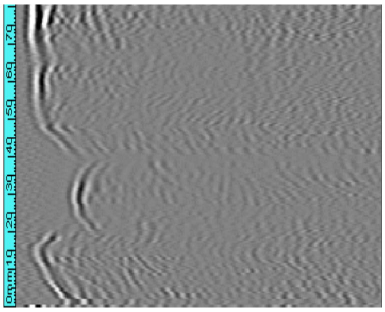

Figure 5b: EDM 4 mm and level difference

4.2 Influence of each perturbing parameter

4.2.1 Forward Methods: TOFD

TSP/stub knuckle

Since TOFD Forward transducers are symmetrical, they will not be as advantageous as FISSCOR or the TOFD Backward configurations as far as access to the zone right below the TS is concerned. Indeed, as the TOFD Forward technique is intended for dimensioning, it is necessary that the summit of the flaw-related diffraction arc is seen, i.e. that the transducer centre lies right over the flaw diffraction tip. It is then logical to find that experimental results show that the smallest PCS TOFD Forward configurations are the ones providing the closest access to the TS.

Welding-induced stub/plate level difference

Results obtained on the second AREVA NP mock-up showed an amplitude decrease of the diffraction echo and of the noise level when transducers were not lying on a flat surface. However, as both amplitudes decreased similarly (same SNR as in the base metal, figure 5), detection and dimensioning performances were not affected.

Grinding-induced wavy surface effect and scratches

Although it was firstly intended to evaluate the influence of each of these parameters separately, this was not possible due to the simultaneous appearance of these phenomena. However, as the second AREVA NP mock-up presented a worse surface state than the first one, it was possible to carry out a comparative test and conclude that the grinding processes do not affect the diffraction echo nor lateral wave amplitude.

Molten metal

Though the molten metal is not considered as a part of the inspection area of interest, it is still possible that the emitting or receiving beam has to cross the weld when detecting a flaw located at the edge of the welded zone. Moreover, if only one scanning direction is considered, for one of the two welds (TS/stub or stub/DP), the transmitter beam will have to cross the weld whereas for the second one, the receiver beam will. Permutation of transducers then showed, that each TOFD Forward configuration was symmetrical in this respect, yielding to retaining only one scanning direction.

The influence of one of the ultrasonic beams crossing the molten metal was then evaluated. It was shown that sizing performances of the technique are not affected by the weld, whereas SNR could be decreased by down to -7 dB (c.f. figure 6), the smallest impact being observed on the lowest frequency configuration.

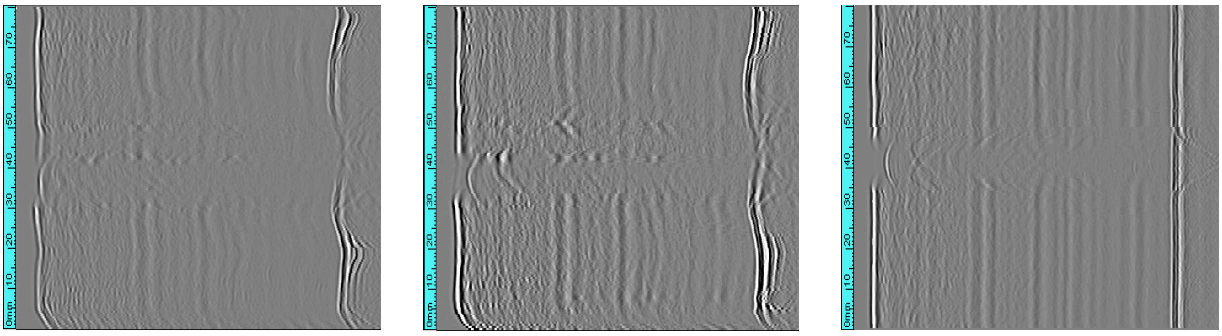

Figure 6 a) : EDM 2 mm in a weld b) : EDM 4 mm in a weld c) : EDM 4 mm in base metal

Skew

Via rotation of one of the EDF mock-ups from 0 to 30° with respect to the scanning direction, it was shown that skew does not degrade detection nor dimensioning performances.

Crack clusters

First considerations on this subject suggested that crack clusters influence could cause detection and dimensioning performances degradations due to a blinding effect. Indeed, as it is expected to detect and size the deepest crack in a cluster, if the latter is located at the centre of the cluster, edge cracks could prevent the ultrasonic beam from reaching it. It is then expected that large PCS/large angle configurations will provide the best results.

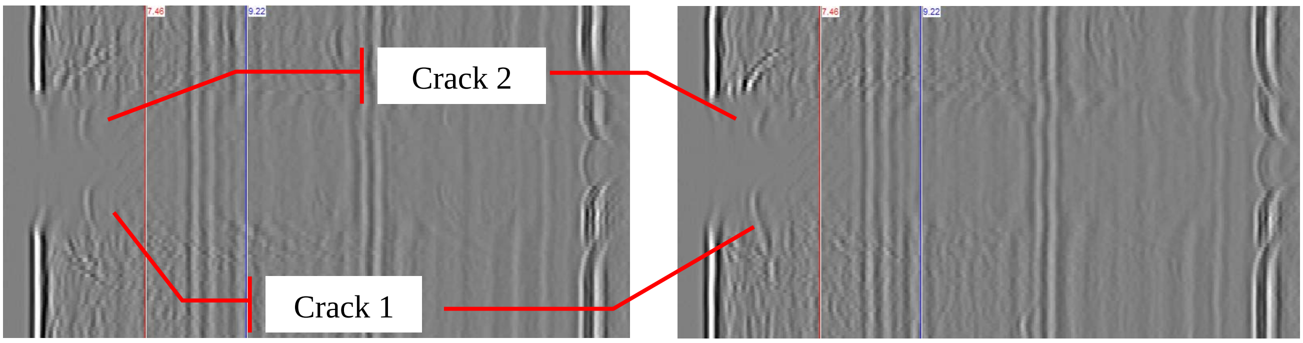

Figure 7 – TOFD PCS 14 mm – SCC mock-up

Tests were then carried out on the 4 mm spaced EDM notches clusters located on the first AREVA NP mock-up and on the cracks of the SCC mock-up. Results on the first mock-up confirmed that the largest PCS and angle TOFD Forward configuration keep its detection and sizing performances, whereas the smaller PCS and/or angle configurations suffer from performances degradation (SNR and/or sizing).

Nevertheless, results on the SCC mock-up revealed that the smallest PCS configuration is the only one to enable an accurate sizing of the 7 mm spaced cracks (c.f. figure 7). This was explained by the fact that only a small PCS is able to “launch” ultrasonic beams between the cracks, thus preventing the occurrence of a masking effect. It is also important to notice that sizing accuracy was mostly degraded with other configurations due to the appearance of mode conversion diffraction echoes.

Crack profile – EDM notch/crack transfer coefficient

From experience acquired on the BMI inspection, the coefficient was expected to lie between -3 and -6 dB for TOFD Forward techniques. To confirm this forecast, experiment was carried out on both EDM notches on one of the EDF mock-ups and on the SCC mock-up. Coefficient was found to lie between +1 dB and -9 dB depending on the configurations.

Diffracting length

Thanks to experiments carried out on EDM notches with same depths but different lengths, located in the base metal of one of AREVA NP mock-ups, it was possible to conclude that the smallest PCS configuration enable detection and sizing of a 2 mm long notch, whereas the other configurations provide sizing of a 4 mm long notch and only detection of the 2 mm long notch.

Tilt

Tilt was considered as an important parameter to be evaluated since SCC mechanism involves intergranular cracks that could present a slanted aspect (up to 30° on the SCC mock-up as shown in Figure 8). Experience acquired on a similar study was confirmed: tilt influence on the TOFD Forward detection and sizing performances is weak.

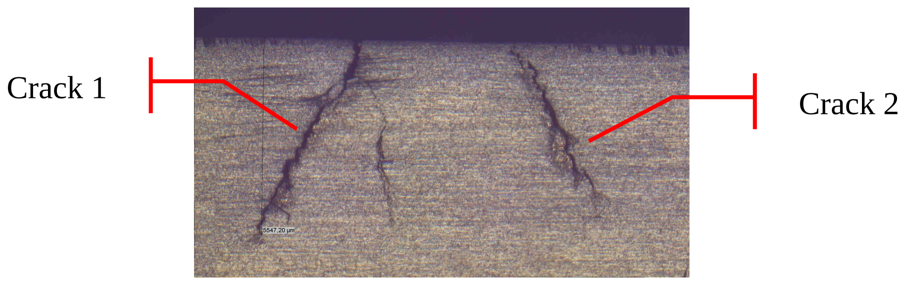

Figure 8 – Tilted SCC on one side of AREVA NP’s mock-up

4.2.2 Backward Methods: FISSCOR and SE configuration

TS /stub knuckle

Configurations emitting upward were chosen since they provide a better accessibility to the knuckle region. Whereas results showed that FISSCOR was able to approach the TS by 12 mm, the SE configuration was proved to be inadequate for this issue because of its large size.

Welding-induced stub/DP difference

Thanks to a decorrelation of the grinding-induced and welding-induced effects, it was possible to prove that the stub/DP level difference did not significantly affect FISSCOR detection performances. However, sizing becomes slightly more complicated, since time of flight should be measured from the surface echo, the latter undergoing the surface waviness.

On the other hand, SE exhibited a 6 dB SNR decrease due to the level difference, thus impacting on its detection performance.

Grinding induced scratches

FISSCOR performances are greatly degraded by the surface state quality: welding-induced scratches could extend the interface echo up to a 4 mm zone below the surface, hence limiting the depth detection range and sizing to 4 to 20 mm.

For the SE configuration, SNR is not affected by scratches, leaving its performances unchanged.

Molten metal

Two emitting directions (upwards and downwards) being considered for each backward configuration, there will always be a configuration for which no weld crossing will be required to detect cracks located at the edge of a welded zone.

However, the influence of the beam passing though the molten metal was evaluated. It was shown that due to a 4 dB SNR decrease, FISSCOR could only detect 4 to 10 mm deep notches located at the edge of a weld. However, for this range, sizing performances remained unchanged. For the SE configuration, no influence of the weld was shown on the SNR, and thus on the detection performance.

Skew

FISSCOR was found to be very sensitive to this parameter, since a 10° skew led to a 6 dB SNR decrease on shallow notches, and even more on deeper ones. This skew value was then considered as the limit for unchanged FISSCOR sizing performances.

For the SE configuration, a 30° skew led to a 8 dB SNR reduction, however leaving the detection depth range unchanged with respect to the base metal one.

Crack clusters

Although FISSCOR was unable to detect individually each of the cluster notches, it provided sizing of the deepest notch. Detection limitation was observed as a result of masking provided by FISSCOR insufficiently large incident angle.

Crack Profile – EDM notch/Crack transfer coefficient

In order to compensate for the tilted nature of the AREVA NP SCC mock-up cracks, FISSCOR angle was modified so that the ultrasonic beam could impinge on the tilted cracks with an incident angle close to 45°. Once done, it was possible to conclude that the transfer coefficient is close to 0 dB.

Diffracting length

Thanks to its small beam size, FISSCOR was able to detect and size the shortest notch (2 mm long), with only a 3 dB SNR decrease. The SE configuration proved its ability to detect the 2 mm long crack, with a 4 dB SNR decrease.

Tilt

As expected, due to the asymmetrical nature of the backward configuration, influence of the tilt on the SNR depends on the tilt orientation with respect to the emitting direction.

Simulation results obtained using CIVA showed that SNR is affected from +8 to -6 dB for tilt angles varying from -20° to +20°. However, sizing performances were unchanged. For SE, SNR was found to be varying from +12 to -8 dB for tilt angles varying between -20 to +60°.

5. Performance demonstration tests

In order to validate the development phase results, tests were performed in an industrially representative situation. To do so, one of the AREVA NP mock-ups was integrated in a full scale SG mock-up. Transducers, whose holders and housings were optimised, were then mounted on a COBRA arm. Tests were then performed to determine whether detection and sizing performances would be degraded in such an experimental set-up.

Obtained results showed that both detection and sizing performances remain unchanged with respect to those defined in the development phase. Moreover, these tests provided the ability to confirm the possible inspection zone for each technique, (Figure 9).

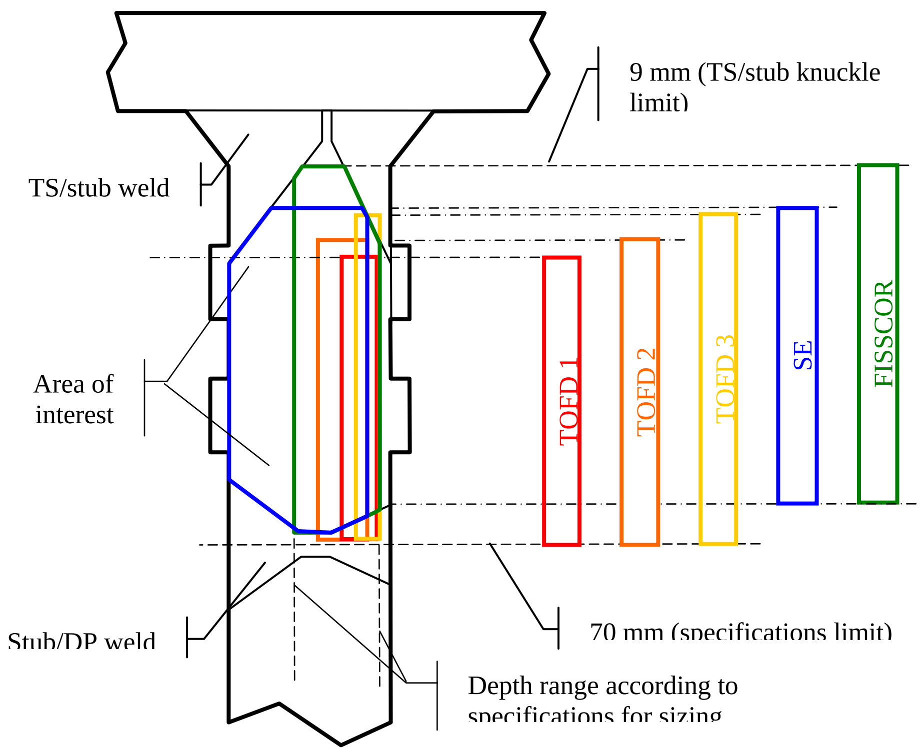

Figure 9 – Wall section inspection capability by transducer

6. Conclusion

This study enabled the selection of 5 techniques (3 TOFD Forward, FISSCOR and a phased-array based SE configuration) suited for the inspection of the stub in the conditions specified by the Utility. Although redundant, techniques were chosen to provide the maximum amount of information about the detection and sizing performances, since the study was conducted in the context of an expert appraisal. The latter also included performance demonstration tests with optimised transducers, in a representative industrial situation. Results obtained demonstrate that detection and sizing performances achieved in the development phase are not affected by the industrial constraints.