Development of a Procedure for the Ultrasonic Examination of Small Size Austenitic Stainless Steel Piping Butt Welds for the Detection of Stress Corrosion Cracking

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Abstract
For the project of austenitic stainless steel butt welds inspection in Belgian nuclear power plants for the detection of stress corrosion cracking in 2 inches and ¾ inch pipes, Vinçotte was requested the study of an ultrasonic examination of such welds and the development of a procedure for an inspection with phased array probes. The study described in this presentation determines the optimal configuration for such examination. Different parameters are taken into account: the wave mode, the frequency, scanning pattern, the insonified area and the ultrasonic beams characteristics. The specific procedure developed and tested in this project on various welded mock-ups allows then to evaluate the detection and sizing capabilities of this process.

Keywords: Ultrasound, phased array, austenitic butt weld, stress corrosion cracking

1. Introduction

Intergranular or transgranular stress corrosion cracking (SCC) attacks the heat-affected zone (HAZ) of austenitic stainless steel (SS) piping weldments in many different industries including chemical processing and electrical generation. SCC in SS piping weldments is a phenomenon in which cracks propagate in a branch-like manner along the grain boundaries or through the grain of the material. Unlike the common defects related to fabrication (slag, lack of fusion, incomplete penetration) or the service-induced flaws such as fatigue cracks, SCC results from 3 distinct factors working in combination: material sensitization (sensitive to grain boundary attack, mainly due to temperature conditions), tensile stress and corrosive environment. The required tensile stresses may be in the form of directly applied stresses or in the form of residual stresses, which are generally introduced by cold deformation and forming, welding, heat treatment, machining and grinding. The ultrasonic examination of austenitic stainless steel welds requires a specific configuration in order to get the best sensitivity to this kind of defect in such material. Typical characteristics are wave type and frequency. During the development phase various parameters were evaluated in order to define a specific procedure allowing for the detection, localization, length sizing (parallel to the weld) and eventually height sizing of SCC at the pipe inner surface in the weld and adjacent base material. To achieve this phase, two different methods were used to assess the different parameters: first, numerical simulation (CIVA) in order to get a first overview of the possible configurations, second, practical demonstration with the use of designed mock-ups to verify the performances.
2. Experimental setup description

2.1 Mock-ups

In the frame of this project, 3 stainless steel piping butt weld configurations have been studied, for diameters ¾” and 2” and wall thickness respectively of 5.56 mm and 8.74 mm. There are two types of junction: pipe to pipe (P2P) and pipe to elbow (P2E). One mock-up for each diameter and each junction configuration, full size (1:1) and containing full stainless steel piping butt weld have been manufactured (Table 1).

<table>
<thead>
<tr>
<th>Block Name</th>
<th>Diameter (inch)</th>
<th>Diameter (mm)</th>
<th>Thickness (mm)</th>
<th>Length (mm)</th>
<th>Arc Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS_Ø2i_P2P_T8.7_01</td>
<td>2</td>
<td>60.32</td>
<td>8.74</td>
<td>500.00</td>
<td>2 x 94.75</td>
</tr>
<tr>
<td>SS_Ø2i_P2E_T8.7_01</td>
<td>2</td>
<td>60.32</td>
<td>8.74</td>
<td>417.00</td>
<td>2 x 94.75</td>
</tr>
<tr>
<td>SS_Ø0.75i_P2P_T5.6_02</td>
<td>3/4</td>
<td>26.70</td>
<td>5.56</td>
<td>500.00</td>
<td>2 x 41.94</td>
</tr>
</tbody>
</table>

In order to simulate SCC, specific inner surface connected rectangular EDM notches (electrostatic discharge machinery) have been manufactured parallel to the weld center line (WCL) in the root or in the HAZ. These reflectors have been manufactured with a length from 4 to 18 mm, a depth respectively from 0.5 to 6 mm and a width of around 0.7 mm. These EDM notches were positioned at different offset relative to the WCL in order to simulate the most critical situations in terms of ultrasonic attenuation and area coverage.

2.2 Automated Ultrasonic Testing (AUT)

For each configuration, in order to optimize the capacity of characterization, an automated ultrasonic testing technique is used. The AUT inspection is based on the use of a two-axes motorized scanner, that encodes the movement of a probe (or probes) properly coupled to the surface. In this case, the displacement is circular and axial, that is to say along the pipe’s circumference or along the weld and perpendicularly to the weld, called a ”raster scan”. The advantage of this type of scanning over the simple “one line scan” is to give more information about the potential flaws with a full echo-dynamic of the flaw signal.

A portable OmniScan Ultrasonic Phased Array System is used (Figure 1.a), with one or two channel (two probes on each side of the weld, depending on the access). The OmniScan is used as “slave” for the AUT technique, which means monitored by computer with a dedicated software (Ultravision 1.1Q5).

The scanning mechanism used is the PIMMS 2000 (Figure 1.b), developed by Vinçotte, adapted in this case for the examination of small diameter pipe welds, working in the single side access (SSA) configuration. The PIMMS motors are powered by a motor-controller which is also managed by the same software.

The technique used is a pulse echo sectorial scan (S-scan) of wave angle beams (depending on the configurations: inspection area, pipe’s junctions, weld’s geometry, etc.) generated by linear phased array probes mounted on specific wedges, which are coupled with water on the outer surface of the pipes. S-scans use a fixed set of elements, but alter the time delays to sweep the beam through a series of angles.
3. Optimal configuration analysis

In order to first determine the adequate wave mode and frequency, the 2 inches pipe to pipe configuration was studied first (dual side access). The notches manufactured in this mock-up are positioned on one side of the weld (close to the weld’s root). Depending on the probe position, on the same side or the other of the weld, the ultrasonic beam would mainly propagate in the base material or would have to go through the weld in order to detect the reflectors in a pulse-echo mode. The detection capability was tested on all reflectors but mainly the results obtained for a reflector of which the height is around 10% of the thickness and the length is around 5 times the height (1 x 4.5 mm) are considered in this paper. The focal depth is adapted according to the thickness of the pipes.

3.1 Wave mode

The 2 types of wave (shear wave and longitudinal wave) were tested during the trials (Figure 2) in order to observe their detection capability. The probe was successively placed on each side of the weld. The Figure 3 shows the numerical and experimental results obtained when the probe is on the same side than the reflector. The obtained results show a good agreement between numerical and experimental results and clearly show the lack of sensibility of the longitudinal waves in comparison with the results obtained with the shear waves. The amplitude difference between longitudinal and shear waves in the numerical simulations is around 3 dB (corner trap signal) and around 10 dB in the experimental results, with a signal to noise ratio (SNR) of around 21 dB for the shear waves and 11 dB for the longitudinal waves. We can observe the tip diffraction signal with the shear waves due to a better resolution (Figure 3.a and b), and some troublesome mode conversions when generating the longitudinal waves (Figure 3.c and d). When the probe is on the opposite side of the weld, the amplitude gap of the detection signal in the numerical simulations between shear waves and longitudinal waves is then around 10 dB (corner trap signal). The experimental results show a lower detection capability of the shear waves with a SNR of only 12 dB and no signal detected for the longitudinal waves. The tip diffraction is no more detected, the possible explanations are that the high frequency components of the signal are more filtered, which lowers the resolution, the detection of the tip may be less sensitive at the necessary higher angles of the incident beams or the tip may be just beyond the spatial angular range of the probe (see paragraph 3.3).
Figure 2. Schematic view of the inspection

Figure 3. S-scans of the EDM Notch detection at 3.5 MHz, (a) and (b) respectively numerical and experimental results for shear wave, (c) and (d) respectively numerical and experimental results for longitudinal wave
When dealing with austenitic stainless steel materials and especially welds, we must take into account the deviation of the ultrasonic beams and the attenuation of the waves: the energy dissipation due to the viscosity of the material and the dissipation due to porosity, small defects or heterogeneities. For anisotropic domains, as SS welds, this attenuation also depends on the direction of propagation [1] and the diffusion is stronger for shear waves than longitudinal waves [2]. However it has been shown [3] that surface-connected planar reflectors, such as SCC, are usually detected using shear waves at 45° in the test material. This is based on the fact that corner reflectors produce higher amplitude signals when insonified with shear waves at 45°. Moreover in some instances, cracks will only be seen with higher angles (60 or 70°) of the shear waves. This is a result of the weld geometry and the relative flaw orientation. Also, higher angles are useful in providing confirmation of the reflector since root geometry reflections are less responsive to these higher angles. So despite the attenuation in such materials and anisotropic behaviour in welds, the shear waves are more sensitive, in the angular range used, for the detection of this kind of reflectors.

3.2 Frequency

3 phased array probes with 3 different centre frequencies (3.5, 5 and 7.5 MHz), generating shear waves, were used during the trials in order to observe the gain in resolution and the detection sensibility (depending on the wavelengths and the possible attenuation in the stainless steel base material, HAZ and weld). When the probe is on the same side than the reflector, that is to say when the waves mainly propagate in the base material or in the HAZ, no specific variation is noticed for the detection sensibility at the different frequencies in the numerical results as well as in the experimental results (with a SNR of around 25 dB). When the probe is on the opposite side, that is to say when the waves mainly propagate through the weld, higher is the frequency lower is the detection sensibility. The numerical results show a strong decreasing of the amplitude, between 3.5 and 7.5 MHz, of around 12 dB due to the attenuation. In the numerical modeling, it is assumed, due to the relative grain size variation (depending on the frequency and the grain orientation), that the base material follows the diffusion behavior of the Rayleigh domain and the weld follows the behavior of the stochastic domain, that is to say that the attenuation coefficient is proportional respectively to $d^4 f^4$ and $df^2$, with $d$ the average relative size of the grain and $f$ the frequency [2]. In the experimental results, on the different reflectors, an average gap of 10 dB is measured between 3.5 and 7.5 MHz. In the specific case of the 1 x 4.5 mm EDM Notch, the detection is possible at 3.5 MHz with the shear waves with a SNR of around 12 dB but no signal is recorded at 7.5 MHz. So for the inspection of these SS welds a lower frequency (3.5 MHz) is then needed and used.

3.3 Volume coverage

For each weld, the inspection must allow the detection of flaws in half of the thickness, from the inner surface, and extended to ¼" (6.35 mm) at both sides of the weld. This volume is schematically represented in Figure 4. This volume must be examined on all the circumference of the pipe. Possible deviations from a complete coverage of this volume can occur depending on the weld geometry, the size of its cap and the type of junctions. Indeed, the device used can only be positioned on straight sections and can therefore have access to only one side of the welds for the P2E junction types (Figure 5.c and d). On the mock-ups, the width of the weld’s caps is around 16 mm for the 2” pipes and 11 mm for the ¾” pipes.
Simulated representations (Figure 5) of the angular range of detection (steering of the angles between 40 to 74° with or without full skip in order to detect the most notches in the mock-ups with the best possible angular sensitivity) of the ultrasonic beams have been realized and confirmed by the experimental measurements of each configuration.

Figure 5. Numerical representation of the volume coverage for each piping configuration, (a) and (b) 2” P2P, (c) and (d) 2” P2E, (e) and (f) ¾” P2P
3.4 Sizing

3.4.1 Length

The length sizing of indications is done using the full amplitude drop method (down to the noise level). For reflectors parallel to the weld, the length size of their indications (generally corner trap indications) are given in terms of the circumferential coordinates measured at the WCL on the external diameter of the component. The accuracy of the measurements mainly depends on the angular aperture and the size of the ultrasonic beam and the welds irregularities. Good results are obtained on the experimental measurements of the reflectors length (average relative error of 20%) and on their spatial positions relative to the surface of the pipe (accuracy of around 1 mm).

3.4.2 TWS

The tip diffraction method is applied for the through-wall sizing (TWS) of indications, if applicable. Indeed it is necessary to detect both the corner trap and the tip of the notch. The reflector must be in the spatial angular range of the probe and have a height bigger than the wavelength. The Figure 3.a and b show a possible TWS close to the limit of resolution. However if the reflectors height is too big, the tip would be beyond the spatial range of detection.

During the experimental measurements the TWS was possible for the reflectors with a height between 1 and 6 mm and manufactured at the WCL or in the HAZ (the probe must be then positioned on the same side). The measurement accuracy was good with an average relative error inferior to 5%. For the other configurations the tip of the notches may be beyond the spatial range of the probe or can’t be detected due to frequency filtering or loss of sensitivity for higher angles of the incident beams (see paragraph 3.1).

4. Completion of the procedure

Based on the results of the development phase, a Semi-Automated Ultrasonic Testing (SAUT) has been retained in order to inspect ASME Code Class 1 stainless steel piping butt welds for diameters ¾” and 2” and wall thickness respectively of 5.56 mm and 8.74 mm. The SAUT inspection is based on the use of a scanner manually driven, that encodes the movement of a probe (or probes) properly coupled to the surface. In this case, the displacement is circular, along the pipe’s circumference or along the weld. It is called a “one line scan”.

The inspections will then be realized with shear waves at the frequency 3.5 MHz. Optimal positions (two axial offsets of the probe front from the WCL) for “one line scans” have been determined during the development phase to insonify the required volume (See Figure 5). The necessary angle beams shall be generated via adapted focal laws. The main characteristics of the PA ultrasonic probe and wedges to be applied for detection and sizing purposes are mentioned in Table 2.
Table 2. UT techniques

<table>
<thead>
<tr>
<th>Probe type</th>
<th>Wave type</th>
<th>Frequency (MHz)</th>
<th>Number of elements</th>
<th>Active aperture (mm)</th>
<th>Wedge type</th>
<th>Refracted angles (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5L16-A15</td>
<td>Shear</td>
<td>3.5</td>
<td>1 x 16</td>
<td>8.0 x 10.0</td>
<td>SA15-N60S-IH</td>
<td>40 – 74</td>
</tr>
</tbody>
</table>

5. Conclusion

A procedure was developed for the ultrasonic examination of ASME Code Class 1 stainless steel piping butt welds for diameters ¾” and 2”. This procedure was developed on real as welded mock-ups with artificial flaws and qualified according to the ENIQ methodology (European Network for Inspection and Qualification).

References

