High Frequency Inspection Solution for Austenitic Stainless-Steel Welds

F. Lachance[1], P. Rioux[1], D. Giguere[1] and J. Turcotte[1]

1 Sonatest, Québec, Canada

Phone: +1 418 683 6222, e-mail: sales@sonatest.com

Abstract

Austenitic stainless steel is well known for its high mechanical properties and corrosion resistance. This material is used in the oil and gas and nuclear industry, where ultrasonic techniques represent an important proportion of the inspection in the quality control process. However, these alloys often are very attenuating and the sound behaviour of this material is anisotropic. Those characteristics are caused by the grain size and orientation, especially inside the welded volume of a component. Conventional ultrasonic approaches have limited inspection performance, while phased-array with focusing capability and beamforming offers broader coverage and better resolution. This article is going to present a quantitative comparison of the signal quality between some configurations and parameters changes on highly attenuative dissimilar weld samples. Results will show that contrary to popular beliefs; quality of the electronic equipment, focusing capability and inspection configuration, along with probe frequency, can also influence the inspection quality. It will also demonstrate that it is not always required to sacrifice sensitivity and sizing capability over SNR for that kind of inspection.

Keywords: ultrasound testing (UT), phased array (PA), stainless steel, austenitic, duplex, dissimilar weld, dual linear array (DLA), transmit receive longitudinal (TRL)

1 Introduction

Stainless-steel alloys are pretty popular for their corrosion protection to chemical processes; processes that can be found in the oil and gas, power generation industries for instance. Welded engineering structures like pipework's, heat exchangers, pressure vessels and LNG thanks commonly use those corrosion resistance alloys (CRA) because they are exposed to these chemical processes every day. Whether in operation or during their manufacturing stage, the welds of these components need to be inspected to confirm their integrity and reduce the risk of failure during operations. So far, the radiographic technology has been, and is still, a very popular and accepted NDT methodology widely approved and used around the world.

With the introduction of portable phased array instruments back in the early 2000s, the ultrasound NDT technique had a huge impact on the weld inspection by bringing an alternative to the classic radiographic NDT approach. These instruments offer state-of-the-art acoustic capabilities to fulfil codes and standards requirements to carry inspection of welded structures in lieu of radiography. Introduced a couple of years ago, some pitch and catch techniques using phased array probes have shown great results for the inspection of austenitic stainless-steel weld inspections. Nonetheless, one may ask what

is the difference between these techniques; what are the limitations? This paper presents a quantitative comparison between different configurations and acoustic parameters to evaluate the quality of the solutions; hence, help identify what solution is most suitable for the inspection of stainless steel welds.

2 Challenges and Limitations

Austenitic stainless steel inspection has always been perceived as a high-end inspection as it requires more equipment and expertise compared to carbon steel inspection. The use of ultrasound NDT technique for quality control of those alloys has been hampered by the physical property of this material. Its microstructure generates beam scattering, yielding a low signal-to-noise ratio (SNR) and a severe attenuation of about 6.4 dB/inch compared to 2 dB/inch for carbon steel [I]. Stainless steel also has an anisotropic property and a velocity change between the weld and the base metal which could generate mode conversion and beam distortion. Those characteristics complicate the characterisation, sizing, and localisation of potential flaws; hence, lowering the probability of detection. It is understood that the solutions and techniques discussed in this paper also apply to other attenuative materials making weld inspection a challenge. These include dissimilar welds made of Inconel or other exotic alloys per example.

2.1 Ultrasonic NDT Past and Current Techniques

The conventional ultrasound inspection is based on the optimisation of UT parameters influencing the penetration, sizing and the SNR. For austenitic alloys, the probe frequency, damping, focal distance, ultrasonic propagation wave mode and inspection angle shall be optimised for better detection and sizing. Also, the base metal and the weld configuration might have different velocities which would refract the beam and therefore generate beam distortion. The positioning error, in some cases, could reach 25% in the distance [II]. The physical limitations and challenges are the same when using the phased array technique. On the other hand, phased array brought an adaptive of the focusing capability which helps optimise the probe aperture and its focal distance. Moreover, the 2D display of the weld volume gives a more intuitive representation of the beam distortion assessment, and the multi-angle inspection eliminates the optimisation requirement of the refracted angle towards the grain orientation. Finally, the recommended phased array technique to inspect austenitic stainless steel welds is often based on a pitch and catch low-frequency configuration reusing the conventional UT approach to optimise the SNR.

3 Method

With reference to Figure 1, the side drilled hole of a highly attenuating dissimilar weld sample has been used as a reference to evaluate the effect of ultrasonic parameters on the signal.

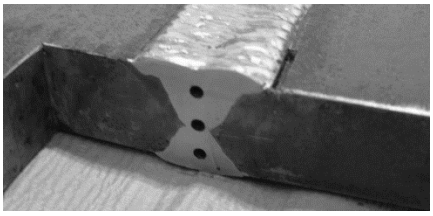


Figure 1: Weld sample used for the study

3.1 Calibration and SNR Evaluation

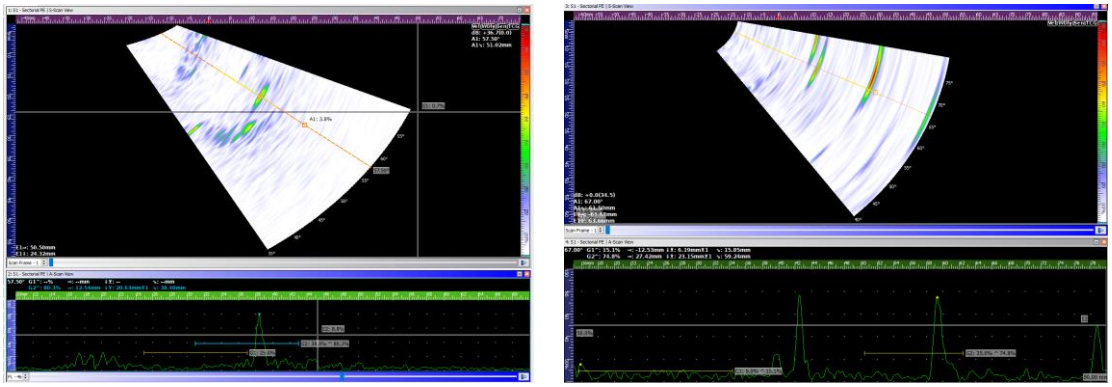
Since the purpose of next section is to compare the acoustic parameters, calibrating every tested configuration could have generated human measurement errors in the manipulation. Therefore, no calibration has been realised before the data acquisition, and the theoretical value of stainless steel velocity has been used. Regarding the time-corrected-gain calibration (TCG), it is recognised in the industry that it is practically impossible or very difficult to build a meaningful TCG curve on an anisotropic material. The SNR formula used everywhere in this paper (1) has been taken from the European standard EN12668-3: 3.4.3.2. The SNR measurement is one way among others to assess the quality of an inspection system.

$$SNR = \text{dB } 80\%_{Noise} - \text{dB } 80\%_{Hole} \qquad (1)$$

4 PA Parameters Optimization - Tests and Results

4.1 Wave Mode Comparison

The sound propagation inside the material can is identified by the ultrasound wave mode. The longitudinal wave mode (LW) is characterised by its parallel orientation propagation and the shear wave mode (SW) by its perpendicular orientation propagation. If the shear wave mode is predominant for carbon steel inspections, the longitudinal wave, in some situations, has been proven more effective for austenitic stainless-steel inspection. Both modes have pros and cons; however, the longitudinal wave is less affected by the microstructure of the material. This behaviour has a direct impact on the SNR as demonstrated in Figure 2. In this case, using the same 5MHz 32E probe, LW mode gives almost 6 dB more of SNR compared to the SW mode.

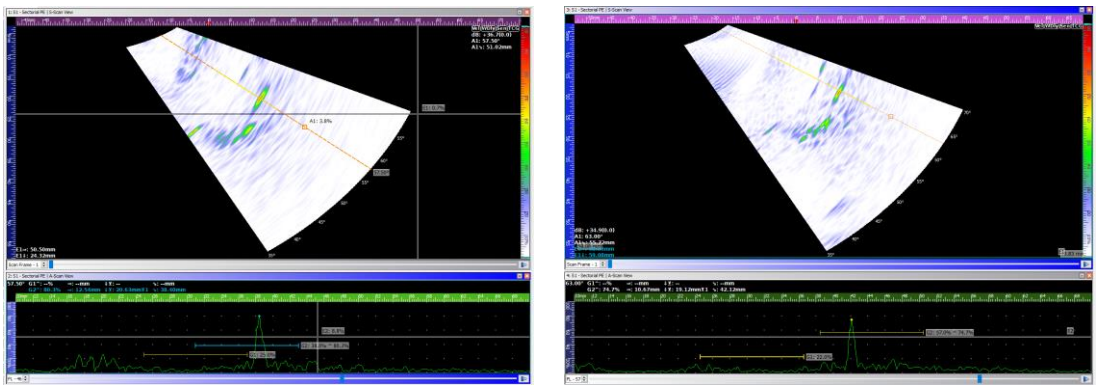


SW - SNR: 9.6 dB LW - SNR: 15.1 dB

Figure 2: Wave mode comparisons

4.2 Phased Array Active Aperture

The number of elements, hence the active aperture used for focusing and steering, shall have a great influence on the readings in terms of amplitude, resolution, and sizing. In Figure 3, a moderate improvement is observed on the 32 elements apertures vs. the 16 elements one. Generally speaking, the more elements used for focusing, the tighter the beam would be but the better the sizing and penetration capability it should produce.



SW 16E - SNR 9.6 dB SW 32E - SNR 13.6 dB

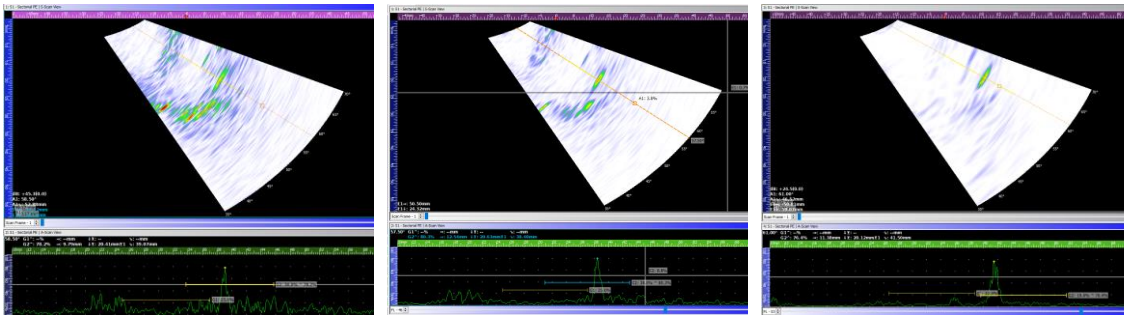
Figure 3 Element number comparison

4.3 Phased Array Probe Frequency

4.3.1 Shear Wave

As demonstrated in point 4.1, the shear wave is the propagation mode that is the most affected by the microstructure of the material. The beam scattering is generated by the grain boundary and is independent of the inspection frequency. However, the sound attenuation is directly linked to the frequency which explains the fact that the SNR increases as the frequency decreases (Figure 4). Even if this wave mode is more affected by the microstructure of the material, it has some clear advantage compared to the longitudinal wave inspection and should be privileged when possible. It has been proven

effective in the past on some austenitic stainless steel weld configurations, and it is strongly recommended for thicknesses between 2 and 10 mm [III].

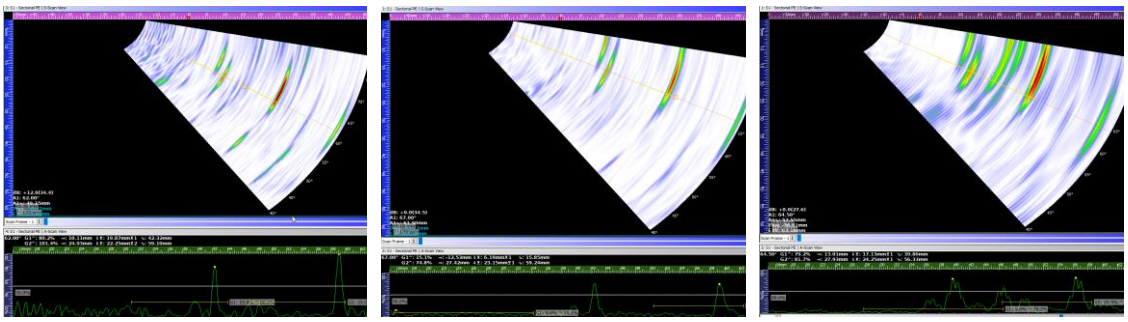


7.5 MHz - SNR 7.5 dB 5 MHz - SNR 9.6 dB 2.25 MHz – SNR 15 dB

Figure 4 Frequency comparison for shear wave

4.3.2 Longitudinal Wave

The longitudinal wave mode is less affected by the microstructure of the material. The beam scattering is smaller making it less dependent on the wave orientation with regard to the microstructure of the weld. Therefore, the effect of the frequency on the SNR is not following the same logic as for the shear wave mode. The longitudinal wavelength is approximated to twice the length compared to the shear wave; it has a direct effect on the sensitivity of the inspection. The sharpness of the beam and the sizing capability are automatically decreased for lower frequencies. Those reasons explain why we had worse results (Figure 5) using a 2.25-MHz probe compared to the 5-MHz one.

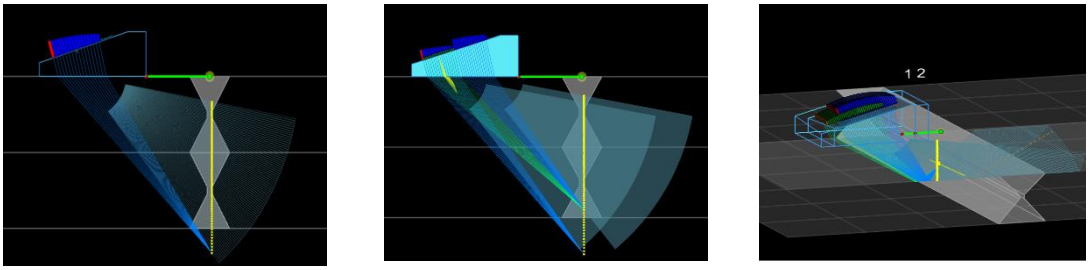


7.5 MHz - SNR 9.1 dB 5 MHz - SNR 15.1 dB 2.25 MHz – SNR 10.2 dB

Figure 5: Frequency comparison for longitudinal wave

4.4 Phased Array UT Configuration Technique

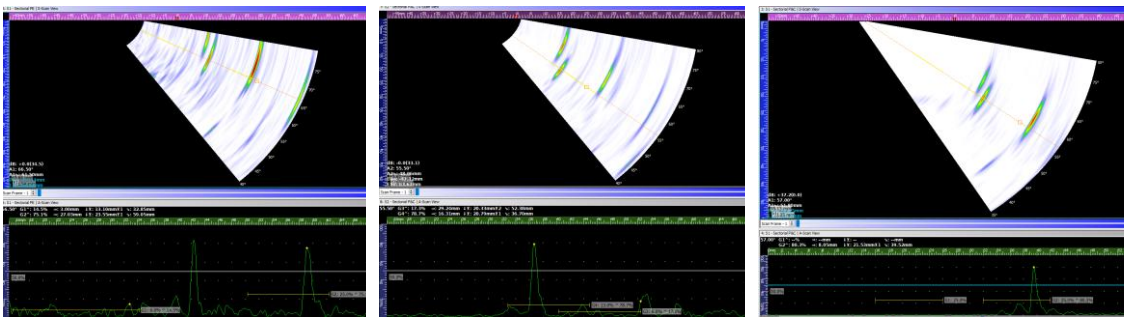
The following phased array ultrasonic configurations have been compared in order to quantify their effects on an inspection: the standard pulse-echo (electronic pulses and receives on the same elements), the pitch and catch tandem (electronic pulses and receives on different elements set within the same wedge), and the pitch and catch dual linear array DLA or transmitter-receiver-longitudinal TRL (electronic pulses and receives on different elements from isolated wedges set side by side), as represented in Figure 6.



Pulse-Echo | Pitch & Catch (tandem) | Pitch & Catch (DLA)

Figure 6: UT configurations

With today's 32 PR (32 elements pulsers & receivers) electronic architectures, the pitch and catch phased array technique is recognised to greatly increase the SNR of an inspection by decreasing the signal noise. Indeed, by receiving on different elements than those who emitted or by receiving on elements connected to an isolated wedge, the induced sources of noise are reduced. Results shown in figure 7 support this; SNR is improved between PE and tandem, and the improvement is even more blatant between tandem and DLA. This being observed, the DLA configuration also has a smaller footprint than the other two configurations because there is no need for damping material to be integrated into the wedge design. The smaller footprint is an advantage for the DLA because it reduces the probe distance to the weld, improving the SNR at the same time.

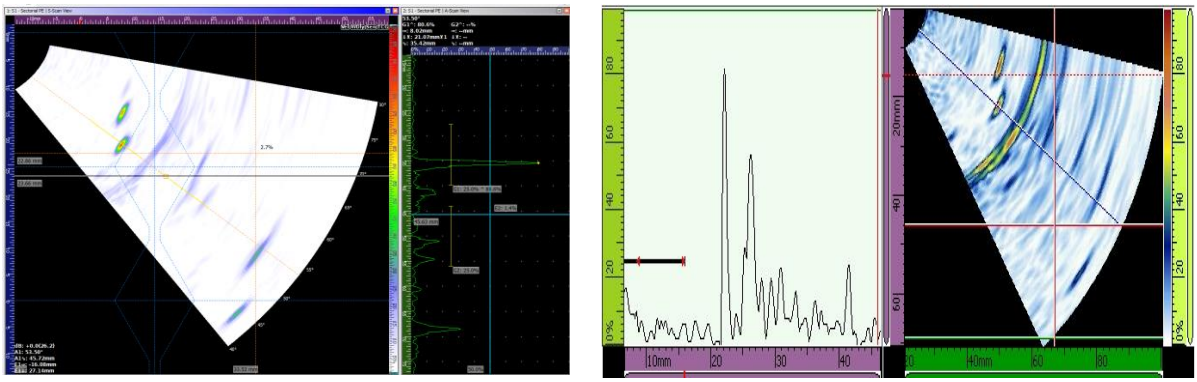


Pulse-Echo - SNR 15.1 dB | Pitch & Catch Tandem SNR 23.7 dB | Pitch & Catch DLA SNR 33.3 dB

Figure 7: UT configuration comparison

4.5 Phased Array Electronic Equipment

The instrument used obviously plays a key role in the overall results. The electronic circuit design does have a direct impact on the signal quality. Though good SNR instruments might not be critical for low attenuation carbon steel inspections, it can be critical for certain stainless steel inspections. Results in Figure 8 show clearly that for the same configuration parameters, the Sonatest Veo+ electronic circuitry significantly improves the signal quality. On highly attenuated material like austenitic stainless steel, it could bring a real valuable advantage.



Sonatest Veo+, 50-V pulser
5 MHZ, PE, 32E, LW
SNR: 14.1 dB

Other phased array equipment, 80-V pulser
5 MHz, PE, 32E, LW,
SNR: 3 dB

Figure 8: Electronic equipment comparison

5 Phased Array DLA Solution - Technique, Tests & Results

In the previous sections, the relative effects of some parameters on the SNR have been demonstrated. From the good results associated to the pitch and catch dual linear array (DLA) acoustic configuration observed in the preceding sections, Sonatest had developed a DLA solution dedicated to austenitic stainless steel, dissimilar and other attenuative alloys weld inspection. The results in this section have been generated using the Sonatest veo+ 32:128PR phased array system, the series of detachable active array head (DAAH) phased array probes and a new line of wedges specially designed to fit the requirements of the pitch and catch DLA and TRL technique (Figure 9).

Figure 9: Sonatest DAAH DLA probes and wedges for TRL technique

5.1 Phased Array DLA - TRL Technique

The phased array DLA solution for an austenitic stainless steel is similar to the recognised TRL conventional UT technique as it is based on a pitch and catch configuration using longitudinal wave (LW) mode. In practice, the phased array DLA LW mode is used without half skip because the back wall echo would create converted SW modes and some noise coming with it. The fact that the phased array LW mode can steer at very high

angles will also help to inspect not only the volume of the weld but also its surface where possible.

In the TRL technique using DLA probes, the wedge design is key. The Figure 10 shows that the cutting angle of the wedge is optimised for LW propagation and there is a roof angle on each wedge, creating a natural focal point. The combination of those two angles will create an effective acoustic area into the weld and the phased array beamforming will ensure a coverage for different angles. During the preparation of the inspection procedure or scan plan, the effective acoustic area and phased array angles have to match the weld thickness and geometry so the transmitter beams cross the receiver ones properly in weld zone. Finally, the wedge needs to be isolated in the middle to get benefits from the low noise pitch and catch configuration.

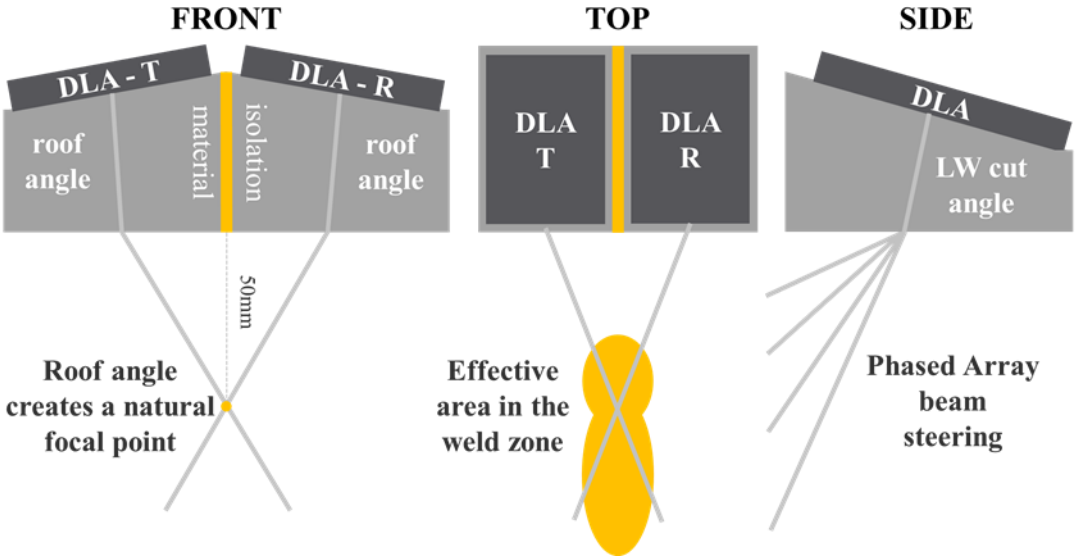
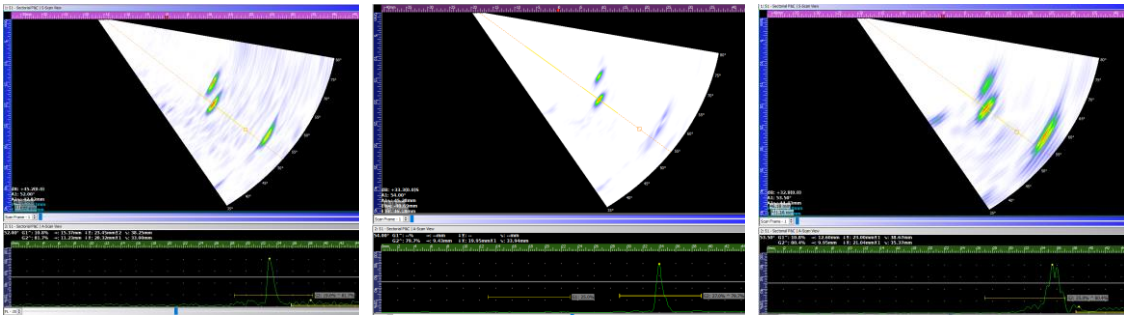


Figure 10: Phased Array DLA – TRL technique, natural focal point and effective area schematic

5.2 Phased Array DLA Tests & Results

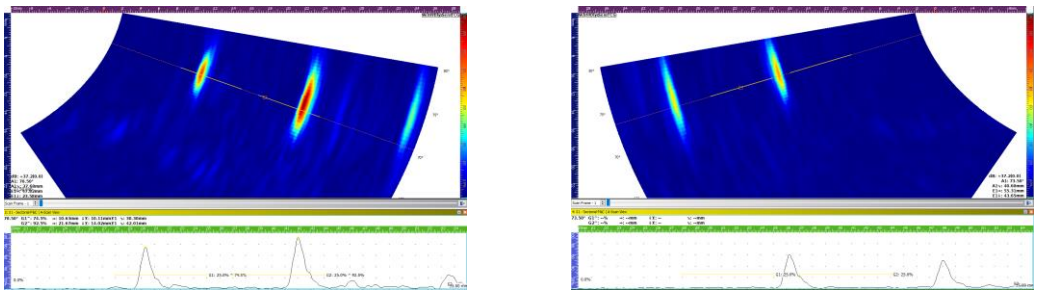
Using the same dissimilar weld sample as in the previous sections, we compared three frequencies of DLA probe configurations. Normally, we would expect a higher SNR using a lower frequency, but surprisingly the 5 MHz offers a better result than the lower 2.25 MHz, refer to Figure 11. Because of the wide variety of alloys, tests using different probe frequencies is important to identify the best solution for inspection since the higher the probe frequency, the sharper the sizing resolution will be.



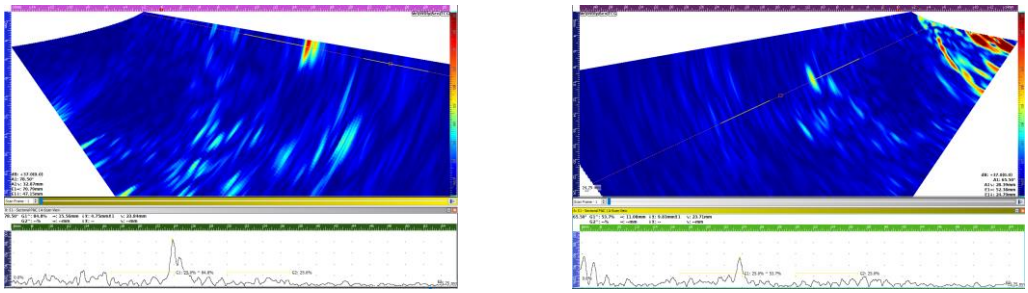
7.5 MHz DLA - SNR 17 dB 5 MHz DLA - SNR 30.6 dB 2.25 MHz DLA - SNR 19.2 dB

Figure 11: DLA solution frequency comparison

Figure 12 shows another sample where the comparison between 5MHz SW and DLA-TRL inspection in the half-skip. The significant 16dB SRN improvement shows the superior performance of the DLA solution over standard SW over a real flaw.



DLA LW in the half-skip – SNR 26 dB



PE SW in the half-skip – SNR 10 dB

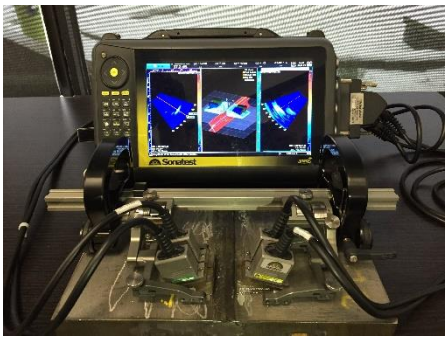


Figure 12: Two-sided inspection comparison on first leg (half-skip) SW vs. DLA-TRL

6 Conclusion

Because of the core variations in the grain structure (coarse grain) of the base material, the solidification point of the welded material and associated residual stresses combined with load induced stresses in the weld area,[IV] it is impossible to define a perfect NDT solution for all stainless steel and other exotic alloys. This paper presented different ultrasonic approaches and compared the key parameters that could affect the signal quality, and ultimately the inspection results. Results show that other parameters like the quality of the electronic equipment, the focusing capability, and the inspection configuration can also influence the inspection results. Of course, the frequency is important and shall be taken into consideration, but it has also been demonstrated that it is not always required to sacrifice sensitivity and sizing capability over SNR for that kind of inspection.

For the challenging inspections like highly attenuative austenitic stainless steel welds, the tested methodology using the Sonatest DAAH phased array DLA probes, TRL technique and veo+ instrument showed promising results. It has been noted that a standard shear wave (or LW if possible) PE technique shall be prioritised when possible because of the simplicity of application. The calibration of the PE technique, for example, is much easier than the calibration using the phased array TRL technique. The team intends to pursue the investigation on this inspection technique and propose some guidelines for the calibration.

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