Application of Phased Arrays for Corrosion Resistant Alloy (CRA) Welds

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Abstract
A common method for inspection of Corrosion Resistant Alloy (CRA) welds is ultrasonic testing. Inspection is done using either conventional ultrasonics or phased arrays. Application of ultrasonic testing to such welds is not as straightforward as carbon steel welds. Conventional angle beam ultrasonic methods cannot be simply extended to CRA welds. There are limitations due to material anisotropy, mode-conversion and cladding on the inner surface. When properly applied, phased arrays using focused longitudinal-wave probes can overcome such issues. The paper presents inspection methodology along with use of specific calibration reflectors for reliable inspection of such welds.

Keywords: ultrasonic testing, phased array, corrosion resistant alloy (CRA), welds, clad, Alloy 625, anisotropy

1. Introduction

Corrosion Resistant Alloy (CRA) lined or cladded pipes are used in high sour hydrogen sulfide oil and gas production fields. Pipes with CRA clad also require CRA welds. Both CRA clad and weld materials are typically Alloy 625 (N06625). Alloy 625 material used in these welds is anisotropic and affects propagation of shear waves by inhibiting their ability to penetrate the structure. The approach is to inspect with refracted longitudinal waves (L-waves). Longitudinal waves are much less affected by material anisotropy, so they can be applied for this application. There are differences in the application of shear waves and refracted longitudinal waves. Conventional single/dual element angle beam shear wave technique cannot be directly transferred to refracted longitudinal wave techniques. Proper application of ultrasonic testing is required for reliable weld inspection.

2. Weld Geometry and Cladding

Typical geometry of CRA welds is shown in Figure 1. To protect carbon steel from sour fluid, the pipe is lined with CRA material and then welded with the same material. Three types of CRA lining methods are typically used in industry: weld overlay clad, metallurgically bonded, and mechanically lined. Typical thickness of CRA clad/lining is 3 mm minimum.
3. Material Anisotropy and Wave Modes

Unlike carbon steel, Alloy 625 is a highly anisotropic material. This means the sound velocity in Alloy 625 varies with grain orientation. Material anisotropy affects shear waves much more than longitudinal waves (1). In fact, shear waves cannot even penetrate Alloy 625 welds. As a result, refracted longitudinal waves are used for inspection of these welds. Refracted longitudinal waves have one problem. Contrary to shear waves that totally reflect, longitudinal waves mode-convert upon reflection. Shear waves when incident at 45°, 60° or 70° degrees at the inner diameter (ID) surface are fully reflected and therefore can be used in both 1/2 vee and full vee modes. Application of both ½-vee and full-vee modes allow shear waves to illuminate the entire weld and obtain full weld coverage. Refracted longitudinal waves mode convert upon reflection and lose approximately half their energy to shear waves (see Figure 2). The same is true when the L-wave returns from a reflector back to the ultrasonic probe. Due to the loss of energy from reflection, refracted L-waves are limited to inspect in ½ vee mode. With the ½ vee mode, a probe placed on the pipe surface cannot illuminate the entire weld. To fully inspect the weld, the weld cap has to be removed and the inspection must be performed both from the pipe outer diameter (OD) surface and from top of the weld cap. Weld cap removal is typically not entertained by plant owners, as it adds extra work in preparing welds for ultrasonic inspection. However, other options for volumetric inspection are limited and the weld cap has to be removed for 100% coverage of the weld.
Figure 2. Longitudinal wave mode conversion upon reflection. Longitudinal waves lose energy by mode conversion to shear waves and cannot be used in the full-vee mode.

4. **Refracted L-wave using Conventional Probes.**

The simplest approach to inspect CRA welds would be to inspect with conventional refracted L-wave probes. These probes are commercially available as single/dual element in three common refracted angles 45°, 60° or 70°. The wedge is cut at a specific angle to produce the desired wave mode and refracted angles. Conventional L-wave probes have limitations. They have a large footprint and no focusing. When applied to weld overlay clad, the large footprint along with the irregular clad surface scatters the sound beam and produces an ID roll signal on A-scan display. Figure 3 shows ID scattering and the ID roll signal from a weld overlay clad. Small ID connected defect signals are masked by the ID roll signal. Conventional L-wave probes can miss ID connected defects in the root area of the weld and are therefore not recommended when inspecting pipes with weld overlay clad.

A special case is metallurgically clad pipes. They have smooth ID surface and do not have the ID scattering issue. Conventional dual element L-wave probes can be used on such pipe welds.

Figure 3. Scattering with conventional UT Probe (a) scattering from ID of weld overlay clad (b) ID roll signal from scattering can mask ID connected defects in the weld root region.
5. Phased Arrays for CRA welds

Phased array probes overcome the weld overlay clad scattering by focusing the beam to the ID surface, thereby reducing the footprint of the beam. With good focusing, ID indications in the clad can be resolved and identified. It is very important to use probes with sharp focusing in the cladded region. Phased Array focusing depends on the active aperture and frequency of the probe (2). Larger active aperture and higher frequencies produce sharper focus. Furthermore, focusing is limited in the near field. The near field of a 5 MHz, 16 x 0.6 mm L-wave probe is only 19.5 mm, so there will be no focusing beyond this distance. This probe is not suitable for inspecting a 25 mm thick cladded pipe. A rule of thumb is to use probe active aperture of at least 0.6 x pipe thickness (with a minimum of 16 mm) and a frequency of 5 MHz. A 16 x 1.0 mm, or active aperture of 16 mm, has a near field of 54.2 mm, so it can be used for 25 mm thick clad pipe. Furthermore, when using a 32 element probe, a 32:128 phased array machine should be used to simultaneously pulse all 32 elements.

Figure 4 shows response from a 1 mm notch in clad using both conventional UT and phased array. Pipe thickness is 32 mm + 3 mm clad. There is no detection of 1 mm notch with the conventional UT probe. The ID roll masks the reflection from the 1mm notch. The notch is clearly resolved with a 5 MHz, 32 x 1.0 mm phased array probe.

![Figure 4](image.png)

(a) Conventional 4 MHz probe. ID roll signal masks 1 mm notch reflection. (b) 5 MHz, 32 x 1.0 mm phased array clearly resolves the 1 mm notch.

6. Calibration - Side drilled holes and ID Notch

The two common calibration reflectors used for carbon steel pipe weld inspection are side drilled holes or 10% T notches (T-thickness). Both these work well for shear waves. With 60 degree refracted shear waves, holes and notch result in almost equal sensitivity. The codes allow the use of either reflector (3). That is not the case with refracted longitudinal waves. Refracted
longitudinal waves mode convert upon reflection at the ID surface and the notch surface. Because of this reason, the reflection from the notch is significantly less than the side drilled hole. Birring (4) shows this difference can be about 16 dB. Figure 5 compares the phased array signals using shear waves and refracted longitudinal waves from side drilled holes and a ID notch. The figure clearly shows a much lower response from the ID notch with refracted longitudinal waves. Therefore, if refracted L-wave sensitivity is set on the side drilled holes, they will miss ID connected planar flaws such as root cracks in the clad. Conversely, if sensitivity is set on the ID notch, the refracted L-wave inspection will be over-sensitive to mid-wall flaws and result in unnecessary rejection. Because of the large difference, refracted L-waves require two separate calibration sensitivities: side drilled holes for mid-wall sensitivity and an ID notch for root sensitivity.

A recommended calibration block for CRA welds is shown in Figure 6. The block includes both the side drilled holes and an ID notch. Mid-wall flaw sensitivity should be established on the three side drilled holes with sound propagating through the weld. ID sensitivity should be established on the notch.

A 10% thickness (T) notch used for piping is not applicable of CRA piping. The 10% T notch is too large for cladded pipes, as an ID defect larger than the clad thickness will compromise the clad and expose the carbon steel to sour fluids. The ID notch for cladded CRA pipes should be about half the clad thickness or 2 mm.

Another way of looking at CRA clad pipe inspection is that the pipe has two components: (a) carbon steel pipe for pressure retaining and (b) CRA clad for corrosion protection. The two are independent and should be treated separately for acceptance. The classic acceptance criteria for carbon steel pipes is applicable for pressure retaining stresses. CRA clad pipe inspection should also be sensitive for any breaks at the clad, and hence the inspection sensitivity at weld root should be based on the ID notch shown in Figure 6.

Figure 5. S-wave and L-wave reflection from side drilled holes and notch (a) carbon steel test block with 2.4 mm SDH and 1.0 mm deep notch (b) S-waves. Good reflection from holes and ID notch (c) L-waves. Poor reflection from notch due to mode conversion.
CRA Calibration shall include both side drilled holes and an ID notch. ID notch should be about half the clad thickness and used for setting ID sensitivity.

7. Conclusions

CRA weld inspection should be considered as two separate inspections: carbon steel pipe for pressure retaining and CRA clad for corrosion protection. Two separate sensitivities are therefore required: side drilled holes for mid-wall and ID notch for weld root. The ID notch should be in the clad and about half the clad thickness.

When using conventional single/dual element L-wave probes, ID scattering from the weld overlay clad can mask root defects. That is a major limitation of conventional ultrasonic probes. Refracted L-wave phased array probes with focusing on the ID surface should be used for CRA welds. Focusing minimizes scattering from the weld overlay clad surface. Phased arrays probes with large active aperture that result in sharp focusing on ID surface are recommended. Phased array probe selection therefore becomes an important step for this inspection.

For 100 % coverage, CRA weld inspection also requires removal of the weld cap.

References