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Considerations about ultrasonic inspection of welded joints using phased array

Gerhard Grün
National Institute for Welding and Material Testing – ISIM Timişoara
Phone: +40 256 491828, Fax: -40 256 492797, e-mail: ggruen@isim.ro

Abstract
In comparison with the ultrasonic conventional examination of welded joints the phased array technique presents a series of facilities and specific advantages of these new examination technique, between which we can mention: a higher examination speed, a better probability of detection of discontinuities, better performances of sizing of discontinuities, bidimensional images, storage of all data, a high reproducibility and reduced security risks.
In the present work are discussed some aspects regarding the manual inspection procedures, the inspection requirements according to various examination codes, the instrument calibration, the coverage of the inspection zone, the scanning procedures and the interpretation of sectorial scanning data.
Keywords: ultrasonic conventional examination, phased array technique, probability of detection, bidimensional images

1. Introduction

The largest applicability of the phased array method and in particular of the portable phased array units is represented by the manual and the semi-automatic inspection of welds and similar components. This paper presents basic principles of the welds inspection using the phased array method, inspection procedures and data analysis in welds using manual and semi-automatic S-scans and E-scans.

2. Manual inspection methods

There are two general ways to inspect welding seams using the phased array technique.

- The emulation of manual monocrystal conventional techniques using the raster scanning technique.
- The execution of a linear scan in order to cover the entire welding surface by linear passing over.

These two approaching ways are graphic illustrated in figure 1 and 2.

According to Figure 1, the technique of raster scanning offers the advantage of simulating current techniques. There is no need of new examination codes. The technique covers the welding surface with multiple angles, so its results will be more reproducible then the ones of the monocrystal conventional approach. The images of defects are superior, too. The raster scanning using phased array doesn't offer the benefits given by the ultrasonic inspection with phased array, which has much higher speed and complete data storage.

According to figure 2, the linear or the one-way scanning method is much faster then raster or monocrystal conventional techniques. It can be codified to save all the data. In essence, this is a simple portable phased array approach for automatic and semi-automatic welding inspections. The linear scanning can be performed either using encoders, either simply, manually. This method offers certain advantages:

- The linear scanning is much faster, maybe 5 times faster then manual techniques, being very effective in costs.
- All data can be saved using semi-automatic scans (with an encoder)
- Even for manual scans, key data can be simply saved by freezing the images.
- The results are highly reproducible, although third parties have to confirm this fact by tests.
- Data analysis is less simple then using the monocrystal conventional technique, as shown in the „S-Scan Data Interpretation” paragraph.

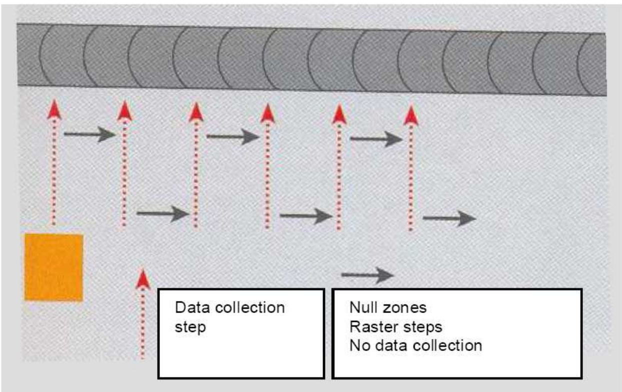

Fig. 1. Schematic presentation of the approach method using conventional raster scanning

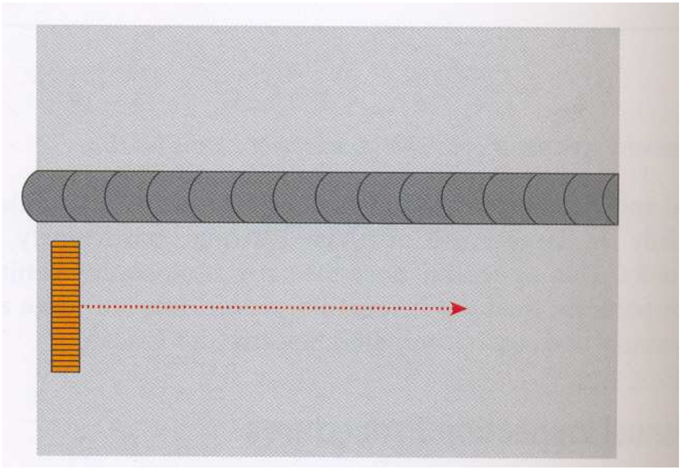

Fig. 2. Schematic presentation of the concept of linear one line scanning

3. Codes and Calibration

When requested, welds must be inspected according to a code or a specification. Normally, the specified inspection codes are developed by large organizations like

ASME, AWS or API. These inspection codes specify the equipment type, the calibration procedures, the scan techniques, the sizing and the characterization procedures.

For phased array, all the codes that were mentioned before accept this new technology, although actual techniques and procedures need to be demonstrated. Each code has its own section for accepting new techniques and procedures, based on performance demonstrations. Typically, based on a set of pieces that include defects, the new technique is compared with a consecrated one. An experimental approach for the ASME code, section V, was prepared using article 14 for new techniques for plates and up to 25 mm pipes using E-scans.

4. E-scans

As opposed to conventional monocrystals, phased arrays may generate ultrasonic beams under multiple angles. Using E-scans (electronic raster scan at fixed angles), a few codes and calibration problems appear, because these ones emulate conventional monocrystal inspections; the calibration and setups are the same as the ones for the manual techniques. The scanning pattern may be different if it is performed using linear scan as the probe doesn't oscillate to detect defects that are oriented under other angles. Anyway, adding the time of flight diffraction will slightly compensate this aspect. Figure 3 presents an E-scan example with an exploring at two different angles, for example, a typical code inspection. It is always first asked for a calibration of the wedge delay.

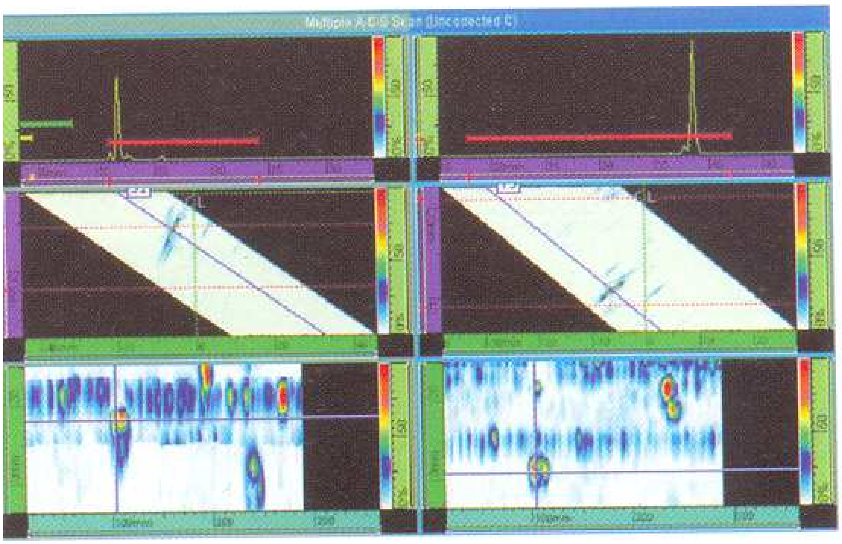

Fig.3. Double E-scan at two different angles on the ultrasonic apparatus, together with A- and C-scans

5. S Scans

The S Scans offer different results. While the normal code procedure consists in calibrating on a cylindrical hole or a constant depth notch of ultrasonic path, with the S Scans this feature gets more difficult. For every angle, the distance to the reflector

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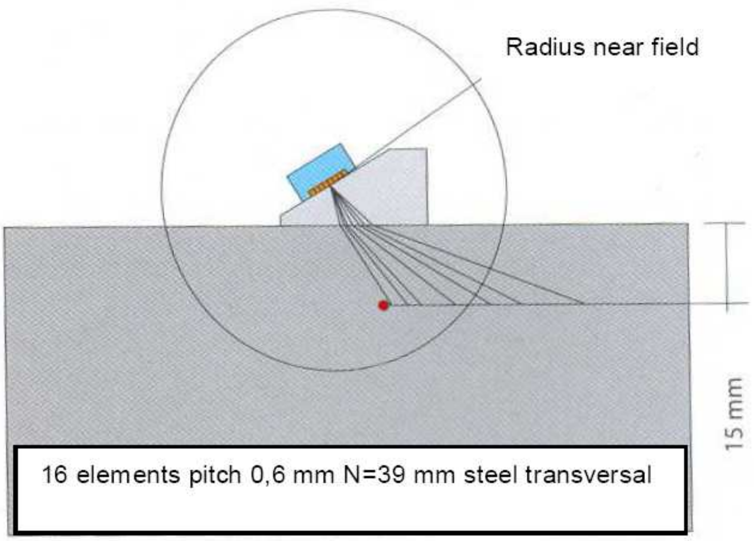
varies in the metal. The path through the wedge and the beam's amplitude vary in the same manner, according to physical laws. This aspect is illustrated in Figure 4.



16 elements, 0,6 mm pitch, N=39 mm shear wave in steel

Fig. 4.The effect of calibration on cylindrical hole with S-scan: different angles, different attenuation, no correction for possible near field effects

The alternative to calibration on cylindrical hole at fixed depth is to compensate the angular beam signal amplitude variations by calibration on a radius, as shown in Figure 5. This one offers a constant ultrasonic path, a constant attenuation and the same near field for all the angles.

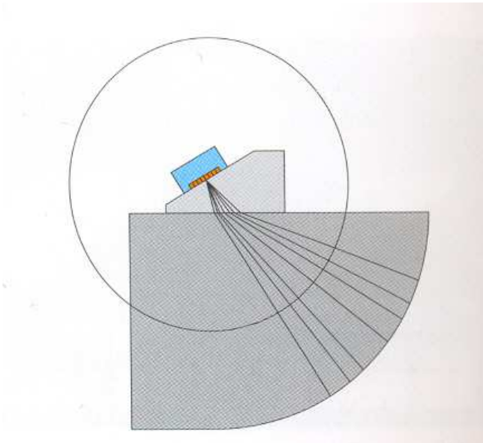


Fig. 5 The calibration on a radius for obtaining an Angle Corrected Gain (ACG).

ACG is requested with a Time Corrected Gain (TCG) for S-Scans. Therefore, the calibration reflector (or cylindrical hole) shows the same amplitude no matter where it is situated in the true depth S-Scan „pie". The same thing is easy demonstrated with the phased array apparatus. Figure 6 illustrates an A-scan envelope of a cylindrical hole set with almost identical amplitudes after calibration.

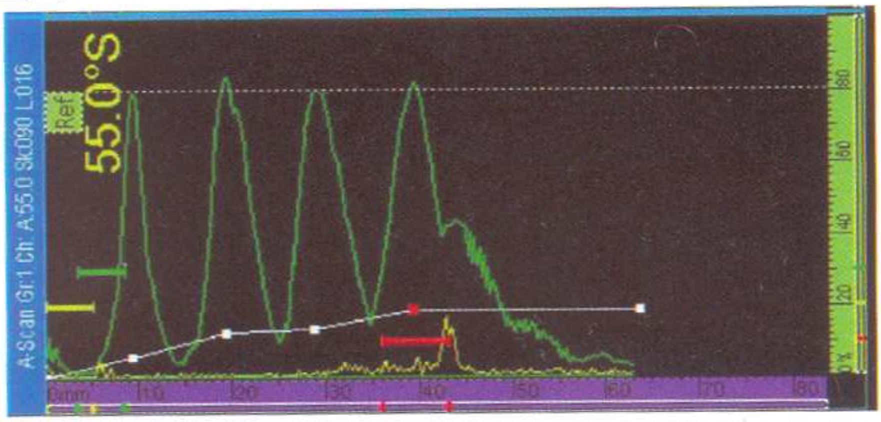


Fig.6. Cylindrical hole scanned using a beam of shear waves at 55º, with calibrated ACG and TCG (low variation of calibration amplitude).

In practice ACG and TCG are combined in a single process using the Auto-TCG function with the phased array apparatus. Despite these calibration requests, it must be kept in mind that S-Scan is a set of A-scans performed at different angles. Once more, it is always requested a calibration of the wedge delay.

The other major result regarding the S-Scans is the „Bias Incidence Angle" or BIA. Codes like ASME don't specify concrete BIA, but they assert that „adequate angles" must be used. Unfortunately, concrete adequate angles are not well defined. Some codes request specific angles, but this approach has its own limitations, too.

BIA's appearance can be easily seen in Figure 7. The optimal position of the probe and the angles for the body and the upper side of the welding are different to the ones for the optimal inspection of defects at the root.

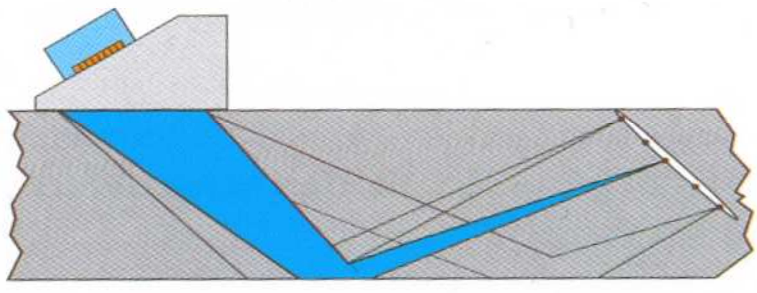


Fig.7. Schematic presentation of the S-Scan inspection of welding. Optimal angles for the middle section are clearly different to the ones for the root's area.

Adequate angles may be modified to discover the optimal coverage. Figure 8 illustrates the rays drawing, showing the number of the S-Scans requested to provide a BIA at ±5º to normal incidence: three S-Scans at different distances to the center of welding.

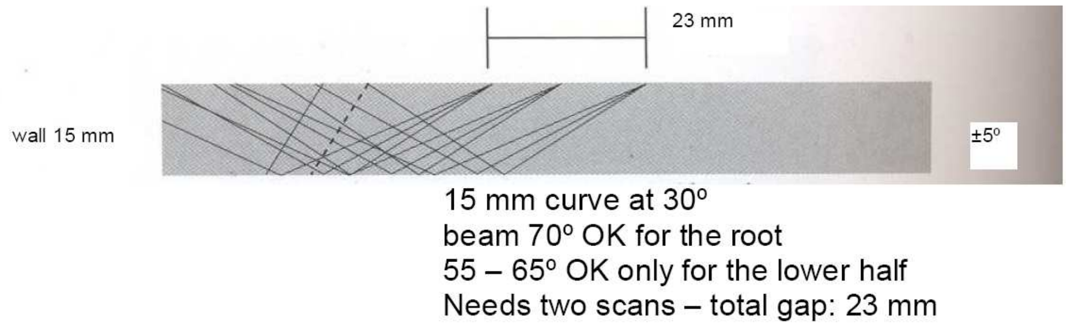


Figure 8 The rays drawing showing the number of the S-Scan passing over requested for a BIA at ±5º to the normal.

Figure 9 shows that for a BIA at ±10º, two scans can provide an adequate coverage. The number of scans is conveniently scalable. For example, the component's thickness doesn't dictate the number of S-Scans. The „opening angle" of the BIA is the one that dictates the number of S-Scans. This problem hasn't been completely clarified in codes.

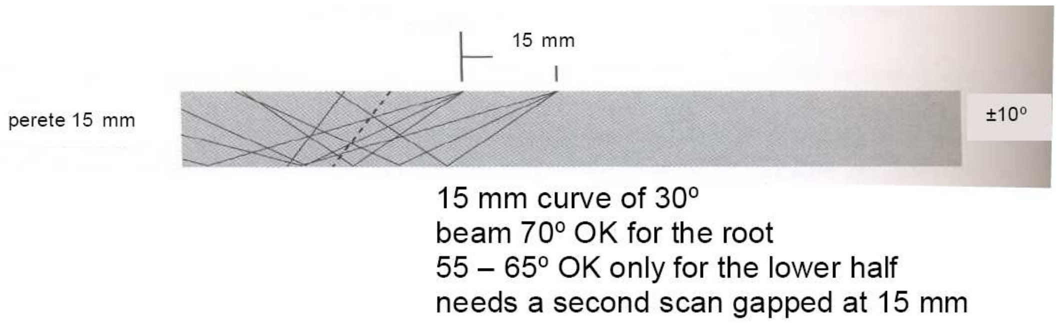


Fig. 9. The rays drawing illustrating the number of the requested S-Scan passings over for a BIA of ±10º to the normal.

The requested number of scans is first of all a geometric effect; in principle, larger apertures request less scans, although other effects, like the near field ones may complicate the problem.

Another problem is represented by the focus, although this is effectively addressed in codes.

It is applied both to S-Scans and E-Scans. Phased arrays can be electronically focused at short distances if they are appropriately programmed. This will generate a large angle beam at distances after the focal point. This effect is illustrated in Figure 10. In practice, the beams may be very weak far after the focal point making the effective focusing impossible.

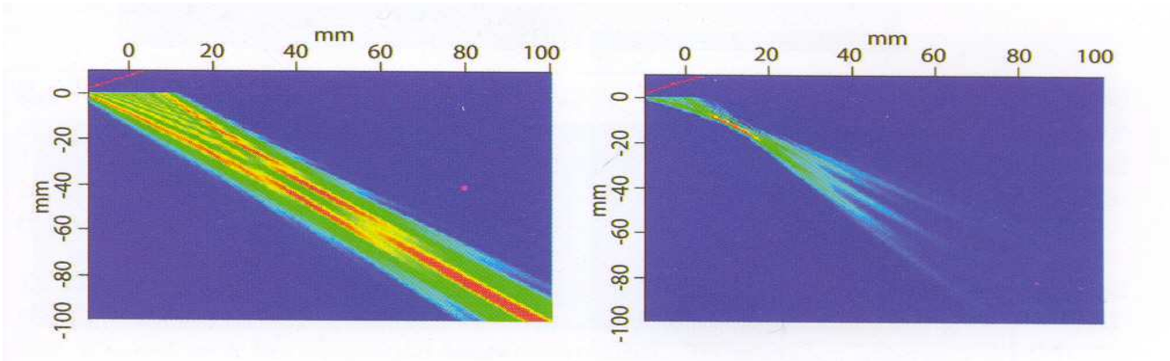


Fig.10. Focus effects modified on beam profiles. *Left:* not focused with natural focal point at 150 mm and beam divergence of 2,4º. *Right:* with electronic focus at 15 mm with beam divergence of 20º.

While no code clarifies the focusing in a specific manner, all the codes request a correct calibration. This fact implies that if the beam divergence is so strong and the signals are so weak to make a correct calibration impossible, a change of the focal point is needed. In case of ASME code, phased array in preparation simply requests for scanning the same focal laws as the ones used for calibration.

6. Coverage

The techniques and procedures must demonstrate the adequate coverage of the weld, of the heat affected zone (HAZ) and of the close material, as specified in the code. In a convenient way, the programs for drawing simple rays are generally adequate to demonstrate the coverage, as shown in Figure 11 and 12. Figure 11 illustrates the coverage of a weld using E-Scans and Figure 12 shows the actual scanning technique, using a reference point in the weld's centre line.

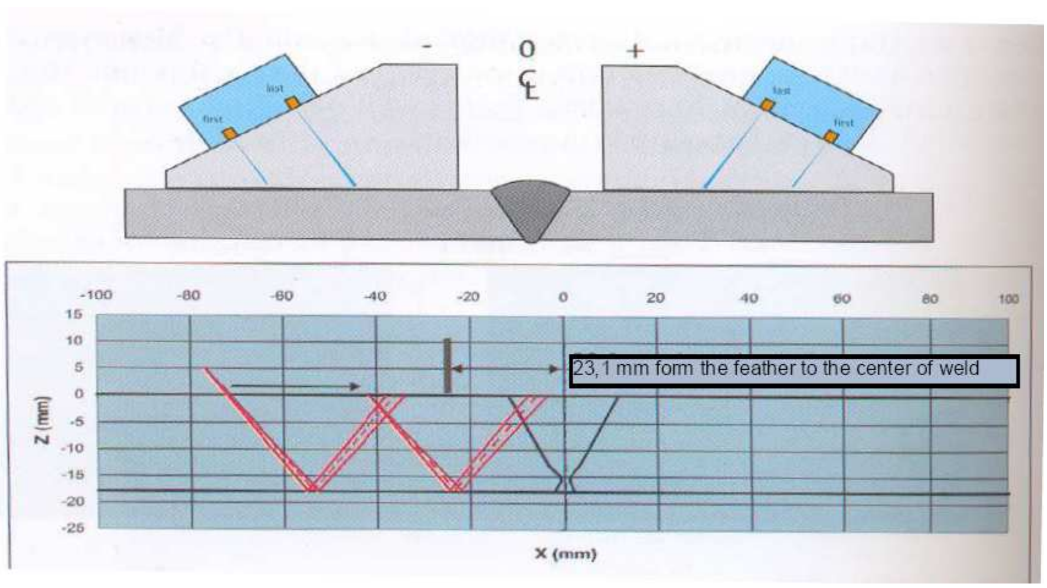


Fig. 11. *Up*: the illustration of the weld inspection using E-Scans
Down: the illustration of the weld coverage using E-Scans

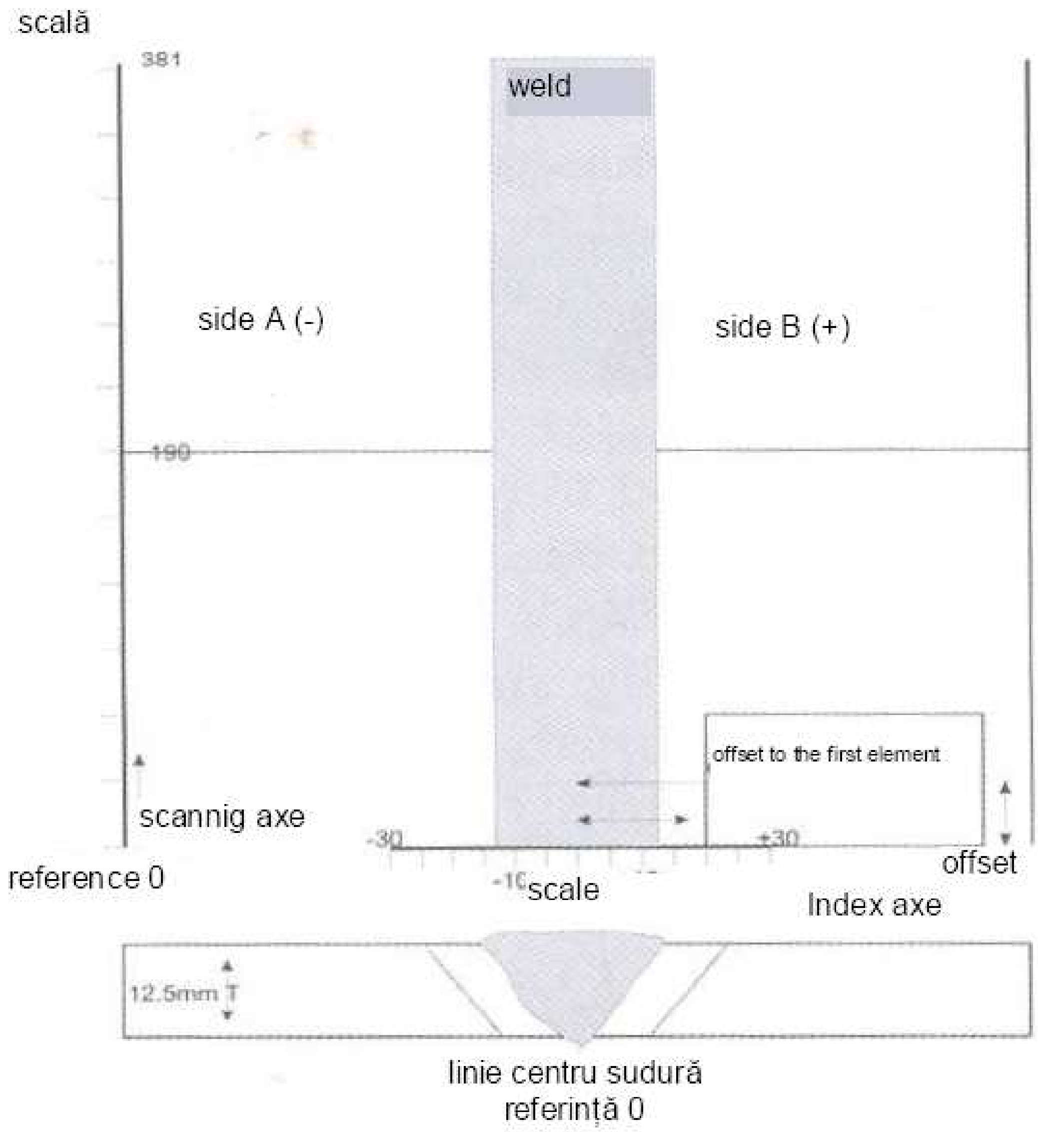


Fig.12. Illustration of the E-Scan procedure, presenting the scan pattern and the distance to the centre of welding.

For this procedure, the operator must record scanning patterns, offsets, locations and dimensions as part of the technique. This aspect must be specified in the code requests.

7. Scanning techniques

A technique for ultrasonic inspection phased array of plates and pipes base materials and welds of carbon or stainless steel has been prepared. This procedure may be applied for components with a thickness between 12 mm and 25 mm. (This gives a qualified area from 0,5 to 1,5 times greater then the examined component, or from 6 mm to 38 mm).

This technique is specified for the Phased Array OmniScan Olympus NDT System according to the ASME Code. A not-blind test (open test) is used to prove the efficiency. An encoder interfaced with the Phased Array OmniScan tool is optional; for example, the scan may be manual or semi-automatic.

The wedge delay and the sensibility calibrations are compulsory. The auto-TCG OmniScan function includes both ACG (Angle Corrected Gain) and TCG (Time Corrected Gain) in a single procedure.

The phased array scanning requests a complete documentation. In detail „the scanning plan must prove, using drawing or a computer simulation, the appropriate examination angles for the angles that prepare the weld's curve (for example, 40 – 60º or 55 – 70º) and which will be used during the examination. This scanning plan must be recorded to prove that the examination volume was examined. This scanning plan has to be part of the final examination report".

The procedure uses the one line scanning technique as shown in Figure 2 for a fast inspection, instead of a raster scanning technique. In detail, minimum two E-scans or S-Scans are performed at two different index points from the weld center on both weld sides to ensure the welding as well as the heat affected zone coverage. Multiple line scans are needed for the materials with a nominal wall thickness greater then 25 mm, in order to cover the specified volume of welding and base material. In a similar way, generic procedures for API and AWS codes have been developed.

8. S-Scan data interpretation

The E-Scan data interpretation is similar to the conventional ultrasonic manual testing, with the advantages of improved imagery and data recording. S-Scans offer other advantages because they use multiple angles and offer a larger coverage. Figure 13 illustrates an S-Scan with techniques of defect localization.

The S-Scan image allows a fast defect evaluation; in this example, both the defects from the interior and exterior diameter can be quickly obtained comparing it with the wall thickness marker (B0 for interior diameter root, T1 for exterior diameter weld top, B2 for an examination step and half root etc). The defects from the middle of the wall will appear between the B and T dashed lines.

In a similar way, the defect sizing offers significant advantages using S-Scans. For many times, the defect edge can be detected, as well as the base, so the diffused edge signals may be used for sizing. Figure 14 illustrates an example of crack identification. In general, the sizing techniques with edge diffusion are much more accurate then the amplitude-based sizing techniques.

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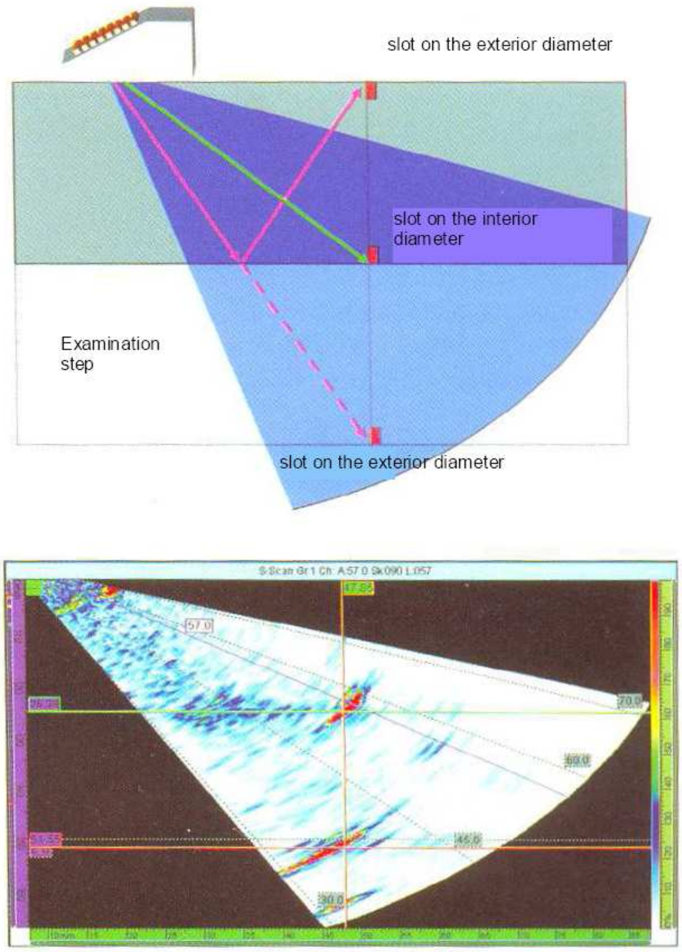

Fig.13. *Up*: an evaluation of the defect localization technique for defects situated at the exterior and interior diameter. *Down*: Resulted S-scan representing the slots

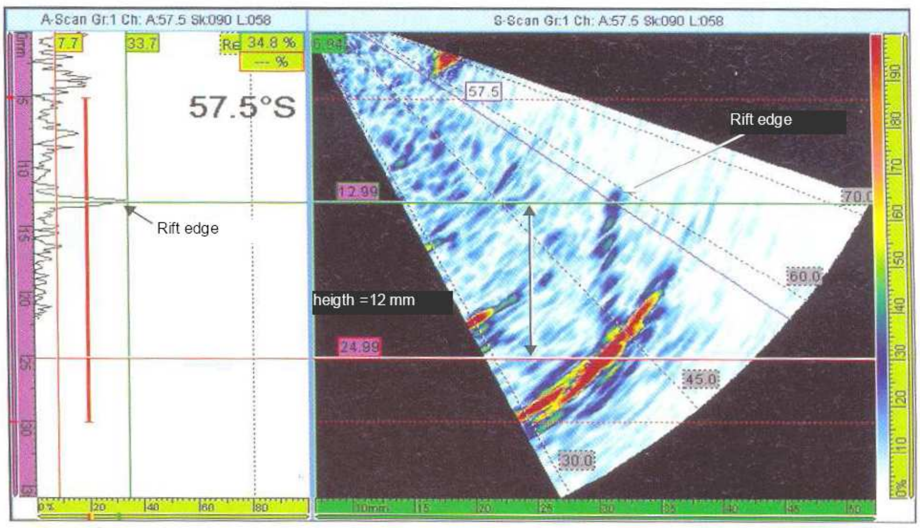

Fig.14. The base and the top of the crack are adequate for a diffusion analysis.
A similar approach may be used for cracks on the exterior diameter and for multiple cracks.

9. Conclusions for manual and semi-automatic inspection techniques

The presented inspection techniques have significant advantages compared with conventional monocrystal inspections:

- speed: many times faster
- imagery: offers improved defect characterization and sizing by retro-diffusion.
- data recording: allows re-analyses at a future moment and is less subjective.
- trust: the defects have to be detected by routine using an advanced imagery
- reproducibility: needs demonstration.