3D WELD VISUALIZATION USING MANUAL PHASED ARRAY

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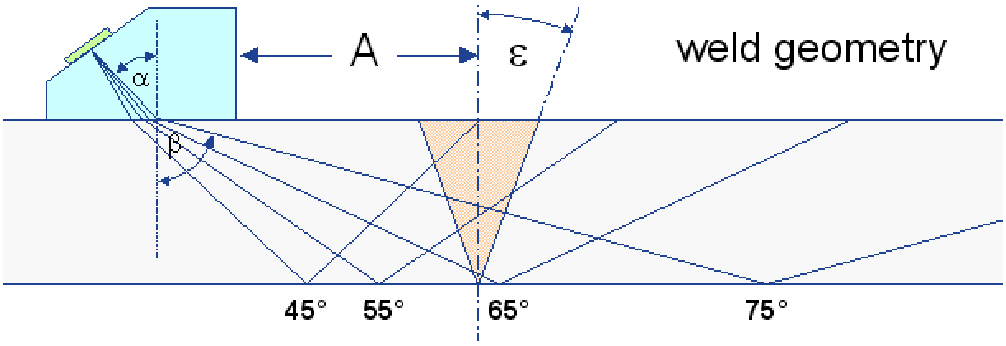
Introduction

With the introduction of Phased Array Technology in manual ultrasonic flaw detectors, not only new possibilities for the performance of the inspection, but also for recording and documentation of inspection results have developed. Especially sectorial scanning (S-scan), where shear waves are transmitted in an angular range including all typical angles 45°, 60° and 70° is the technique of our interest for manual inspection of welds. We will define the geometrical scan requirements which have to be obeyed when scanning welds with different thickness and weld preparation, and will present general solutions, demonstrated with a practical example. Here we will show how inspection results are displayed and recorded in real time, and how these data may further be processed using an external PC.

Geometrical consideration

Conventional weld inspection using single element angle beam probes is performed by moving the probe in a zigzag path from the weld cap to ~1,3 skip distances along the seam. Signals exceeding the registration level are further evaluated by the operator and documented. At least a 2-dimensional probe position device would be required, in order to automatically record and locate defects. Even here a possible rotation of the probe is not considered. In most cases simple position encoders only allow a 1-dimensional probe positioning, i.e. only the coordinate along the weld will be recorded. Using such a system for phased array weld inspection will require a fixed distance of the probe with respect to the weld geometry, and then defects may directly be located. In addition to this, special precautions must be followed in order to meet the reflection characteristic of flat defects, like lack of side wall fusion: Such a reflector will only be detected in case it is hit nearly perpendicularly. According to the ASME code we allow a deviation of the 90° angle to the flat reflector of ±5°. From this it is understood why the weld preparation needs to be included into the geometrical approach, fig 1.

Fig. 1:
Beam angles relative to weld geometry



Flank coverage

The angle of the weld flank (weld preparation angle ε) should be known. From this we derive the angle to the weld flank ±5°. Depending on the offset A of the probe to the weld we can calculate the flank coverage, including the percentage of the weld flank that is hit by the sound waves within the optimal angle ±5°. In the geometrical sketch, fig 2, we directly observe that a secure detection of flat defects at the weld flank is only guaranteed, in case scanning at more than one probe offsets will be performed.

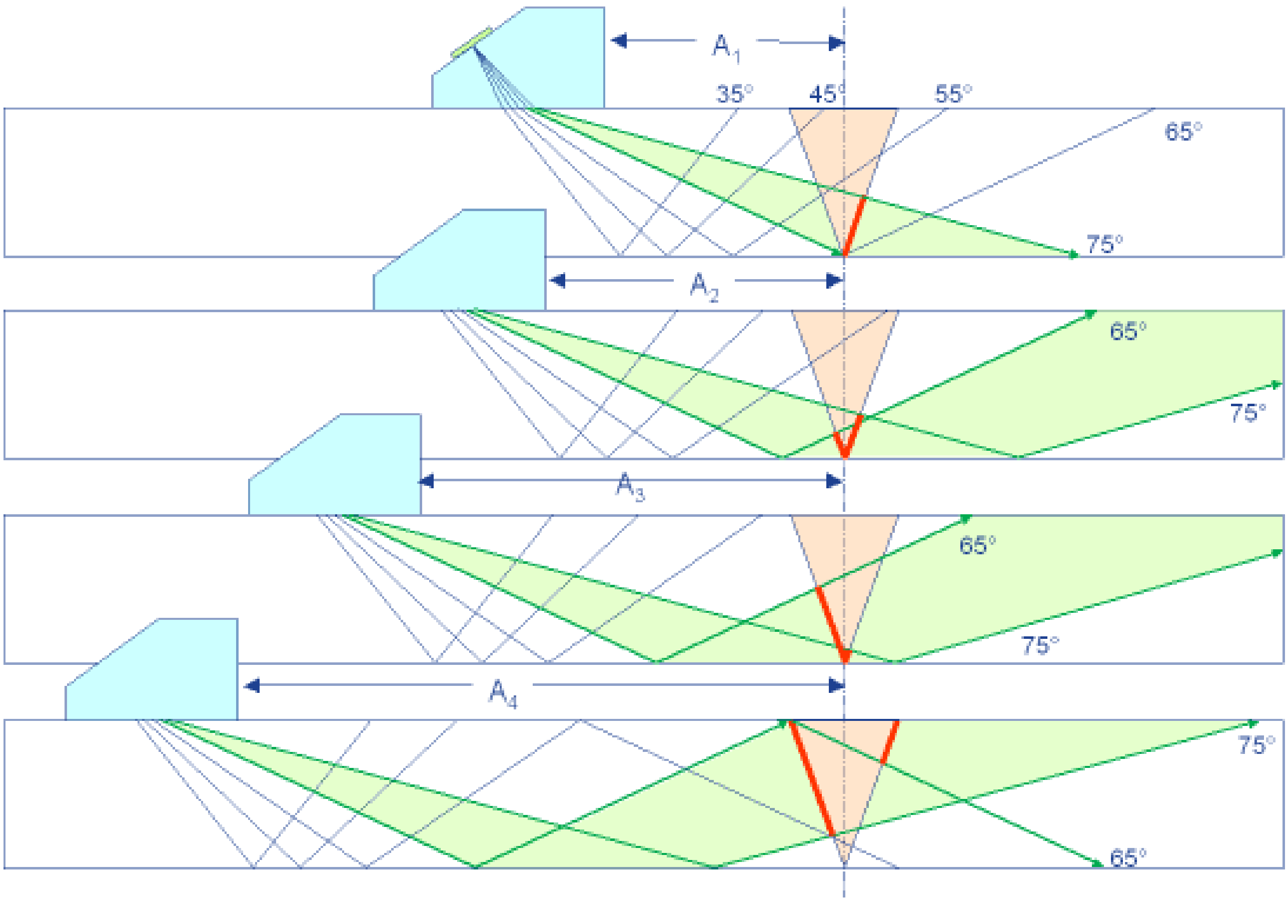


Fig. 2: Full coverage of the weld flank

For symmetrical V- and X-welds with known weld preparation angle ε and root width W the necessary probe offset can be derived geometrically. Amongst the weld geometry also some probe data are required: Using the sectorial scan the probe's X-value (distance: sound index point – front edge) depends on the calculated angle of incidence α:

$$\boxed{x = WF - Z \cdot \tan\alpha} \qquad with: \ \alpha = \arcsin(\frac{c_1}{c_2}\sin\beta)$$

WF = wedge front (distance: Center of the transducer – front edge), see fig. 3
Z = vertical height (distance: Center of the transducer – coupling surface), see fig. 3
α = angle of incidence β = angle of refraction (shear), see fig. 1
c_1 = sound velocity in the wedge (longitudinal)
c_2 = sound velocity in the material (shear)

From the weld flank angle ε the optimal beam angle is β = 90° - ε, and the two limiting angles follow: $\beta_1 = \beta + 5°$ und $\beta_2 = \beta - 5°$. The shortest offset A_1 corresponds to the geometrical requirement at which the sound path with β_1 hits the weld flank at half skip, fig. 3 (top), and for the longest offset A_2 the sound path with β_2 hits the weld flank at full skip, fig. 3 (bottom). For both these offsets, the depths can be calculated at which the marginal beams hit the weld flank, and thus the weld coverage will be given:

$$t_1 = \frac{2T \cdot \sin 5° \cdot \cos \varepsilon}{\cos \beta_1}$$

$$t_2 = \frac{4T \cdot \sin 5° \cdot \cos \varepsilon}{\cos \beta_2}$$

with:

- T = plate thickness
- ε = Preparation angle
- β_1, β_2 = beam angles of the ±5° margins

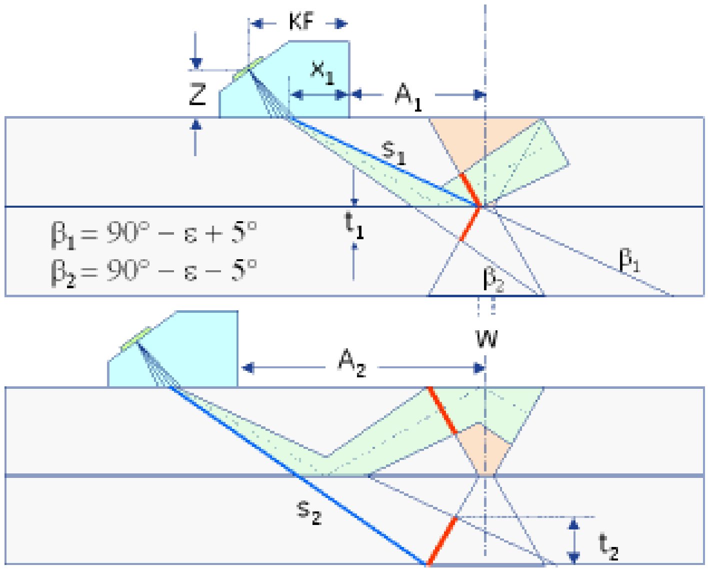


Fig.3: Probe offsets and flank coverage

For a full coverage of the whole weld flank the sum $t_1 + t_2$ should be larger than the plate thickness T. If this is not the case a third offset will be required in between the A_1 and A_2. The offsets A_i behave linear to the plate thickness T, and may therefore be described by a linear equation $\mathbf{A_i = a_iT - b_i}$. The coefficients a_i and b_i depend on the probe/wedge geometry and the weld geometry. For the probe used here the following coefficients for symmetrical V- and X-weld are given (root width W not considered):

<u>Example:</u> 30 mm thick V-weld with 30° preparation angle and a root width of 4 mm leads to an offset of A_1 = 53 mm, a depth range of ~19 mm to 30 mm, (=37%). At the offset of A_2 = 91 mm the covered depths are 0 mm to 16 mm (=54%). The middle part of the flank from ~16 mm to 19 mm is not covered, so that a 3rd offset of A_3 = 72 mm will be required.

	Weld preparation: 20°				Weld preparation: 25°				Weld preparation: 30°			
	V-weld		X-weld		V-weld		X-weld		V-weld		X-weld	
	a_i	b_i	a_i	b_i	a_i	b_i	a_i	b_i	a_i	b_i	a_i	b_i
A_1	3,7	12	1,9	12	2,7	12,5	1,4	12,5	2,1	13	1,1	13
A_2	4,7	13	2,3	13	3,9	14	2	14	3,4	14,5	1,7	14,5
A_3	-	-	4,5	13	-	-	3,7	14	-	-	3,1	14,5

Table 1: Coefficients for offset calculation of V- and X-welds

Also note, that with thin welds (T ≤ 9 mm) the offsets will become very small. Testing may then no longer be possible in case the probe interferes with the weld cap. However, testing may still be possible, if you add one full skip distance related to the optimal beam angle to the calculated offset. With symmetrical X-welds (30° weld preparation) the lower flank will be scanned in leg 1, the upper flank via one reflection (leg 2). Here, only one offset is sufficient, since the full upper flank will be covered by the optimal beam ±5°. For the lower flank 2 offsets are required (47% from required 50% coverage), so that in total 3 offsets will be required. With a given root width W the offsets increase by the fixed value of W/2. With more complex weld geometries mathematical formulae may still be derived, however, graphical solution may then be more useful, especially with the support of software tools that allow to see the all sound beams related to the weld geometry (ray tracing).

Practical application

Typically, with weld inspection using sectorial scanning an angular range of 40° to 70° (maximum 35° - 80°) will be used. The angular resolution may vary between 0.2° to 5°, however, the maximum number of beams is limited to 128, leading to one sector image. With typical ~7 kHz pulse repetition frequency 55 S-scan can then be displayed per second, but reducing the number of beams will lead to much higher display rate, e.g. ~200 Hz with 36 beams. This leads to a sample distance of 0.5mm when moving the probe at a speed of 100 mm/sec. Using the phased array ultrasonic flaw detector Phasor XS®, a 16 element probe on a wedge, and a reference block with side drilled holes at different depths, the amplitudes of the holes will be recorded with all angles to calculate the distance and angle dependent sensitivity compensation: With active TCG (time corrected gain) echoes from all holes will be displayed with the same echo height, independent of angle and distance. A position encoder, fig. 4, attached to the probe (4 MHz, 16 elements), allows the recording of the probe position when moving the probe along the weld. The flexible magnetic tape, fig. 5, guarantees a constant distance of the probe with respect to the weld. The instrument's screen displays one selectable A-scan and the S-scan. For easy identification of signals additional leg lines and a background drawing of the weld contour (weld overlay) will also be displayed. This helps in addition to better differentiate defect echoes form geometrical indications.

Fig. 4: Phased array probe with position en-

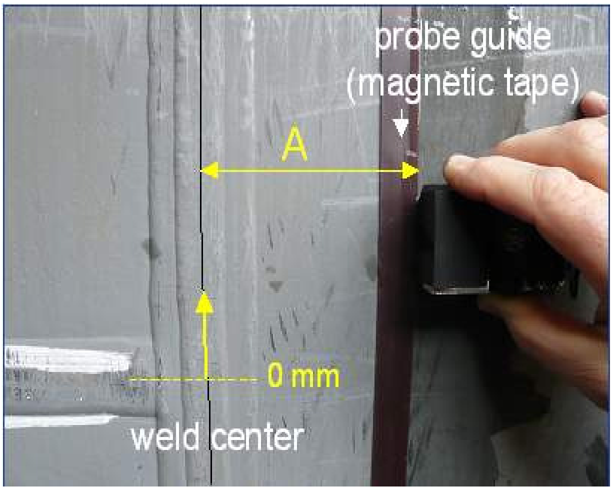


Fig. 5: Probe and magnetic tape for weld scanning at constant distance

Recording of inspection data

For each angle of the S-scan the maximum signal amplitude in both gates together with the corresponding sound paths will be stored at each tick of the encoder. With 36 beams the dataset will contain 72 pairs of amplitude/TOF values (~145 Bytes). An encoder sample distance of 1mm will produce 145 kB of data for a scan length of 1m. During scanning with recording all signals will be displayed in an image showing the probe position vs. the angle (uncorrected C-scan), fig. 6. The color coded echo amplitudes are displayed in a coordinate system with probe position on one axis and beam angle on the other axis. The color palette has been composed in such a way to directly identify echoes with respect to the recording threshold: echoes above 80% are red with changing to black, 79% - 40% = orange to yellow, 39% - 20% = green to blue, and 19% - 0% blue to white. Positions of indications and their lengths may directly be evaluated from this image, surface distances and depths are evaluated offline using cursors in the frozen or recalled image. Knowing the weld geometry, the probe offset to weld center and the length coordinate from the encoder, we calculate the coordinates of all indications and allocate them to the tested volume leading to the corrected C-scan (top view), longitudinal B-scan (side view), as well as any transversal B-scan (end view).

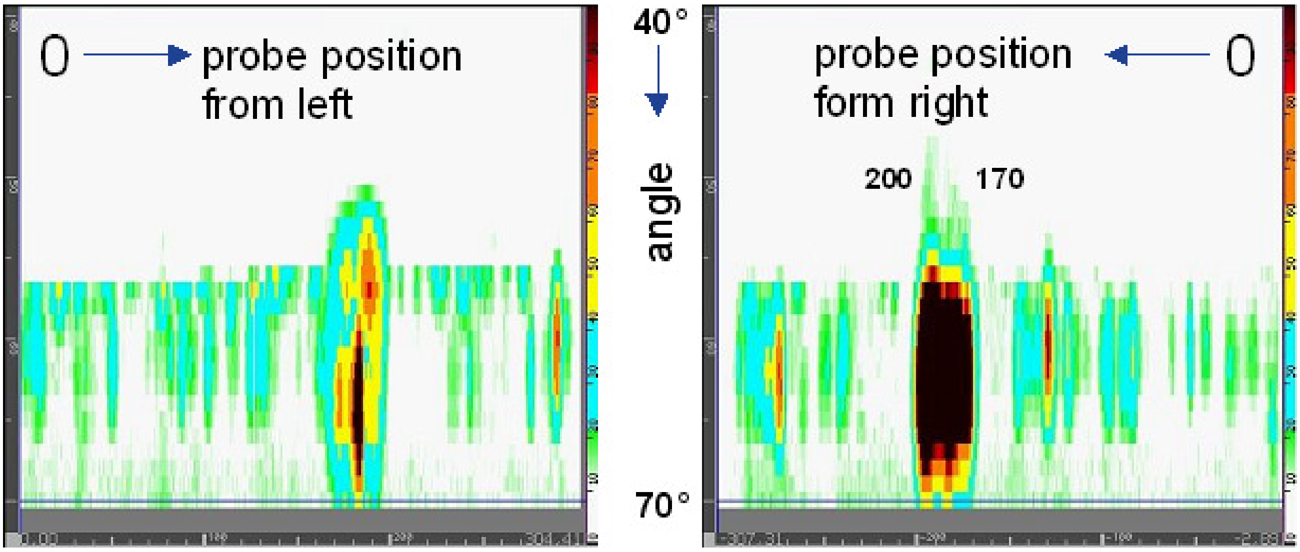


Fig.6: „uncorrected“ C-scan for A = 30mm

Documentation

Real C-scans may also be shown using the software program Rhythm UT®. In this example showing a 19.5 mm thick X-weld, scanned at a probe offset of A_1 = 11mm from right, the two defects are not clearly seen (10% - 30% FSH). At A_2 = 21mm you will see the geometrical indications from the root and cap clearly separated from each other, and with fairly high amplitudes, but also the lack of fusion defect appears more pronounced. At a probe offset of A_3 = 30mm, fig. 7, the lack of fusion defect is hit perpendicularly, giving a very high amplitude response (>100% FSH). The area of porosity is shown with amplitudes in the range of 20% - 40%, clearly separated from the geometrical indications. Also the scan from left shows the two defects, but with lower amplitudes.

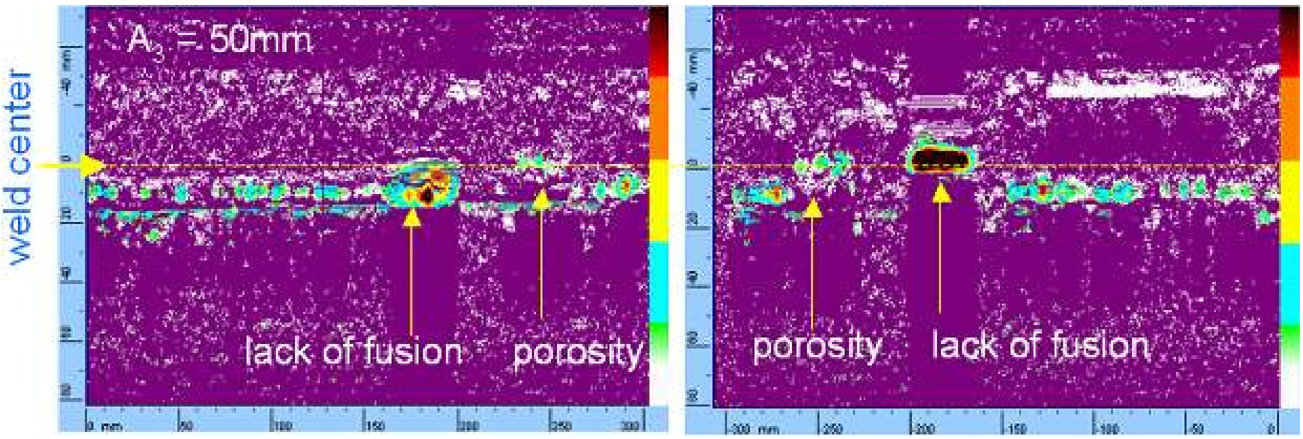


Fig. 7: C-scan of the weld, A = 30mm

Comparison of the results with other NDT techniques

The results are compared with the results of two further techniques, fig. 8: In the X-ray film (middle) both defects are shown, however, the lack of fusion defect requires a contrast amplification, because the inclination of the flat defect does not lead to a pronounced difference in density. On the other hand the porosity is clearly seen. The scan of the weld with TOFD (bottom) also shows a clear proof of the two defects. The lack of fusion defect is displayed with only one indication from a depth of 7mm. From this you can conclude, that this defect is running up to the surface or very close to it. Porosity lies in the same depth.

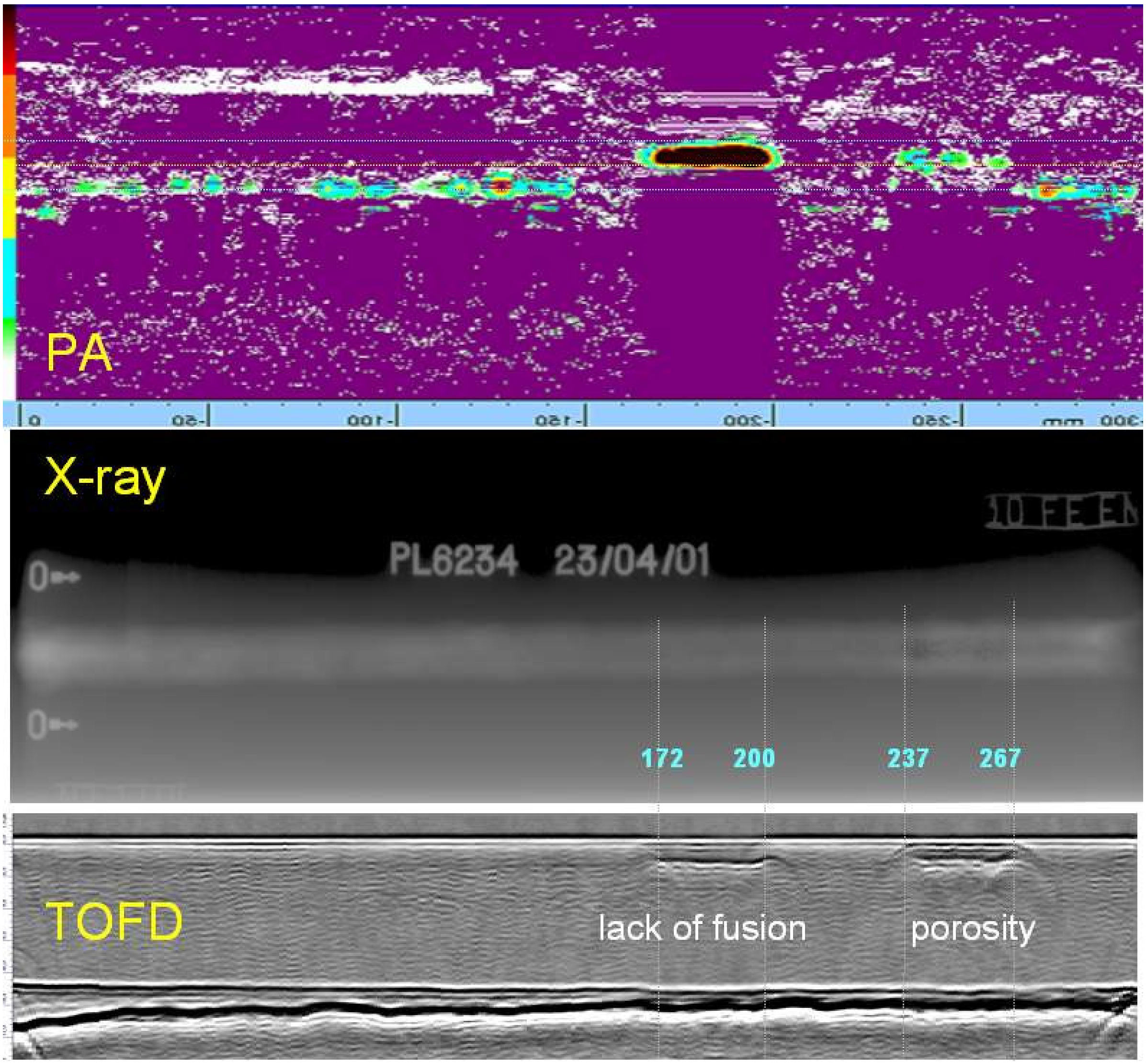


Fig. 8: Comparison: Phased Array – X-ray - TOFD

The accordance of the results of the three different techniques proves that phased array multiple angle scanning of welds will detect all possible defects safely. Different to the conventional scanning technique the weld is scanned at 2 to 4 fixed offsets to the weld from both sides using magnetic guiding strips. Already during scanning the operator sees all signals in the uncorrected C-scan, and may evaluate the indications with respect to their echo height and their location within the weld. True-to-scale images will then be generated from the stored data, allowing views from all sides including a 3D presentation of defects with respect to the weld geometry. Since the weld volume has completely been scanned and the results have been stored, the documentation delivers even more information compared to the X-ray film. Therefore phased array weld scanning may replace X-ray inspection which is appreciated in many cases for practical, safety and economical reasons. Also compared to TOFD phased array weld inspection has no disadvantages, except the more precise depth measurement of indications due to evaluation of the tip diffraction signals in TOFD, instead of echo evaluation which is additional affected by the influence of the beam divergence.

3D Weld Visualization

Stored data can easily be converted into the three dimensional defect coordinates. In a first step we have transferred these coordinates into the weld geometry using MATLAB®, Fig. 9a.

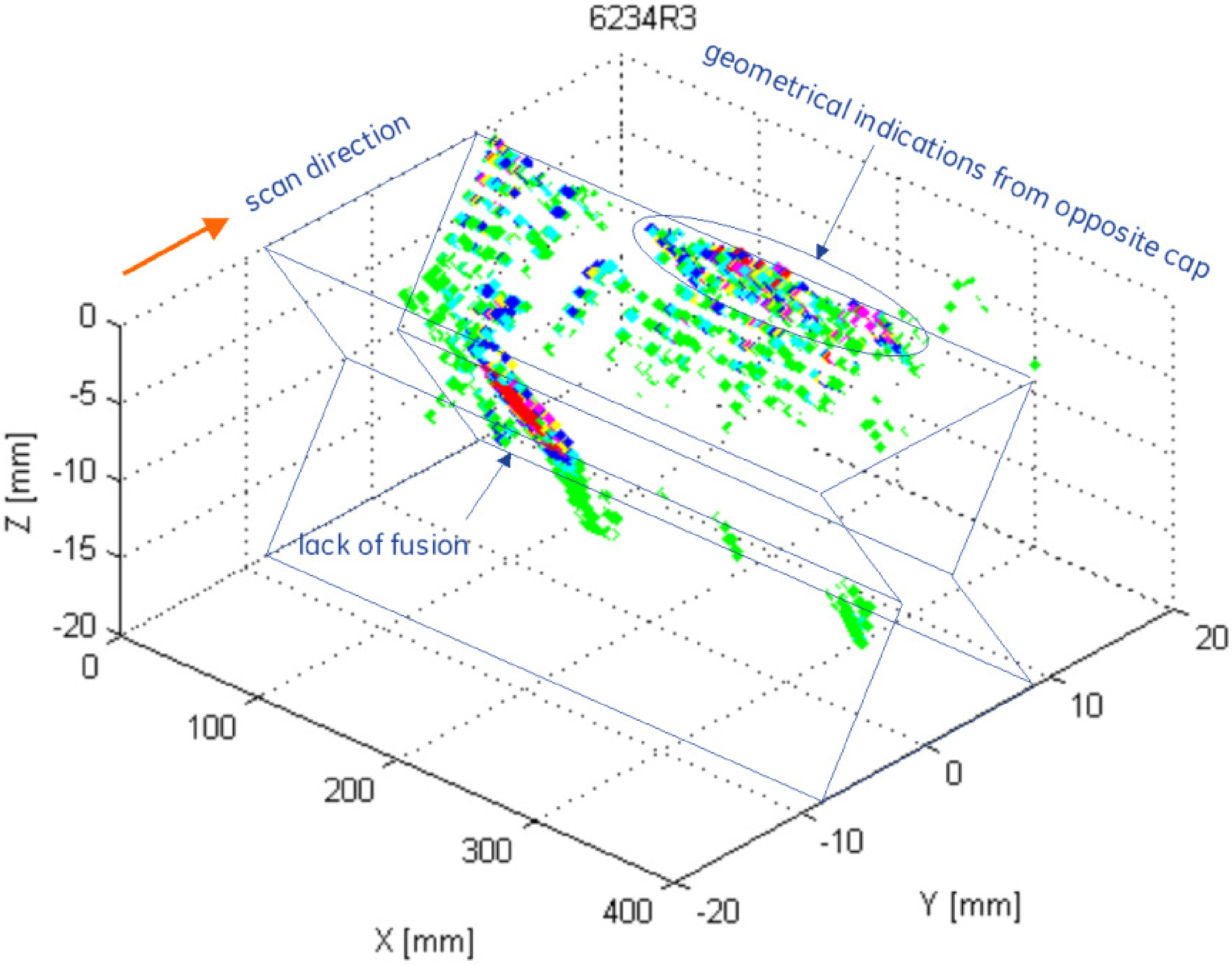


Fig. 9: 3D view of weld 6234 (with MATLAB)

MATLAB allows you to rotate the 3D image to any wanted view. Fig 10 shows the C-scan (top view) image of the weld.

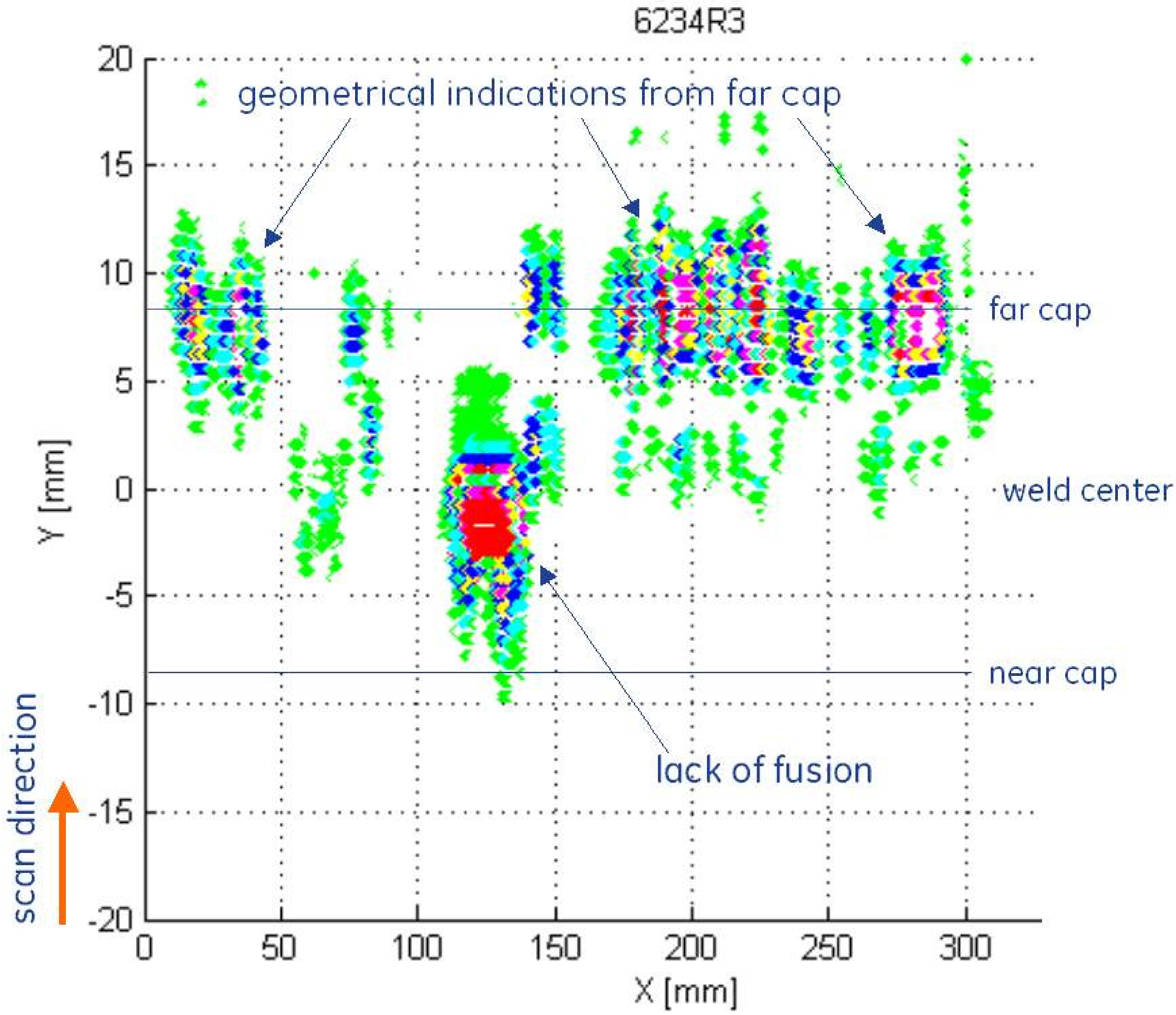


Fig. 10: C-scan (top view) image of weld 6234 (MATLAB)

A 3D close-up to the region of interest is shown in fig. 11, and the top and side view in fig. 12. The relating amplitudes have been converted into the following colors:

0 – 15%	white	60 – 75%	yellow
15 – 30%	green	75 – 90%	magenta
30 – 45%	cyan	>90	red
45 – 60%	blue		

80% corresponds to the reference of 3mm side drilled hole.

In the next step a proprietary software needs to be developed for an easy 3D data processing. Code compliant echo amplitude evaluation will be possible using special amplitude color scales which are related to the recorded DAC.

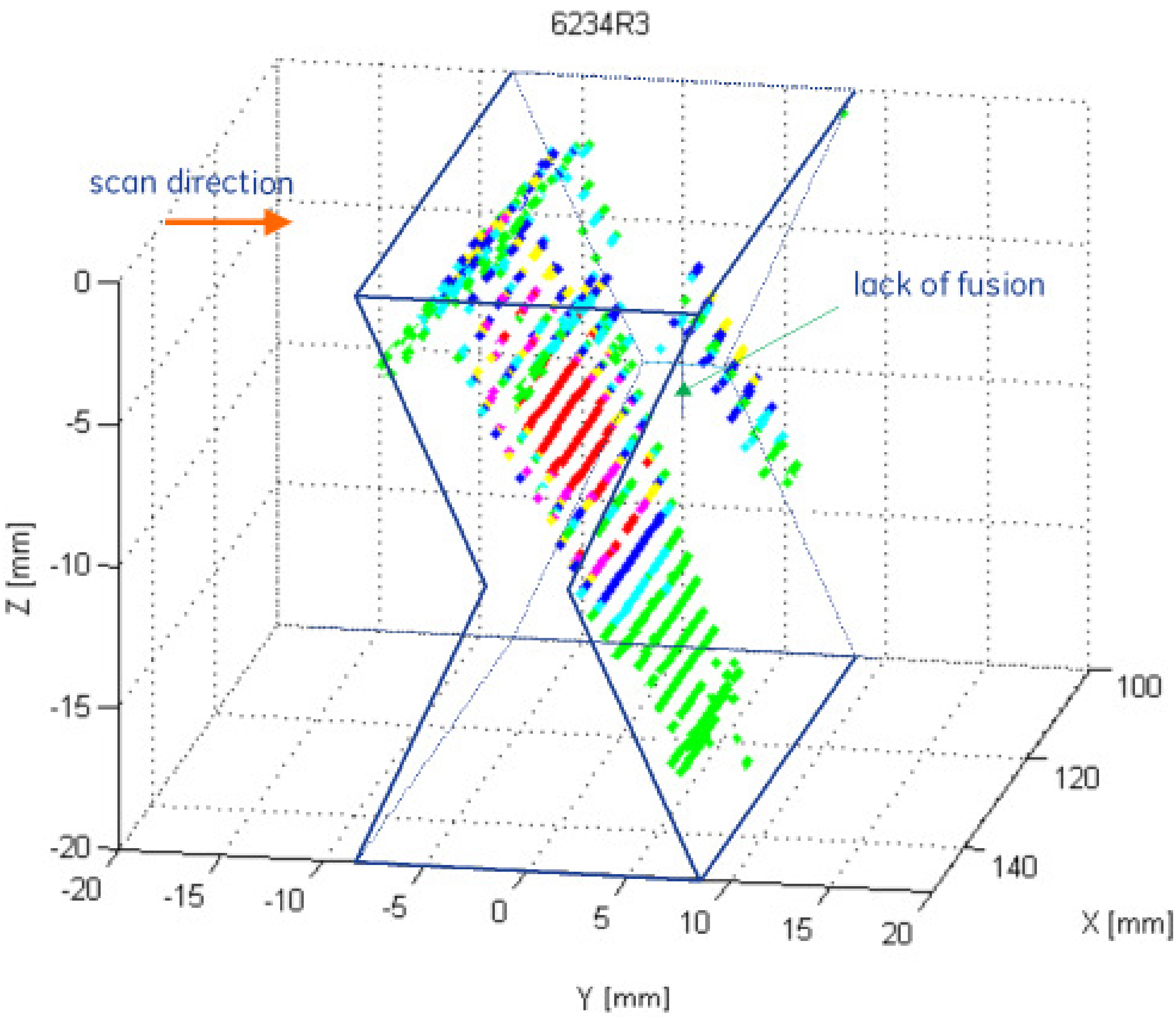


Fig. 11: 3D close-up view of the lack of fusion defect in weld 6234 (MATLAB)

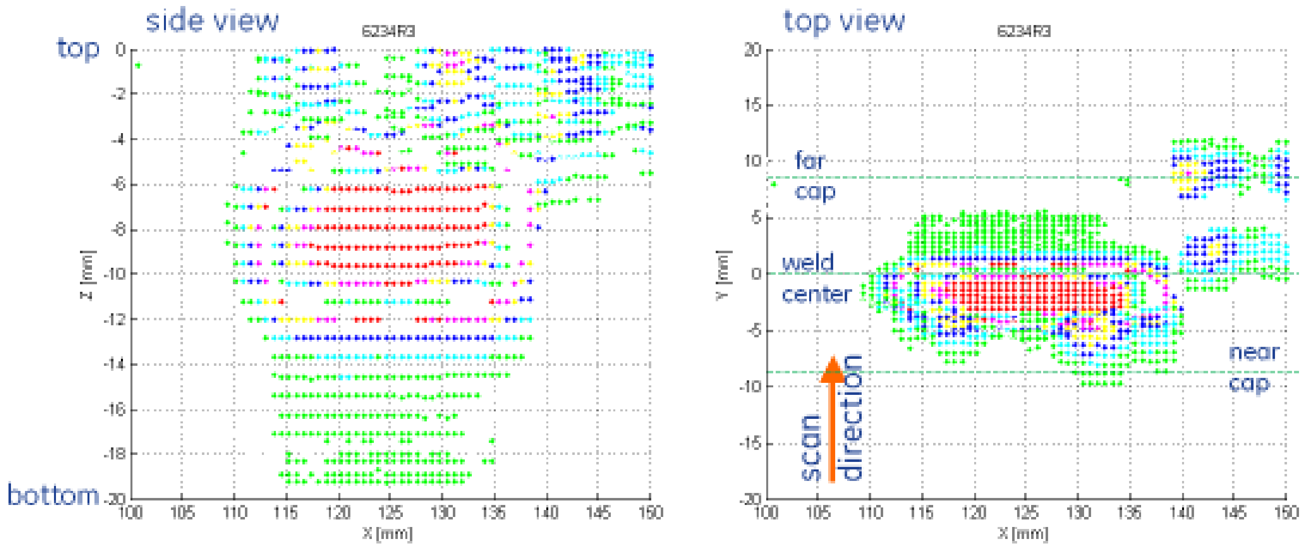


Fig. 12: Side and top view of the lack of fusion defect (MATLAB)

Summary / Outlook

Real time recording of inspection data during manual weld testing with the multiple angle phased array technique (S-scan) offers a series of advantages:

- The weld volume is scanned with all angles at once
- Indications appear true-to scale in the S-scan with weld overlay, allowing a direct location and a clear differentiation between defect and geometrical indications
- During manual weld scanning indications (color coded amplitudes) will be displayed in real time and automatically stored (fast and with low memory requirements)
- Further processing of the inspection data on a PC allows corrected views from all perspectives including 3D images

Testing welds with multiple angle phased array and the reconstructed images illustrate the completeness of the inspection, and may therefore be regarded as being comparable with X-ray inspection according to ASME Code case 2235. Even amplitude evaluation according to various standards is possible using the color coded echo amplitudes, as well as DGS evaluation in phased array.