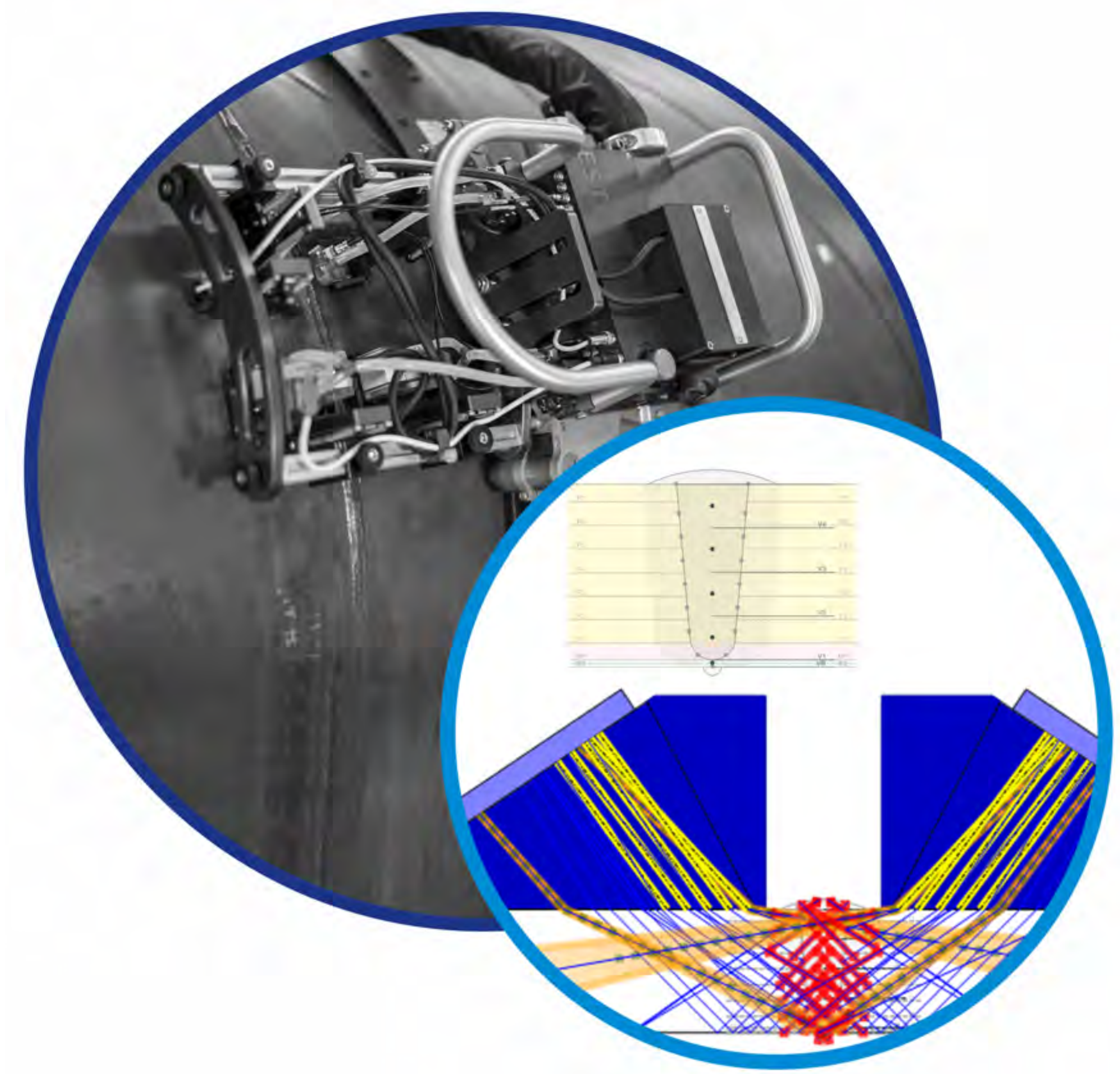
Automated Ultrasonic Testing of Pipeline Girth Welds



Fundamentals & Applications for Non-Destructive Testing

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Automated Ultrasonic Testing of Pipeline Girth Welds

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Eclipse Scientific

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CHAPTER (4): BEAM ANGLES - DESIGNING A TECHNIQUE

"In science one tries to tell people, in such a way as to be understood by everyone, something that no one ever knew before. But in poetry, it's the exact opposite." Paul Dirac 1902-1984

A "technique" is a term that may have several meanings in NDT. For our purpose the term will refer to the set of detailed instructions that allows a zonal inspection of a girth weld. Essentially this would define the probe parameters:

- frequency
- element diameters or number of elements
- refracted angles
- focal lengths
- whether or not the conditions require pulse-echo or pitch-catch configurations

Techniques would also require that the zones be defined and the targets recommended that will provide good detection sensitivity. Aspects of how the parameter controls are maintained would not be included in the specific technique, but would reside in a more general overriding document (i.e. the AUT Inspection Procedure).

In addition to the standard zone considerations, we need to consider the placement and details for volumetric targets. Consideration may also be required for transverse scans if stipulated in the contract as well as the sort of TOFD that would best be suited for the application. Some weld configurations will be ill-suited to a single zone target to address the full weld volume. For these conditions we must also look at the possible need for special targets (centreline).

4.1 DEFINING FUSION ZONES

In the general overview, of the zonal discrimination method, we indicated how the weld is divided into zones typical1y 1-3mm high and how beam angles are selected to optimise response off the fusion face of the weld bevel. It is not necessary, and not even normal, that all the zones in a zonal technique be equal in vertical extent. Much of the design is dictated by bevel shape. The root land and the "hot pass" in GMAW bevel designs are usually significantly different angles. Figure 4-1 illustrates two of the variations on GMAW weld bevels.

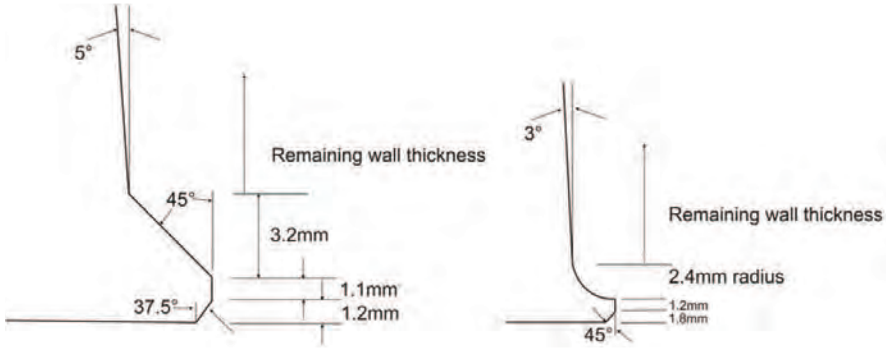

Figure 4-1 GMAW bevel preparations (exact heights and angles may vary slightly)

On the left in Figure 4-1 is the modified J-bevel (CRC style) and on the right is a typical version of the J-bevel. Most such welding configurations have a fixed set of dimensions for the lower aspects of the bevel and then the upper portion has a small fixed angle that extends to the applicable wall thickness.

With the consideration that the geometry is fixed for such a weld profile, it can be an easy matter of arranging a standard set of angles for the lower geometry and then simply adding on the necessary zones for the upper (fill) region. For example, the CRC bevel would always have root, LCP and lower and upper hot pass zones, note here that we will always assume the CRC configuration uses 2 hot pass zones. Some inspection companies have opted to cover this area in a single zone. When one considers that the 3.2mm vertical extent is actually composed of a surface 4.5mm long, it is much larger than any typical beam spot size used. Centring a single beam in the hot pass would risk missing unfused areas in the upper and lower corner regions of the zone.

Then, the number of fill zones would depend on the wall thickness. Similarly, the J-bevels would have the root and hot pass as a common shape. A similar treatment of the vertical and angled portions of the root could (and should) be used as was the case for the CRC with a root and LCP zone. The hot pass, being a simple radius, would typically have one portion that would be targeted and the straight small angled portion above would simply vary the number of fill zones used. Recently, with the advent of effective focussing by phased array probes, a small zone is often added at the top of the fill. This is an attempt to provide better discrimination between surface-breaking and subsurface flaws.

The root region of both the modified J and the J-bevels should have 2 angles of examination. In the J-bevel there may not always be the small chamfered face (shown as 45° in Figure 4-1). Even then a second angle should be used. This is because the root of a pipeline weld is in a fracture-critical position, i.e. flaws in this region could present a higher risk of failure. For the chamfered face we would try to arrange an ultrasonic beam to make a perpendicular incidence on the fusion face. For the 37.5° angle, illustrated on the root on the left, this would mean using a 52.5° refracted beam. For the 45° chamfered angle, of the profile on the right, this would mean using a 45° beam.

The vertical land is a common feature in most weld bevel preparations. It may be raised slightly above the inside surface as in the examples in Figure 4-1, or it may extend to the inside surface.

Contrary to some beliefs, the LCP region in the CRC bevel (or the raised vertical land in the J-bevel) does not provide a direct target for a pulse-echo technique. Instead, the sound path followed returns to the receiver via a "quasi-tandem" path. By this we mean a bounce is made off the vertical and then inside surface to return along a parallel, but off-set, path from the transmitted pulse path. Figure 4-2 illustrates the bounce-path taken by the centre of beam ray that would be aligned to detect this "imbedded" condition.

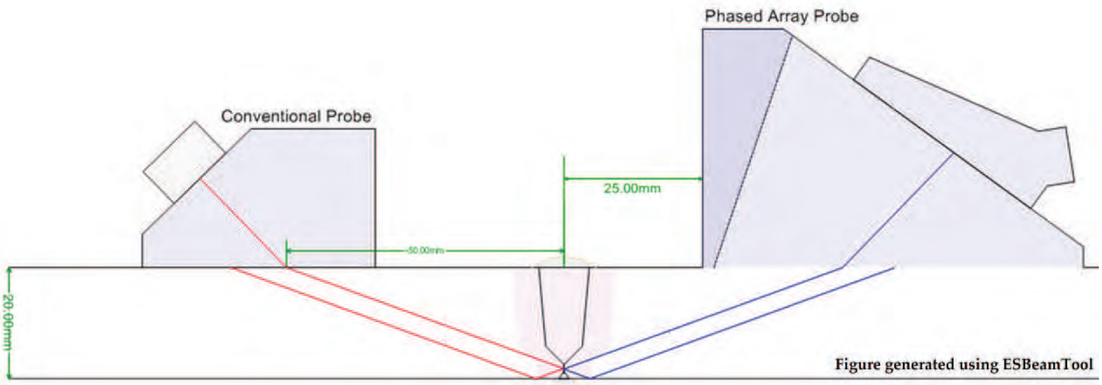

Figure 4-2 Quasi-tandem sound path for vertical land near root

Typically, this vertical land is inspected using a high angle shear wave beam (typically 65°-75°, a 70° path is indicated). The higher angles are more likely to be used on thinner material to allow the probe nose sufficient space from the weld cap. The single element option has always suffered from the inability to optimise on the off-set return path. Its positioning was always just a compromise to get a suitable signal from the reference target. Figure 4-2 shows the advantage of a phased array probe, where the probe can be configured to transmit with one group of elements and have another group optimise as receivers for the returned off-set path.

There was some thought that a direct path was being followed, but this would only apply to a tip-diffracted signal off the upper portion of the vertical flaw. The presence of the tip-diffracted signal can be seen under ideal conditions on the calibration target. Figure 4-3, a captured A-scan, shows the early arrival tip signal (from the 2mm diameter FBH target in 9.8mm wall pipe) and the much larger quasi-tandem signal arriving later.

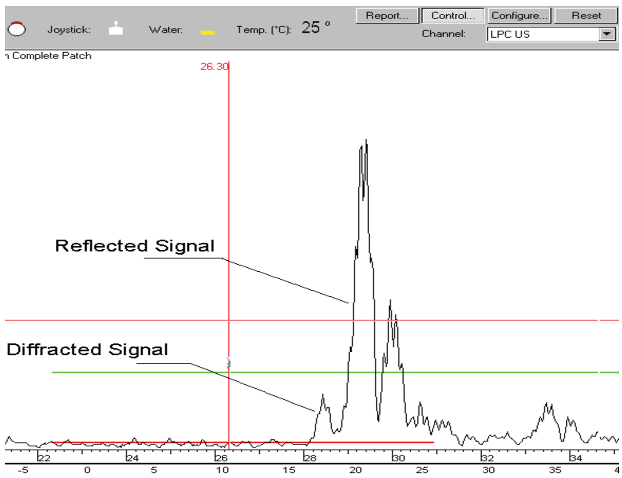

Figure 4-3 LCP target with tip and quasi-tandem signals

When inspecting the root bevel (chamfer) it was noted that an angle would be selected to try to make a perpendicular incidence on the face of the bevel. For thin wall (typically less than about 12mm) the exit point of a probe would be only about 12-15mm from the centreline. This is very near the cap edge, so it is common to use a 1.5 skip path for such conditions. The restriction of the cap and moving the probe back to the 1.5 skip standoff is indicated in Figure 4-4. For phased array probe placement the entire set of beams must be configured from a single probe standoff position. This would almost certainly require that the path for the root chamfer target be based on a 1.5 skip sound path.

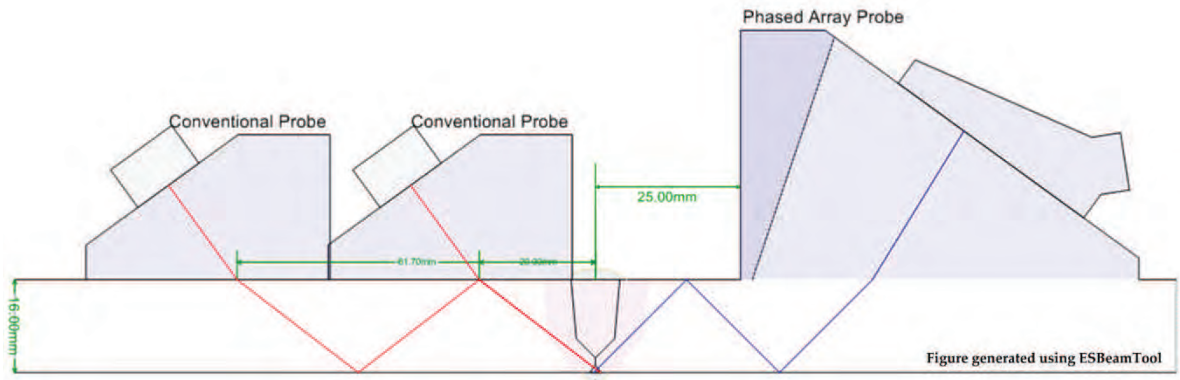

Figure 4-4 1.5 skip path for root chamfer zone showing conventional and phased array options

In both examples used in Figure 4-1 a hot pass region exists. This is a common welding pass in pipeline fabrication. In fact the hot pass seems to be a term unique to pipeline welding. It is derived from the manual down-hand welding technique. After the root pass is in place, it is generally very convex on the exterior side of the pipe. Normally the root pass is ground to eliminate the excessive convexity. The weld root is not entirely ground out, but only enough to expose “wagon tracks” (i.e. lines of slag that are on either side of the built up convex region). The purpose of the hot pass is primarily to burn out the “wagon tracks”. Ideally, this is achieved leaving the joint free of undercut and some filling of the joint is also accomplished. To do this, a high current is normally used making the process “hot”. In fact the electrode can overheat in the manual process. It is not clear if this is a truly equivalent case, if the welding process is mechanised GMAW where the root pass may even be deposited by an internal welding machine. In any case, in pipeline parlance, the pass over the root is traditionally termed the “hot pass”.

In the modified J-bevel (CRC) the hot pass is indicated as having a vertical extent of 3.2mm and depending on the process, the J-bevel uses a radius shape of about 2.5mm. In the J-bevel the radius merges with the straight portion of the small angle bevel, so the actual vertical portion of the hot pass may be slightly less than the radius. However, for the modified J-bevel (CRC) the hot pass is a flat surface on a 45° slant. This presents a 4.5mm surface length. For the radius condition of the J-bevel we can use a single flat-bottom hole target that is usually inclined at 45° and is tangential to the radius. In the chapter on zone separations we considered focussing methods and limitations. Beams for this application of AUT are typically focussed to about a 2.5mm diameter. This provides a spot size almost the same as the radius portion of the hot pass for a J-bevel. However, the CRC bevel would have a length greater than the spot size. This would risk that portions of the fusion face would not be fully covered at the correct angle to detect non-fusion. This is illustrated for the 2 weld bevel types in Figure 4-5.

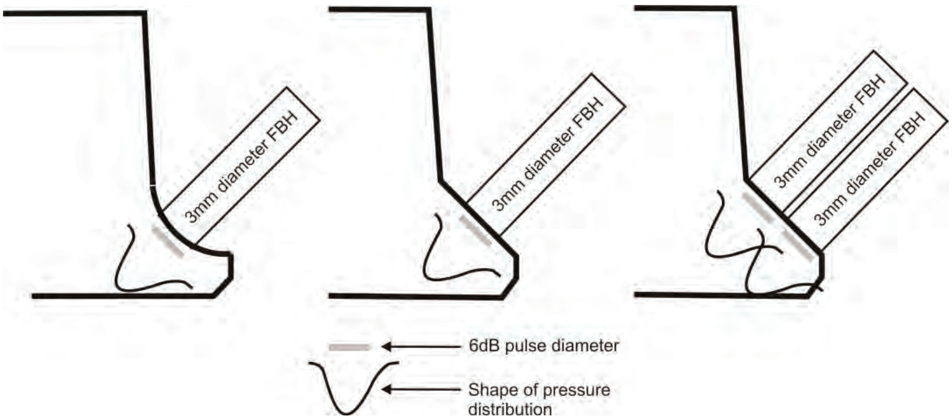

Figure 4-5 Hot pass beam coverage

In Figure 4-5 we have indicated three bevel profiles with rectangles representing a 3mm diameter flat-bottom hole. A grey bar is drawn indicating the approximate 2.5mm 6dB beam diameter and a curve is indicated to represent the pressure drop-off that would result as the beam is measured from an on-axis peak to the lowest pressures off-axis. The image in the middle of Figure 4-5 indicates how the pressure drop is inadequate to ensure that the entire hot pass is examined with just a single beam directed in the middle of the hot pass zone. The only effective option is to use 2 targets with the centres ⅓rd from each edge of the hot pass land (as indicated by the profile on the right in Figure 4-5). A similar concern for the poorly oriented beam relative to the lower part of the hot pass in the J-bevel where the bevel is nearly horizontal, has prompted at least one company to use a 2mm FBH target instead of the 3mm FBH used on the fill zones. This is an attempt to increase detection sensitivity to the poorly oriented surface.

It is worth noting that for the CRC style bevel, the lower hot pass zone requires a skip that is close to the point on the inside surface where the excess metal from the root pass occurs. If the root geometry has a small wander or is slightly wider, or if the guide band on which the probes are mounted is only slightly off the ideal position, it may result in portions of the beam entering the excess metal of the root instead of skipping off the smooth inside pipe surface. This causes annoying root geometry signals. To avoid this or to reduce the occurrence, it is common practice to now use an angle that allows a skip point farther from the root centreline. Most operators now use a 50° refracted angle for the lower hot pass and 45° for the upper hot pass. This has the effect of reducing the amplitude of the reflection from the target due to the 5° off-angle reduction in return pressure. Some extra gain is therefore required, making this a bit of a compromise, since adding too much gain would also result in sensitivity to the weaker off-axis components that were still able to drop into the root geometry. The small positional differences are illustrated for the two hot pass beams in Figure 4-6.

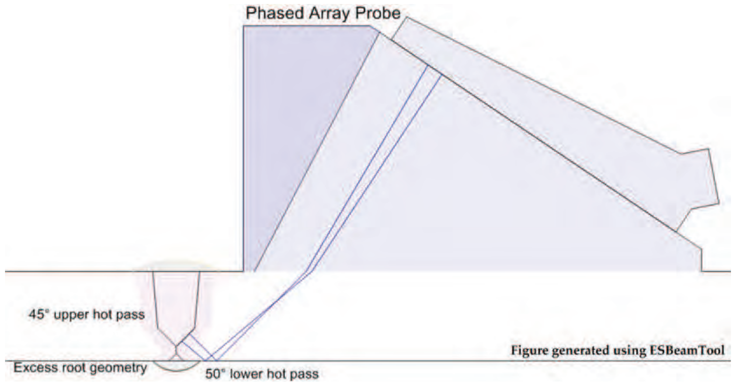

Figure 4-6 Accommodating root geometry for the lower hot pass zone

In the upper region, the small angle portion of the bevel completes the typical GMAW weld preparation. This angle is anywhere from 1° to 15° and is considered the fill region. It is usual to divide the portion above the hot pass into zones of equal vertical extents. The sizes of the zones are not fixed to a specific height. If they were this would usually result in a partial zone. The offshore pipeline code DNV OS F101 recommends that zones not be greater than a 3mm vertical extent. With the advent of improved focussing using phased array probes, an extra zone is often added at the outside surface of the pipe. This is typically fixed between 1.2-1.6mm. A 16mm wall pipe, with a J-bevel with zones as illustrated in Figure 4-7, would have 7 fusion zones and 3 volumetric zones.

Zone dimensions that are useful include the zone height and the depth to the bottom of the zone (depth to bottom is useful when indicating the depth to which a repair is required). Table 4-1 indicates the vertical extents and depths to the bottoms of the zones that could be used for the AUT inspection technique of the weld illustrated in Figure 4-7.

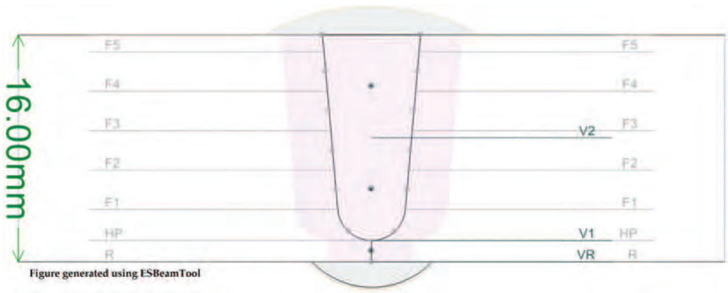

Figure 4-7 16mm J-bevel typical zones (including volumetric)

Table 4-1 16mm wall zone dimensions

Name	Height (mm)	Depth (mm)
F5	1.2	1.2
F4	2.78	3.97
F3	2.78	6.75
F2	2.78	9.53
F1	2.78	12.31
HP	2.19	14.5
R	1.5	16
V2	7.25	7.5
V1	7.25	14.5
VR	1.5	16.0

Software is now available to carry out these calculations, but guidelines are useful when doing this manually. Some of the zones are clearly a fixed value. The root, without a chamfer, merits its own zone (1.5mm). The hot pass is defined by the point the fill line intersects the radius (2.19mm). In a 16mm wall thickness this leaves 12.31mm. It would be acceptable to make 4 simple zones in this space, each 3.08mm high. For some applications, however, it is useful to provide a Cap Zone so as to aid in discriminating between surface breaking and subsurface flaws. A 1.2mm cap zone is about as small as can be had and still obtain adequate signal separation between the Cap Zone and the next fill zone under it. As with fill zone heights, the Cap Zone height can also be adjusted and has been set by different companies between 1.2mm to 2mm high.

If we insert a fixed height cap zone of 1.2mm, this height is subtracted from the 12.31mm of fill region giving 11.11mm. With 4 zones in the remaining 11.11mm, they are each 2.78mm high. Had we opted to divide the 11.11mm fill region into 3 zones, they would each be 3.7mm high. This is an excessively large zone and would not be useful for most applications. The importance of maintaining small zones is discussed later when considering acceptance criteria.

Therefore, when designing a technique for a specific bevel and pipe thickness, some judgement is required. Which option is used will require several considerations. These might include:

1. The acceptance criteria to be used on the project
2. Specific requirements of the customer
3. Vertical extent sizing techniques to be used (if used)
4. Bevel shape
5. Quality of the beam focussing achieved by the probes available
6. Wall thickness (path lengths)

The considerations for the geometry (shape and size) of the weld preparation and the probe quality are, unfortunately, variables that make this an empirical judgement. Any person designing the technique must have some prior idea of the capabilities of the probes being used. This knowledge is now more readily available as a result of system qualification requirements imposed by some agencies.

The entire zone discrimination technique relies on obtaining information from the separate vertical intervals. Yet, as noted, concerning the use of a 2-zone hot pass, the size of the zone might be too large and portions of the fusion face could be missed if the beam coverage is not matched to the zone size.

When discussing calibration setups we will later explain the recommended overlaps between zones. This has been touched upon, as demonstrated in Figure 4-5, where the two adjacent pressure curves are seen to overlap slightly. But, if the zones are too small, the overlap may be excessive and this will mean that the operator cannot decide which zone the flaw originates from. These considerations for zone separation should be addressed in the applicable Code or Specifications issued for AUT quality and may also be considered factors in how the information will be used with respect to the acceptance criteria for a given project.

We identified factors for technique development consideration that relate to the ultrasonic capabilities of a system. Focussing parameters consider how a focal spot in an unfocussed beam (i.e. from a flat element) is smallest at the near field distance and can be made smaller by focussing the beam to a shorter distance than the near field length. Therefore, any item that limits the ability to control the beam size will limit the ability to obtain good zone discrimination. For example, if a technique requires that the beam travel a long distance (e.g., very thick wall dimensions or very thin wall, where a multiple skip path may be required) it will mean that a large probe aperture and or high frequency is required to ensure that the near field is far enough away so that focussing at the fusion line will be possible.

The bevel shape also dictates how effective the zone separation of even a well-focussed beam will be. Beam dimensions are defined perpendicular to the beam axis. But for the small angle fill region most techniques will use some tandem configurations that employ an oblique incidence of the beam and rely on a bounce path back to a separate receiver (or separate receiving group of elements for a phased array setup). As a result of the oblique incidence, the angle made to the fusion face means that the focal spot dimension no longer matches the size of target zone concerned. Instead, it is the length of the hypotenuse of the triangle made with the fusion face that defines the "effective" spot size. This is shown in Figure 4-8.

Most techniques will have the beam, intersect the bevel, as it slopes with the top towards the beam and most will use a refracted angle not less than about 45°. This will result in the range of spot sizes being increased to an "effective" spot size of 1 to 1.4 times, the calculated spot size. This implies that for perpendicular (pulse-echo) incidence there is no increase in the calculated spot size due to projection, whereas for 45° incidence of the beam on the target plane there is an increase of 1.4 times the ideal spot size due to the projection of the beam angle at the intersecting face.

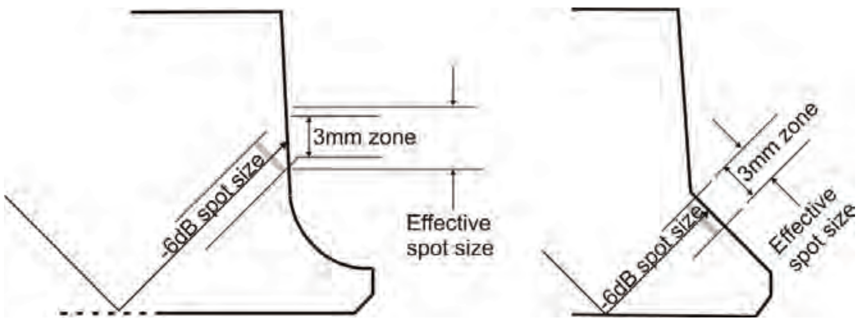

Figure 4-8 Effective spot size increase due to oblique incidence

The ability to separate the zones becomes more and more difficult with a small fill angle, long sound path to the point of fusion line intercept and small diameter or poorly constructed probes. For the example of a J-bevel with a 3° fill bevel in a 15.8mm wall, the sound path for a 45° beam increases as the beam is directed at depths farther along the second half of the skip path to the fusion line intersection.

There are two main items of concern:

1. The probe parameters need to provide a good spot characteristic to focus at the correct steel path
2. The zone size needs to be comparable to the "effective" spot size

Figure 4-9 indicates the 2 fill zone options. One is slightly larger than usually recommended and the other slightly smaller than is easily achieved by most focussing techniques. On the left are 3 fill zones, each 3.5mm high, and on the right are 4 fill zones each 2.6mm high.

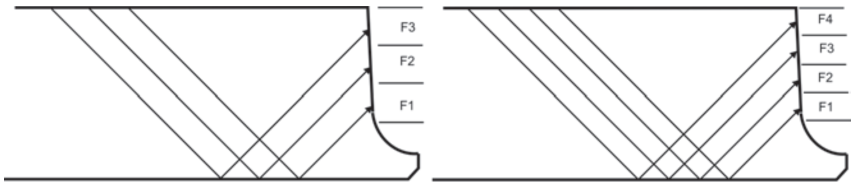

Figure 4-9 Fill zone options

To get a better understanding of the probe parameter considerations we will use a mono-element conventional probe. We can tabulate the steel paths for the beams and add an equivalent steel path distance to allow for the wedge path. Estimates are based on the wedge material being cross-linked polystyrene and having an acoustic velocity of 2350 m/s. For the purpose of this illustration, we will assume a wedge path of 10mm (this is equivalent to approximately 14mm in steel).

The considerations given will, for now, contemplate that a tandem configuration will be used in the fill zones. Figure 4-9 indicates a 45° refracted beam is used and directed to intersect at the midpoints of each of the fill zones for either a 3 or 4 fill zone on the 15.8mm wall with the 3° bevel. The term "corrected" in the Table 4-2 merely indicates that 14mm has been added to allow for extra time in the wedge. Values are rounded to the nearest mm.

Table 4-2 Tabulated data for probe selection

Zone	3-Zone: Corrected Steel Path (mm)	4-Zone: Corrected Steel Path (mm)
F1	46	45
F2	51	49
F3	55	53
F4	NA	57

A flat (unfocussed) 12.5mm diameter 7.5MHz probe has a near field length of 91mm in steel in shear mode. It also has a spot size of 3.3mm diameter. 3.3 mm would be considered too big a spot to use unfocussed, but having a 91mm near field it allows some room to focus the beam. The range of steel path differences tabulated is not too different from one zone to the next. The difference in range covered by the 45° sound paths to the targets is only 12mm (45mm to 57mm). It is very improbable that a probe manufacturer would make such small increments between radii of curvature in a lens or curved element. Although some refinement of focal spot might be possible using phased array focussing, the fact is that the focal "spot" is more like a fuzzy zone along the beam axis. Theoretical calculations are made based on a single frequency but most probes are fairly broadband so the frequency-dependent near field calculation makes this an imprecise position.

For single element probes where the element is curved, probe manufacturers in North America generally provide a probe based on a specified nominal frequency and the element curved with a radius of curvature (ROC). In North America the ROC is usually given in increments of "inches" that may be converted using a millimetre equivalent, e.g., 3 inch ROC, or a 75mm ROC, 5 inch ROC or a 125mm ROC. This is considered the "geometric focus".

Looking at Table 4-2 above, we can approximate the position where the focal distance should be, to the nearest millimetre. This would be near 50mm for most of the targets. Therefore a 12.5mm diameter 7.5MHz probe with a 50mm ROC might be an intuitive first trial for an effective spot size of the fill zone targets. But the beam from such a probe does not in fact focus at 50mm. Modelling indicates that the focus in steel for such a probe is at 20mm, this is indicated in Figure 4-10. The graph on the right is the amplitude distribution across the beam at focal point (20mm).

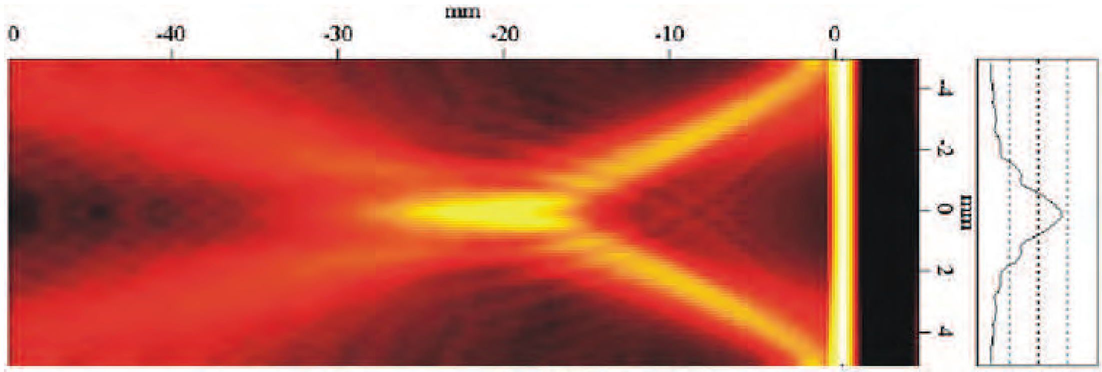

Figure 4-10 12.5mm diameter 7.5MHz 50mm ROC (shear mode in steel)

The reason for this non-intuitive alteration of the focal distance is because the calculation doesn't use a 1:1 ratio of focus to velocity units. This requires calculation of the focal distance, based on a ratio with velocity, so an ROC of approximately 2.25 times that of the 50mm should be used. This would mean that ROC or the geometric focus does NOT equate to actual focal length in the medium under test. This would be an important consideration when purchasing a spherically focussed mono-element probe. Therefore we could consider that a probe with some greater near field is required. The best practical way to do this is to consider a larger diameter element (since higher frequency than 7.5MHz is not practical for weld inspection by shear waves). A standard diameter in NDT might be considered 20mm. At 7.5MHz the near field length in steel for the shear mode of a 20mm diameter element is 234mm and has a 5.4mm diameter spot at that position. When focussed with a 125mm ROC the beam focuses as shown in Figure 4-11. The graph on the right is amplitude distribution across the beam at focal point (50mm).

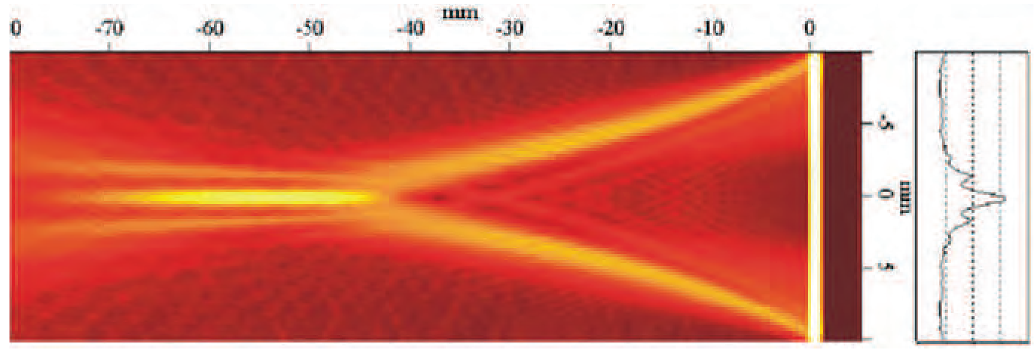

Figure 4-11 20mm diameter 7.5MHz 125mm ROC (shear in steel)

This focus provides a spot of only 1.3mm diameter at the area of interest (45-57mm along the steel path). It is conceivable that we could use a smaller diameter element and thereby have a lesser degree of reduction in the spot size from the natural focus (near field spot size). But this is done at the risk of working with a smaller concentration of pressure due to the smaller focussing effect of the off-axis lobes. But even with a 12.5mm diameter 7.5MHz probe some refinement of the beam is achieved as shown in Figure 4-12 where we see that the spot diameter is approximately 1.9mm. The amplitude distribution on the right indicates a weaker response in the focal region.

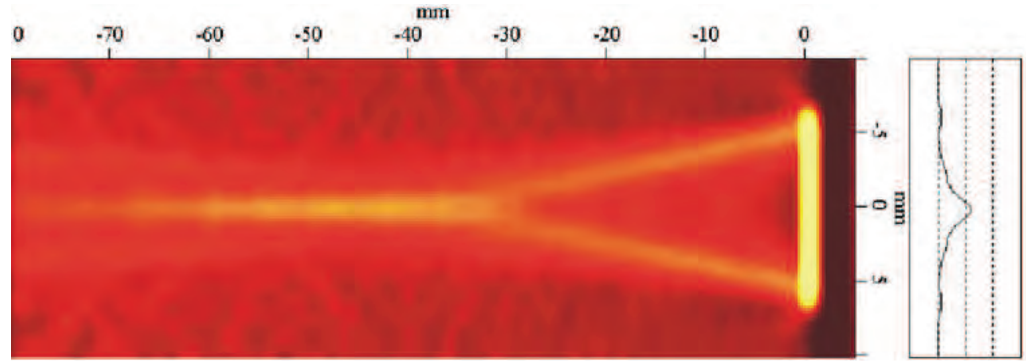

Figure 4-12 12.5mm diameter 7.5MHz 125mm ROC (shear in steel)

It is worth noting that similar treatment of focussing can be achieved with phased array probes. Modelling the beam from a phased array probe with an aperture of 13mm (i.e. equivalent to the 12.5mm mono-element probe), we identify the depth equivalent to the sound path range of interest (45mm to 57mm) or about 38mm depth at 45° refracted angle. The focussed beam produced is seen in Figure 4-13. It has a useful range of approximately 15mm, either side of the 50mm sound path, to the peak response.

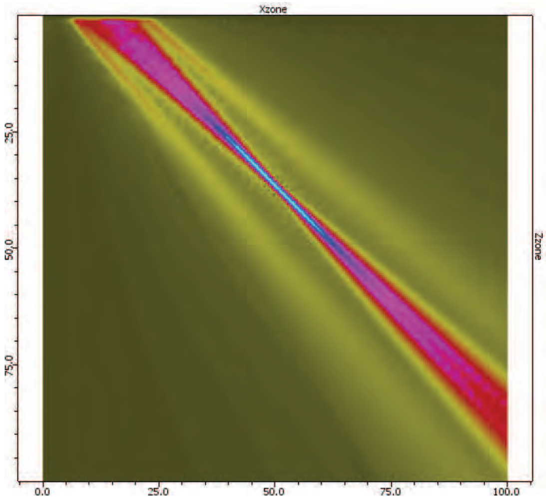

Figure 4-13 Equivalent phased array beam focussed at 50mm sound path

This apparent digression to spot sizes is again brought back to the concern for zone sizes. For the steel path distances of concern, in Table 4-2, we are now able to select a probe having a spot size between 1.3mm to 1.9mm diameter. Having determined that the refracted angle used for the 3° bevel is 45°, the beam would impinge on the fusion line at 42° from the perpendicular. The effective beam spot size as projected in the vertical plane can be calculated as follows:

$$S_{effective} = \frac{S}{\cos\theta} \tag{4.1}$$

Where;
S: Nominal Spot Size

For our condition, of a maximum spot size of 1.9mm and an angle of 42°, the effective spot size in the vertical plane is 2.6mm. It is now much easier to decide which zone numbers to select for the technique. The 3-zone option has vertical extents each 3.5mm. This is significantly larger than the effective spot size of the projected beam. The 4-zone option has vertical intervals 2.6mm. This matches the effective spot size. Although some overlap, of the pressure components less than 6dB down from the maximum, may contribute to the signals from adjacent zones, the overlap should not be too significant.

There is another consideration that will help us decide the zone sizes. In preparation for this portion of the technique, dealing with the fill zones, it was decided that a tandem approach would be used. This is typical for inspection of a near-vertical fusion face. Even if the cap geometry did not entrap the beam reflected from a buried non-fusion flaw, the tandem return path could not address the condition where the flaw was surface connected and not as deep as the centre of the beam (i.e. incomplete fusion at the cap or sometimes called missed edge). Such a condition creates a corner reflector which can provide a large amplitude signal. Although having a large upper zone, with the main target centred 1.75mm below the surface, would mean only off-axis portions of the beam could be used to detect missed edge that was limited to the upper 1mm depth. The tandem detection of the subsurface 3mm target is illustrated in Figure 4-14. The tandem path back to the receiver is not able to ensure that a signal returns to the receiver elements. Tandem configuration for large upper fill zone it must rely on off-axis beam to detect missed edge. As well, we will later discuss the issues of large zones and sizing accuracy for critical surface flaws when using fracture mechanics derived acceptance criteria.

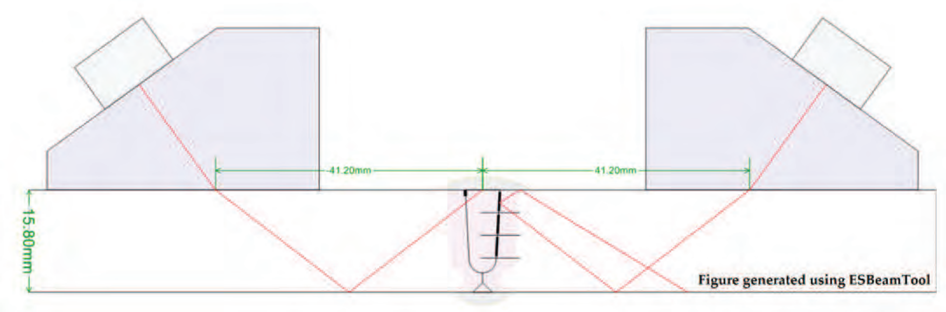

Figure 4-14 Tandem configuration for large upper fill zone

If smaller zones are used (such as the 2.6mm zones for the fills in Figure 4-15) there is a better possibility that the tandem path for the uppermost fill zone could detect small surface breaking flaws. This is due to the fact that the missed edges would be closer to the centre of the beam.

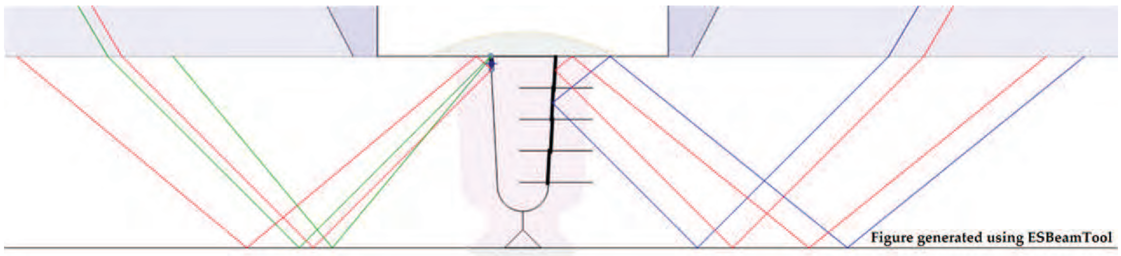

Figure 4-15 Upper corner detected by tandem when positioned for shallower position of smaller upper zone

Figure 4-15 illustrates 4 Fill zones with 3mm diameter targets (black lines on the right side of the bevel) and a phased array probe configured to detect the targets using a tandem path. However, now that the zones are smaller, the centre ray of the beam is positioned higher for the uppermost zone. This will provide a better opportunity to also detect the missed edge corner. Detection of the missed edge by the tandem path is illustrated by the rays on the left side where a small 1mm surface breaking target is placed.

Most GMAW bevels have the uppermost zone configured using a pulse-echo technique. Together with the smaller zone sizes, the pulse-echo beam provides a reasonably effective detection method for both the surface breaking and the slightly subsurface flaws, since even the slightly subsurface flaws provide a quasi-tandem path (similar to that described for the LCP) easily detectable in the pulse-echo mode. When discussing calibration signal analyses, we will see how sensitive the pulse-echo probe is to the surface breaking notch, as compared to the slightly subsurface flat-bottom hole (FBH).

With adequate focussing, as provided by the phased array systems, a small uppermost zone (1.2mm to 1.6mm) can be incorporated into the technique. This uses a tightly focussed pulse-echo beam. Sufficient zonal separation can be achieved, for the next zone down, using a tandem-configured beam.

Some have suggested that a high-angle compression wave be used for the uppermost zone. This is sometimes referred to as a creeping wave. It has had reasonable results in controlled environments but the signal quality is difficult to maintain in field conditions. Water for coupling is constantly moving across the face of the wedge. This usage results in surface waves causing noisy signals that often mislead the operator into thinking there are flaws, where none exist. Another problem with the high-angled compression wave is its poor ability to discriminate between surface and subsurface flaws. Most calibrations that use the so-called creeping wave are unable to separate the uppermost zone target, from the adjacent target, without resorting to the use of a very short gate to avoid deeper signals. This then prevents the detection of the region past the fusion line of the bevel.

In the foregoing description of the tandem configurations for inspecting the fill zones we addressed only the transmitted beam. To afford the smaller spot size provided by increased focussing it is best to try for a short sound path to the zone target. In a tandem pair of mono-element probes, with the transmitter forward and the receiver behind, the forward probe would usually have the shorter sound path to the target and thus would usually serve as the transmitter. The receiver can be an unfocussed element; however, work with phased array systems has shown that signal-to-noise ratio is improved when focussing is applied to the receiver elements as well.

When tandem arrangements are required the positioning of probes can be problematic for the conventional mono-element options. Mono-element probes require small adjustments of the exit points to maximize the signals from a tandem path. But with the need to mount each probe on a separate wedge to accomplish this optimisation, there comes a point where the transmitter and receiver cannot be spaced close enough to each other due to the physical limitations imposed by the wedge sizes. Phased array probes do not suffer this limitation because it is possible to select the transmitting and receiving elements such that they can even overlap.

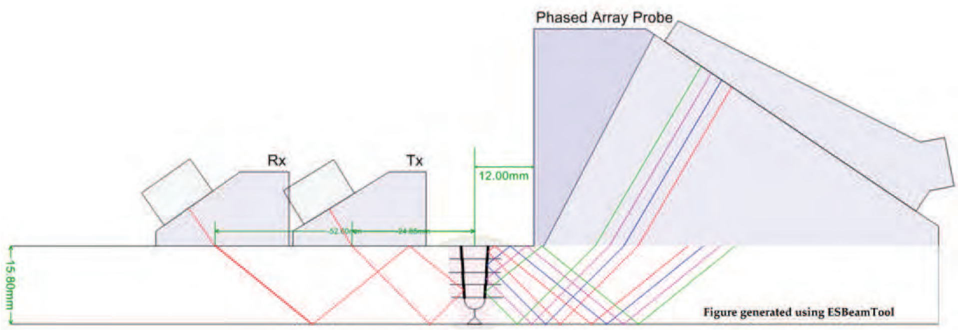

Figure 4-16 Single position for phased array probe can provide tandem path for all zones

Figure 4-16 illustrates how a single phased array probe addresses all 4 zones from a single position. On the left the tandem pair of conventional probes for Fill 1 has the front of the receiver nearly touching the back of the transmitting wedge. Some modification of the wedge shape or probe dimension might be possible, but at some point the exit point spacing will be too small to accomplish a tandem path within the shortest skip paths. The problem in this illustrated case occurs as early as Fill 2. Figure 4-17 indicates how the transmitter and received probes must be separated to accommodate the skip paths. The tandem path for Fill 1 is illustrated on the left. The overlapping probe positions for Fill 2 are indicated with the receiver positioned as Rx2 on the right. Rx2a indicates the probe position that would be used to accomplish the detection of the reflected tandem path from the Fill 2 zone. This indicates that a double skip path is required. The option can be viable but the reflected signal suffers from a large beam spread as compared to the single skip and is therefore much weaker.

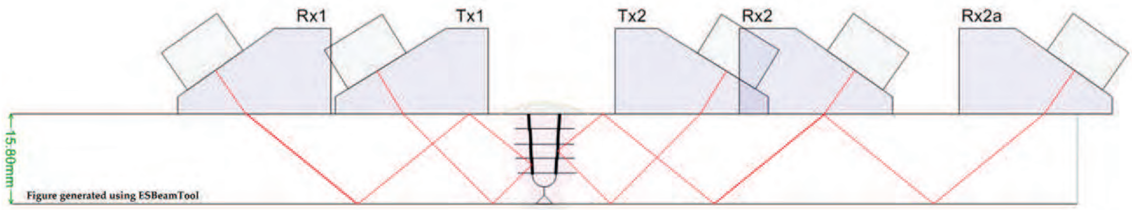

Figure 4-17 Double skip tandem path to receiver when single path space is inadequate

The close spacing of the transmitter and receiver elements could be considered one of the limitations of the mono-element probe systems as compared to the phased array systems. However, for thicker-walled welds, there can be a maximum limit to the spacing between the transmitter and receiver that can be accommodated by the phased array systems. This may require custom designing of the phased array probe or it may require that the affected zones are addressed by a tandem mono-element probe pair while the rest of the weld is inspected with the standard phased array probe.

4.2 VOLUMETRIC DETECTION

In the early 1990s one of the short-comings of AUT was its perceived inability to detect porosity. It was eventually determined that the flaw was in fact often "detected" but due to the irregular nature of the reflecting surface it provided a much lower amplitude response than the more serious non-fusion that had been the main concern for inspection of the GMAW welds. As a result of the lower response amplitude, it was often ignored because it was below the evaluation threshold.

Early efforts to assess porosity were burdened with the requirement to make AUT results compare exactly to radiography. This meant that the "projected area" of porosity was to be determined. But such a quantification of the flaw is not possible with AUT. In fact it is not even consistently assessed with radiography. When several experienced radiographers are given a radiograph of a weld with porosity and are asked to determine if the porosity is 3%, 4% or 5% of the projected area, it is rare to have all agree on which classification to use. In the end it is a qualitative, not quantitative assessment being made.

Early efforts [26] attempted to use an area relationship similar to that used by the Krautkramer AVG method to assess the reflective area of the porosity. This proved as inconsistent as radiography but it was apparent that porosity had to be characterised before any attempts at quantification could even be considered. The earliest imaging formats, as illustrated in Figure 2-5 and Figure 2-6, were poorly suited to characterisation of porosity, but the irregular travel times to reflectors in a mid-wall area did provide some indication that it was different from the non-fusion which was characterised with a constant time of arrival. In 1992, both Canspec (Edmonton, Canada) and RTD (Rotterdam, Netherlands) experimented with full waveform data collection. This became the tool that significantly improved characterisation of porosity. The B-scans, or mapping channels as they were called at the time RTD when scans did not actually save the underlying waveform but instead mapped the response as a simple bitmap-style image, were soon essential extras added to the data acquisition systems to assist in identifying volumetric flaws.

The zonal discrimination technique is mainly used as a method for estimating the vertical extent of planar flaws. But non-specular reflecting flaws (e.g., porosity and slag) are quite a different issue and suggestion that quantification of their vertical extent is moot. A study in the Cleveland Cardiac Clinic [27] used quantified pore concentrations from uniform micro-pores in a known volume. In spite of a difference of a factor of 5 between the lowest and highest concentrations of pores (100 to 500 micro-pores per cm^3) the maximum deviation between the amplitudes of the signals from these pores was less than 0.5dB and the relationship was not linear; e.g., 200 micro-pores per cm^3 provided a higher signal than 400 micro-pores per cm^3.

Amplitude responses from porosity are the sum of the interference phase effects between point emitters having interrupted a plane wave front. Even when the pore sizes are identical, as in the medical studies, the distribution pattern will cause the interference pattern of the reflected wave to be variable.

The preferred technique for porosity identification now uses 1.5mm diameter flat-bottom holes (as initiated by NOVA Pipelines about 1995). But this is not used to establish a separate zone channel. Instead, the target merely sets a position by which the beam can be assured of providing coverage in the correct region. Gain is added to bring the 1.5mm FBH to 80% and the colour palette for the B-scan selected such that low-level noise is not causing an excessive background.

Porosity detection cannot be considered with the same sort of go/no-go philosophy that the fusion line flaws are treated. Unlike fusion line flaws that occur at a predefined time along the sound path, porosity can occur anywhere from the Heat Affected Zone (HAZ) on the probe side to the HAZ on the opposite side. As well, the pore (s) may be distributed at considerable distances off the beam centre axis. All these factors indicate that the amplitude of the response from a single pore can provide no assurance of its size. Even a cluster of pores cannot be assessed for severity by simply looking at the integrated amplitude response since the reflected interference pattern may be constructive or destructive and off-axis components could be weak, merely by their position in the beam, as opposed to their size being small.

Since the first application of this technique was on relatively thin wall, the specifications for volumetric targets were simple. For wall thickness less than 12mm, a root and mid-wall target at half the wall thickness were used. For thicknesses over 12mm the mid-wall target was changed to 2 mid-wall targets at 1/3 and 2/3 depths plus the root notch or FBH. It is conceivable that the root volumetric channel could use a separate probe and a different FBH target, but more often the root probe for the fusion line was used. This would be fired as a separate channel with about 6-8dB more gain than that in the zone channel. Since extra gain was used and the fact that a colour palette with a low colour threshold level was used, the off-axis sensitivity of the probe was effectively increased. The mid-wall targets have almost always been 1.5mm diameter FBHs, angled at 45° and having the FBH centre on the weld centreline. The best probe angle for these targets was a 45° refracted shear wave. Depending on the system, the probe frequency is between 4MHz to 7.5MHz. One company has used a variation on the 45° standard target. They opted for a 50°, 1.5mm FBH that was configured to be detected in the first half-skip for the lowermost volumetric target.

As wall thicknesses being inspected increased on AUT projects, it became apparent that the 1/3 & 2/3 hole positions would not provide adequate volume coverage in all cases. Even though most systems use some form of a divergent beam (flat element), the vertical beam spread of a probe has practical limitations. Figure 4-18 shows a divergent beam approaching a typical 45° inclined volumetric target. The 20dB beam edges are represented for a 12.5mm diameter 5MHz probe. These have a divergent half angle of about 3°. By the time the beam reaches the target, it has a width approximately 6.4mm across. However, when projected to the vertical (as we did for the tandem receivers) the 45° beam angle interacts over a vertical extent of approximately 8 to 9mm. This dimension varies with distance travelled and the actual divergence characteristics of the beam. If we are working in a range of wall thicknesses of 25mm and using a separate beam for the root area, three such beams can provide a reasonable coverage of the vertical cross-section, i.e. approximately 4mm for the root volumetric and about 8mm for each upper volumetric probe (with allowance for some overlap). This is an empirical guideline. In reality, the spacing of the volumetric beams will be based on the ability to detect the adjacent volumetric targets in the calibration block to ensure that the desired coverage is obtained. This is then verified by small amplitude responses from the adjacent volumetric targets displayed on each volumetric display.

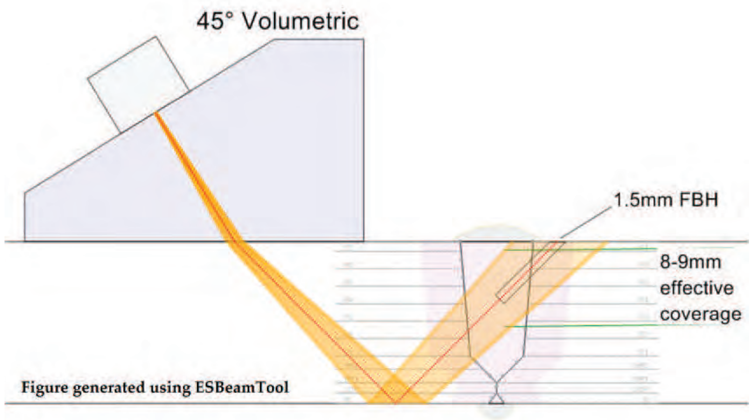

Figure 4-18 Approximate vertical coverage by a volumetric probe

For a fairly thin wall (e.g., less than about 10mm) it is reasonable to design a technique that has only a single upper volumetric channel in addition to the root volumetric channel. This might be placed approximately halfway through the thickness from the outside surface. For thicknesses over about 20mm, volumetric coverage is best addressed with a minimum of one volumetric fill channel for every 8mm of wall thickness, e.g., for a 32mm wall thickness, 4 volumetric channels plus the root volumetric channel would be recommended.

For wide opening weld bevels (e.g., single V 60° included angle) the coverage for volumetric detections may not be adequate with a single line of targets at the centreline. Wide open V bevels may require an extra set of targets offset from the centreline to assure that the upper volumes near the bevel are also being addressed.

More details on the arrangements for volumetric coverage will be addressed in the descriptions of calibration block designs and on calibration scan analysis to show how volume is verified by seeing the targets above and below.

4.3 SOME TRANSVERSE IDEAS

The GMAW process has been designed to minimize the occurrence of cracking when all the welding parameters are correctly adhered to. However, there are some occasions where the process controls are not well controlled or there may be other applications where AUT is used but when GMAW is not the welding method. In those cases there is a risk of crack formation. When the cracking is parallel to the weld axis, the standard probe configuration for zonal discrimination is usually adequate to detect the crack, especially when augmented with TOFD. However, when the failure is transverse to the weld axis, the reflecting area of the flaw is incorrectly oriented to be detected by the standard configurations; even TOFD will not be able to ensure a useful detection signal when the beam is directed parallel to the flaw axis.

A transverse crack can have several causes. Some people may group transverse cracking as a form of cold cracking as it is normally formed after the weld metal has solidified [28]. These are also considered a form of hydrogen cracking due to the presence of dissolved hydrogen in the material in many instances, where the transverse cracks originate. Hydrogen cracking, also known as cold cracking or delayed cracking, occurs in ferritic weldable steels; generally occurring immediately after welding or a short time thereafter, but usually within 48hrs

On breaking open the weld at a cold crack, the surface of the crack is normally not oxidised, even if they are surface breaking. This indicates they were formed when the weld was at or near ambient temperature. A slight blue tinge may be seen from the effects of preheating or welding heat. Transverse cracks originating in the HAZ are usually associated with the coarse grain region. The transverse crack can also occur with rapid cooling of the weld and HAZ of high carbon or high alloy steels as well as when excessive joint restraint exists.

Therefore, although the GMAW process is not normally prone to transverse cracking, there may be times when the engineering concerns dictate that it should be monitored. In AUT applications this will require special probe configurations. Due to the concerns for consistency of sensitivity and the need for coupling checks there are only a few practical options for an AUT setup to include transverse scanning.

The ideal condition for any ultrasonic inspection is that the weld cap be removed. This ensures easier probe approach to half-skip inspections, avoids misleading geometry signals and allows full surface access for a transverse scan. Although such a condition is very rare in pipeline construction, there may be some welds where concerns for fatigue or other environmental concerns could rationalize the removal of the stress raiser formed by the weld cap. Such a condition would permit one or more probes or one or two linear phased array probes to be positioned straddling the weld and configured to monitor for surface breaking transverse cracks. Such an ideal condition is indicated in Figure 4-19.

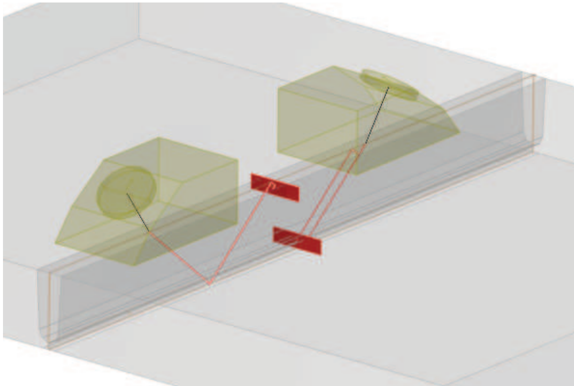

Figure 4-19 Transverse scans with no weld cap

In Figure 4-19 the probes are symmetrically placed with respect to the beams. Both can be used to gate the inside and outside surfaces. Moreover, by suitable spacing, the fact that they are facing each other allows them to be configured to provide coupling checks.

When the weld cap is not removed the only option that permits a suitable method for coupling check is a pitch-catch configuration with the probes straddling the weld and skewed anywhere from 30° to 60° from the weld axis. This configuration, shown in Figure 4-20, relies on a backscatter from a transverse reflector for the flaw detection and a through-transmission to the opposite element of the other transverse pair to verify coupling. Illustrated are 2 probe pairs straddling the weld cap, along with ID and OD notches positioned to show which way the beams are configured to redirect the transmitted beam back toward the receiver on the opposite side of the weld.

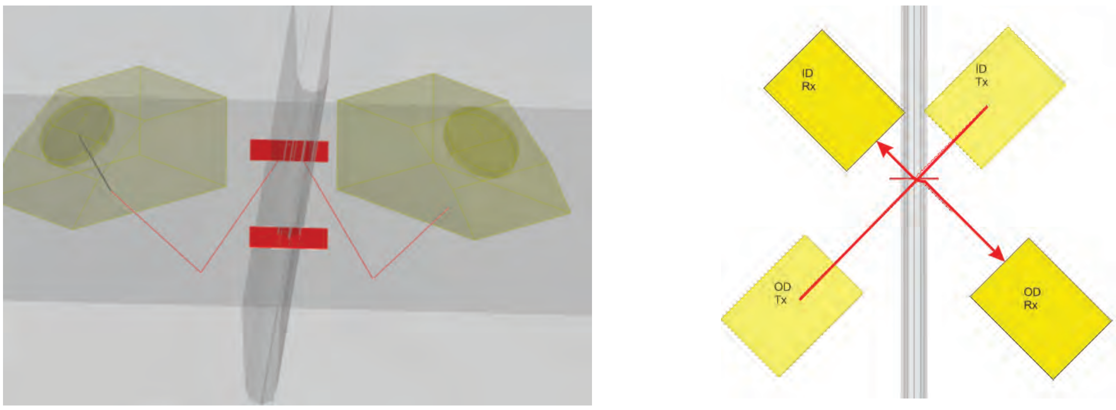

Figure 4-20 Transverse scans with weld cap

Both the techniques indicated are configured to detect corner reflectors breaking either the inside or outside surface. Except for very thin wall pipe (e.g., <12mm) neither technique can adequately provide coverage for a mid-wall transverse flaw that does not propagate to one of the surfaces. This would require a series of tandems for each interval of vertical extent in the weld as is used for the near-vertical bevels along the fusion line. Some caution must be used here lest the concern for a low probability flaw creates an unnecessary burden on the inspection system. If a system is designed to treat the transverse direction in the same way that the axial direction is inspected, many false calls could result. A common flaw in welding is a short transverse non-fusion called a "stop-start". These can occur anywhere in the weld and can have the same ultrasonic characteristics as a small transverse crack might have. Moreover, it should be noted that the transverse crack is also considered a delayed crack and may take up to 48 hours to occur. When AUT, or any NDT, is completed only minutes after the weld is completed, the possibility still exists that the delayed action can occur after the inspection. Some precautions can be taken, by adding the transverse scan, but should not be considered 100% assurance against a flaw that has potential for delayed formation.

4.4 ADDING TOFD

The Time of Flight Diffraction (TOFD) technique has been around since the early 1970s but has not received the recognition that it perhaps merits. In some circles of the NDT industry it has been touted as something of a "solution for all problems". In fairness, it can provide excellent detection for many flaws, and in some situations it is even adequate as a "stand-alone" NDT technique. At an early date in the development of AUT, using zonal discrimination, it was suggested that TOFD could replace the zonal technique. However, the limitations of near surface detection and the time required to size flaw heights using the tip diffraction sizing algorithms, made it less attractive as a stand-alone technique for pipeline girth weld inspections. In the mid 1990s, RTD of Rotterdam began using a TOFD module with their Rotoscan inspections. It was an extra cost, as they ran a separate programme to address the TOFD (RotoTOFD). It was apparent that the TOFD did not improve speed of inspection nor did it add significant sizing accuracies to the fracture mechanics technique being used at the time. However, it did add a much better method of identification of potential false calls. The presence of mismatch (high-low) and certain cap and root geometry signals was often being incorrectly identified as rejectable conditions when using just the zonal probes. Adding TOFD virtually eliminated the false calls and still provides the "potential" for improved sizing under some conditions.

For most pipeline wall thicknesses a single TOFD pair is adequate. Thick sections (e.g., >35mm) could take advantage of 2 TOFD pairs; one for the upper 12-15mm and a separate one for the remaining wall. Phased array systems now often incorporate a dedicated TOFD pair of mono-element probes (typically 15-20MHz) and configure a separate phased array focal law using the phased array probes at 7.5MHz. Oddly, it is the lower frequency probe that is often seen to be more sensitive to the near surface breaking indications; this is probably due to the increased beam spread of the lower frequency. Depending on the project needs, two zone TOFD techniques could also be used on thinner wall welds (i.e. >15mm).

Both conventional single element and phased array probes have been operated in AUT TOFD applications. Early efforts used relatively large, low frequency, poorly damped probes (e.g., 10mm diameter, 4MHz with 3 cycles). This creates a dead zone of nearly 10mm, in some applications. For a 15mm wall thickness this would allow only the bottom 5mm to be assessed and even that would be poorly assessed due to the long ring-time. Today, most AUT systems prefer smaller diameter, higher frequency and highly damped probes. Typically a single element pair would be matched at 3mm to 6mm diameter, 10-20MHz and a single cycle (i.e. >90% bandwidth). Phased array systems are capable of using a small number aperture (6-7 elements), but they are limited to the same nominal frequency as the other focal laws used for the zonal discrimination. If they require improved TOFD, phased array systems are equipped with the ability to address "dedicated" mono-element TOFD probes having higher frequencies and different dimensions.

TOFD is considered a non-amplitude technique but some minimum and maximum sensitivities must be established and a method of duplicating scan level from system to system should be incorporated into the procedures. TOFD sensitivity may be configured by setting the amplitude of the lateral wave or by setting the response off a calibration target such as a tip diffractor or a side-drilled hole.

4.5 SMAW AND SAW NEEDING VERTICAL TARGETS

AUT has been used on shielded metal arc welding SMAW (or manual "stick" welding) since the early 1990s. Since the welding process is manual, AUT cannot perform a true "process-control" and its function reverts to that of the traditional check on workmanship that radiography previously provided. But the sort of flaw most commonly found in SMAW is not the fine non-fusion that is the concern in GMAW. Instead, slag, hollow bead, porosity, etc. are the common flaws. These are, for the most part, volumetric flaws. Since the orientation of flaws in SMAW is therefore more likely to be random, certain differences in AUT configuration are recommended. One is to use a slightly higher sensitivity. This can be accomplished by calibrating on 1.5mm or 2mm diameter FBHs or using lower amplitude for an evaluation threshold.

Another significant difference between GMAW and SMAW welding is the bevel shape. "Automatic welding" using GMAW is sometimes referred to as narrow gap welding. This is seen to follow from the very small bevel angle in the fill regions. With a J-bevel having a radius in the hot pass region of on the order of 2.5mm, it means the opening at the hot pass can be as small as 5mm when the land faces are made to contact. With only a 1° or 3° bevel angle above the hot pass, even a thicker wall pipe may have an opening of only 6-7mm at the outside surface. But a manual preparation is typically a 60° included angle to a small root land as indicated in Figure 4-21. The welding rod diameter is not a thin piece of wire but has some dimension, typically 3-5mm across, to allow for the required flux coating. This requires enough space that the manual operator can place the rod at the bottom of the weld without risk of accidentally striking the arc too far up the bevel face.

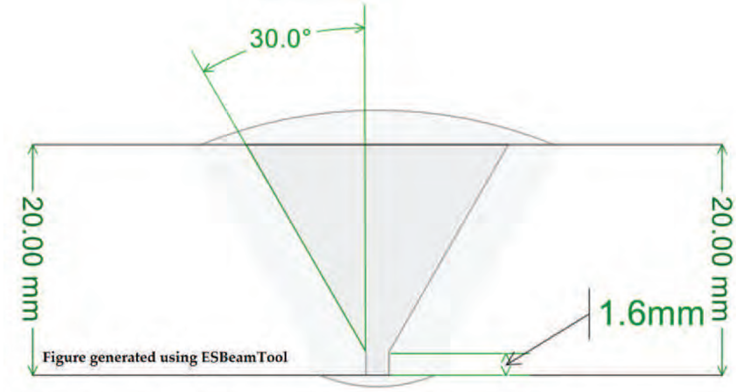

Figure 4-21 A typical manual welding bevel preparation

In a GMAW inspection configuration the weld centreline is never very far from the theoretical fusion line. Contrasting this, the 60° included angle in a typical SMAW weld ensures that as the pipe wall gets thicker, the beam, that is intended to cover the fusion line, has more and more difficulty making a good approach to the centreline, thus ensuring the full volume coverage required by code. This is shown in Figure 4-22.

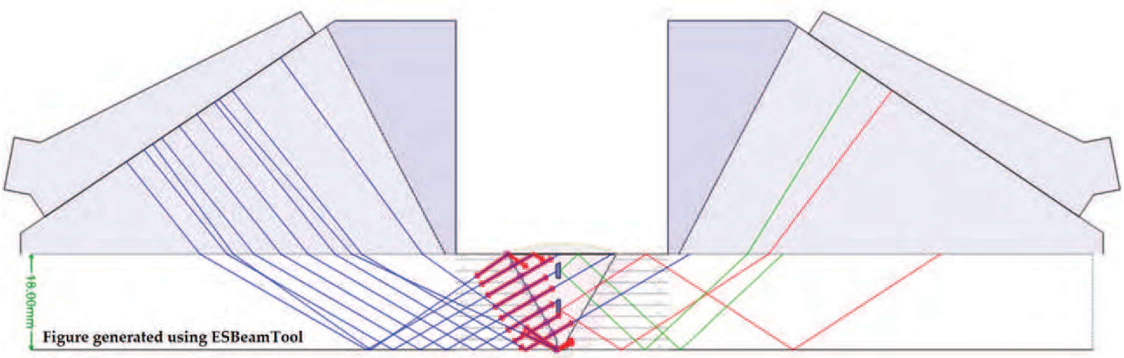

Figure 4-22 Fusion line beam path inadequate for pulse-echo return path from centreline in SMAW

A flaw on the weld centreline that is vertically oriented would be unlikely to be detected by the standard pulse-echo techniques optimised on the bevel fusion face. Even though the gated region may cover the distance well past the centreline, the beam is reflected upwards off a centreline vertical flaw and does not provide a direct path back to the probe.

When this problem occurs it is advisable to add one or more dedicated centreline channels to the inspection technique. These would be positioned where a potential centreline flaw could be missed by a specular reflection from the fusion line beam. It would use a tandem configuration to ensure that any centreline flaws have a receiver optimally positioned to detect the re-directed beam. Due to the wide opening and relatively large included angle, similar concerns can be seen in some compound bevels including those where submerged arc welding (SAW) is used for some or all of the joining process. The placement of special centreline targets in a SAW weld setup is illustrated in Figure 4-23.

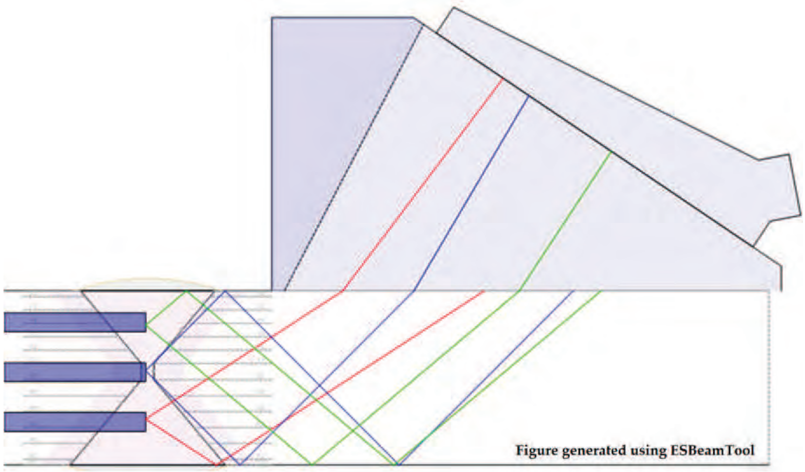

Figure 4-23 Centreline targets for SAW weld