ULTRASONIC INSPECTION OF PIPELINE SPLIT-TEES

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Abstract: For repair and hot-tapping of pipelines in the field, often so-called repair sleeves or split-tees are used. These consist of two semi-circular pipe segments, joined by two longitudinal welds and attached to the pipe by two circumferential fillet welds.
Whereas the Time of Flight Diffraction (ToFD) method is successfully applied for inspection of the ***longitudinal*** welds, NDE possibilities for the circumferential ***fillet welds*** are limited. Radiography is not an option, a.o. because of the thickness variations. The weld's complex, varying geometry prevents a reliable volumetric ultrasonic inspection.
N.V. Nederlandse Gasunie and Röntgen Technische Dienst bv in The Netherlands are conducting a modeling study in order to optimize parameters for inspection by ultrasonic phased arrays and ToFD. The ultimate goal is to achieve a level of NDE reliability for these welds that is comparable to that of circumferential butt welds. The presentation will highlight some results and provide an outlook on the implications of split-tee fillet welding and NDE.

Introduction: In The Netherlands, manual ultrasonic examination of circumferential fillet welds of assemblies used for repairs and hot-taps on gas transport pipelines became mandatory early 2003. This decision was related to failure of a split-tee fillet weld in November 2002. Before 2003, the examination requirement of these fillet welds had been Magnetic Testing only.

Pipeline repairs and hot-taps are usually performed on gas transport pipelines during operation, meaning that the pipeline is under full (gas) flow and pressure. The presence of the gas flow results in extremely high cooling rates during welding. Special precautions are taken to ascertain that possible weld defects will not result in cracks that propagate into the original pipe wall. These measures include optimized welding procedures and consumables (if anything fails it will be the weld rather than the pipe's parent metal). In addition, welders are especially trained for this activity. Their skills are annually tested within a recertification scheme.

After manual UT became mandatory early 2003, an NDE procedure was developed covering the perpendicular fusion line (between sleeve and weld) only, using standard pulse-echo UT probes (45 and 60°) and an arbitrary sensitivity setting using the DGS approach using a 2 mm dia flat bottomed hole as a reference reflector. Performance level of this approach was evaluated by means of a Round Robin test covering four fillet welds and five UT operators. In this exercise, not only the intended artificial defects were detected but also many typical fillet weld-related small non-relevant imperfections were found. In practice, this result could lead to unnecessary repairs, which could represent a safety risk by itself.

In order to improve the quality level of UT on split-tee fillet welds, a computer modeling study was initiated as a joint effort of N.V. Nederlandse Gasunie and RTD bv. This study is performed in two stages:

- modeling performance of UT based on conventional probes as a function of geometry, defect type/size and probe angle; this part of the study can directly be compared to practical experiments performed on test welds, thus validating the model;
- using the model to optimize NDT parameters, in which exercise also phased arrays and Time of Flight Diffraction techniques are included. This aims for a full volumetric examination.

This paper summarizes results of the modeling study, experiments and preliminary conclusions for future split-tee welding and NDT. The typical geometry of a split-tee fillet weld is shown in fig. 1. Fig. 2 shows a split-tee during welding in the field.

Fig. 1: Typical Split-tee in lab. Photograph: Gasunie.

Fig. 2: Split-tee during welding. Photograph: Gasunie.

In-service welding of pipelines: There can be two reasons for welding on pipelines under operating conditions. Firstly, the need to make a branch connection by a split-tee or so called "weldolet" ("hot tapping"). Secondly to repair a pipe that has been locally corroded or mechanically damaged by using a "repair sleeve". What these two constructions have in common is the presence of two circumferential fillet welds to connect the split tee or repair sleeve to the pipeline.

Metallurgically, these welds are of main concern. The gas flow results in extremely high cooling rates, with hard and brittle heat affected zones in the parent pipe metal as a consequence. In addition, the fillet weld configuration itself is more crack sensitive compared to the relatively small pipe wall thicknesses, because of its typical shape and constrained condition caused by the relatively heavy wall of the split tee or repair sleeve. Although pre- and post weld heat treatment could be carried out to improve the weld's quality, these measures are impractical and costly. Also, avoiding burn through, high heat inputs softening the pipe's heat affected zone are not possible.

Despite all these challenges, Gasunie has successfully welded hundreds of hot tap and repair sleeves during the last few decades, on pipeline material qualities varying between the old high carbon API X 52 (carbon equivalents up to IIW 0,51) and the modern thermo-mechanically treated high-strength X70 materials. For instance, heat affected zone hardening in old pipe material could excess almost 500 HV under rapid cooling and low heat input conditions, nevertheless still weldable without any (cold) cracks! Successful welding under these extreme conditions was only possible by especially trained welders, well-balanced weld procedures, sound weld bevel design and proper quality control of all relevant parameters.

The success of the weld process itself is mainly featured by its especially developed weld consumable. Extreme low hydrogen ($\leq$ 2,5 ml/100 gr), low yield ($\leq$ 425 N/mm2), low carbon ($\leq$ 0,01 %) and high toughness are the most important properties of the weld metal deposit, avoiding (delayed) cold cracking. In addition, temper bead welding softens the pipe's heat affected zone to a more acceptable hardnesses in the range of 350-400 HV.

Despite these preventive measures, failure rate of hot tap and split-tee repair welding is in the range of 10^{-3} - 10^{-4}. This performance level may be sufficient in many cases, but increasing awareness of (societal) risks demands better performances, equivalent to the acceptable failure rate of pipeline construction girth welding of about 10^{-5} - 10^{-6}, at least. Therefore, Gasunie aims to improve the integrity level of hot tap girth fillet welding with a factor of 100. Complete volumetric inspection of the girth fillet weld, including heat affected zones at the weld toe, underbead parent pipe metal zone and vertical fusion line should contribute to this enhanced performance level. In practice, this means that the Probability Of Detection of a new volumetric inspection technique should achieve more than 90%, preferably higher. This challenge is the main drive to support the development of advanced NDT techniques such as ToFD and Phased Array, to inspect these critical fillet welds.

The typical geometry of a split-tee or repair sleeve fillet weld is shown in fig. 3.

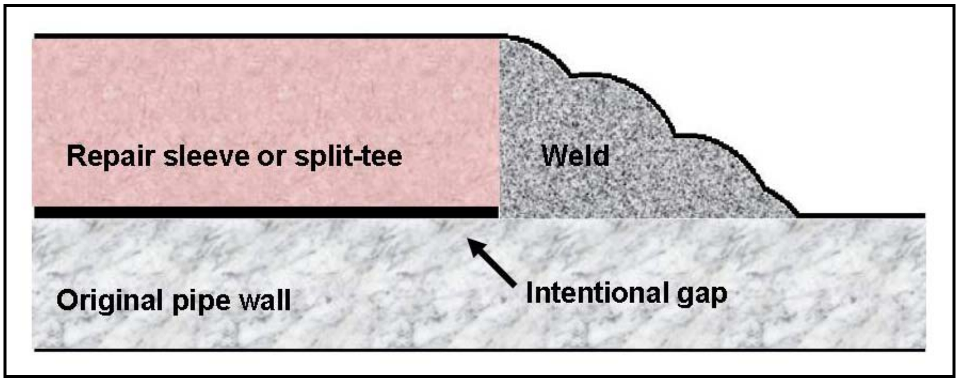

Fig. 3: Typical split-tee geometry

Description of the model: In the frame of another project "Phased Array Imaging", carried out by RTD bv in cooperation with Delft University of Technology, a model has been developed that will be used to develop and optimize imaging of weld defects using Phased Array technology [1]. This model is based on a finite difference scheme, and was developed in a MathLab environment. Unlike other (acoustic) models, this model is an elastic one and takes into account all possible reflected and mode converted signals that can occur during travel of an ultrasonic wave front through solid material.
Of course, the fact that the model is two-dimensional prevents that defect length is taken into account. The model assumes defects to be longer than the beam width in lateral direction.
The model enables implementation of any geometry in a two-dimensional plane. The object's boundaries can be defined as "hard" (reflective) or "soft" (absorbing) for ultrasonic waves. Reflectors of any shape, dimension, orientation and nature can be built in. Parameters such as ultrasonic frequency, resolution, element size, range and defect characteristics can be varied. The model provides visualization of the moving wave front as well as energy distribution in the beam and in the component. In addition, the A-scan is calculated, providing information on signal amplitude, transit distance and signal shape. Measurements on given reflectors can be scaled to a reference reflector, the same way a calibration prior to a real ultrasonic inspection is performed. Amplitude scaling can also be performed off-line.
Once all parameters have been set, each simulation typically takes two hours on a 3 GHz Intel Pentium 4 PC with 1024 MB of memory. Series of simulations, for instance where a full scan over a defect is required between half and full skip, the same way an ultrasonic operator would scan, take a few days to calculate. The position increment in this case is typically 1 mm.
Simulation parameters used: In phase 1, where the primary objective was the evaluation of conventional UT performance, the following parameters were varied:

- Two typical geometries, within the boundaries of visually acceptance were selected: “ideal” and “irregular”;
- Two typical sleeve thicknesses were chosen, 10 and 18 mm;
- UT probe parameters were derived from standard angle transducers of 45, 60 and 70°, 4 MHz;
- Lack of fusion type defects in the fusion line between repair sleeve and weld were used, under 90 and 45°, with varying height, as well as underbead defects at the toe of the weld and slag-shaped defects.

In fig. 4, the situation and the primary parameter settings (starting conditions) for the simulations on the thinner sleeve (10 mm) on the “ideal” geometry are shown. In fig. 5, the geometric parameters and defect types (boundary conditions) are shown. For this figure, a macro photograph of a split-tee fillet weld was used. Varying all combinations of these parameters, the total number of simulations amounted to approx. 200.

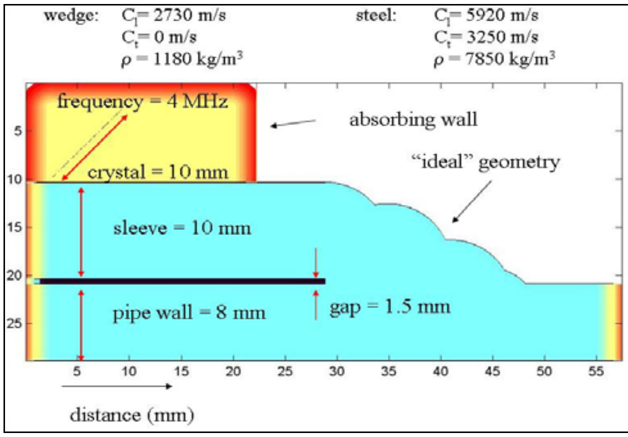

Fig. 4: Ultrasonic and material parameters

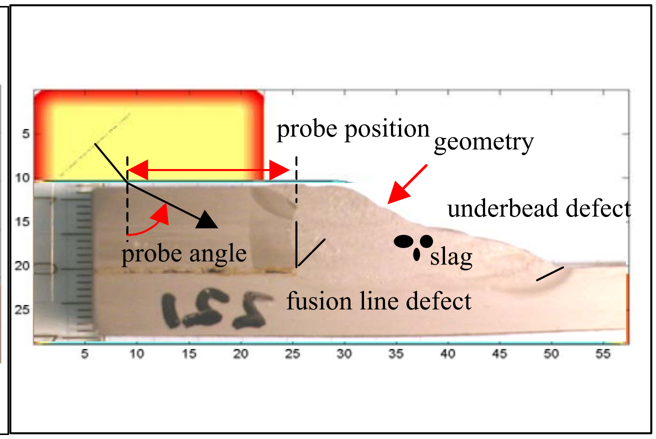

Fig. 5: Geometric parameters and defect types

Round-Robin tests: The results of phase 1 modeling were compared to the outcome of a series of inspections (round robin test) on four representative repair sleeve fillet welds with sleeve thicknesses of 10 and 18 mm. These welds contained multiple defects. The round robin test involved five UT level II ultrasonic operators, who inspected the welds according to the same written procedure. Sensitivity was based on 2 mm diameter flat bottom hole (DGS method). All welds were also examined with an optimized RT technique for reference purposes, using single wall single image exposure (which is, in practice, not possible for obvious reasons). Destructive examination of the welds is planned at a later stage, reason why the present results can only be preliminary.

Results of phase 1 modeling: From the modeling results, the following could be learned:

- Indications of fusion defects at the vertical fusion line (between sleeve and weld) appear at a range where no geometrical echoes are detected. This leads to a clear detection of these defects, not disturbed by geometry. Because in a paper like this no moving images can be included, fig. 6 shows two captured images of the simulated moving wave front. In fig. 6A, the wave front generated by the crystal is just about to hit the fusion defect. Part of the ultrasonic energy has already reflected against the gap between sleeve and pipe wall. Blue is compression waves in this figure, red is shear waves. In fig. 6B, the signal has just hit the crystal (blue wave front just behind the crystal), reception has just taken place, and the A-scan has been detected with a good signal to noise ratio.

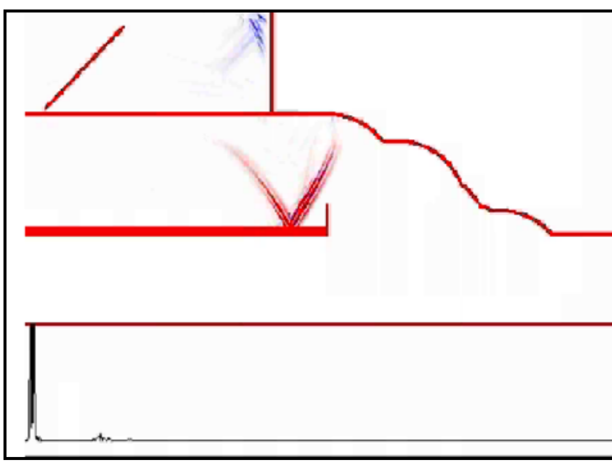

Fig. 6A: Wave front is about to hit defect

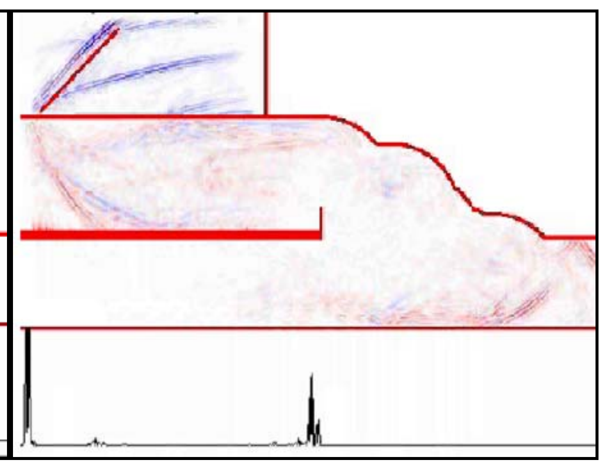

Fig. 6B: Reflected wave front just hit crystal

- On vertical fusion defects in the vertical fusion line, there is a good relationship between defect height and amplitude for defects up to approx. 4 mm. Above that height, amplitude is saturated and, on defects higher than 6 mm, even reduced. As a result, large defects (8 mm and up) give an amplitude comparable to that of much smaller defects (e.g. 3 mm). This effect is especially present when 60 and 70° probes are used on defects originating from the gap (inside of the sleeve). This means that discrimination between small and very large defects on the basis of corner effect alone will not be possible. This is shown in the graph of fig. 7, which is the result of a series of simulations whereby defect height was increased in 0,2 mm increments and the amplitude for each situation was stored. Simulated reference sensitivity was 80% screen height on a 5 mm high defect, in order to keep the signals within the dynamic range. The top half of the figure shows intensities in the ultrasonic beam.

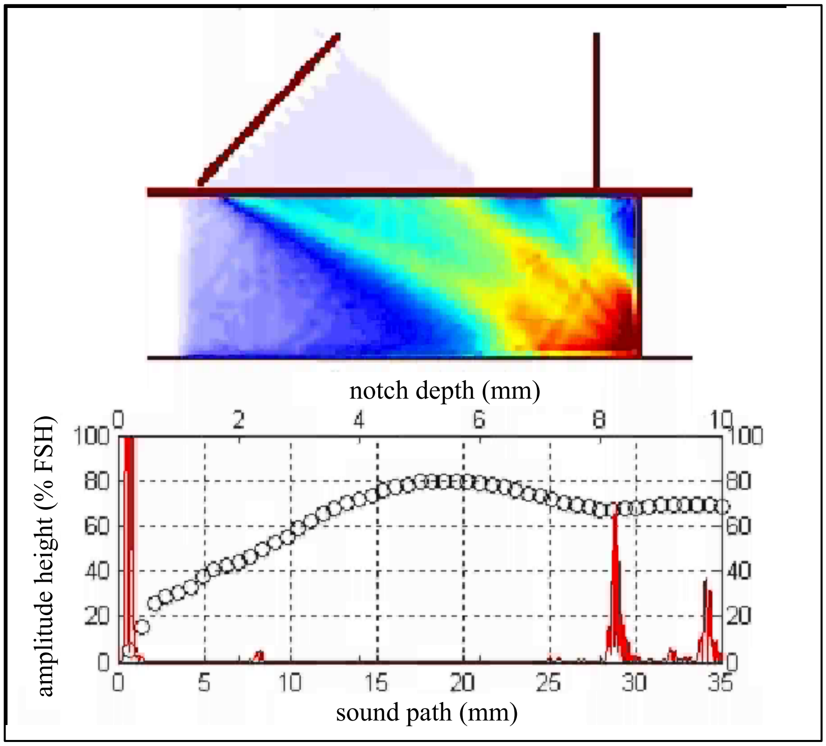

Fig. 7: Amplitude as a function of defect height (fusion defect, corner effect)

- Reflection against the gap between sleeve and pipe wall, and subsequently against the weld cap and back, generates a clear signal if no significant fusion defect originating from the gap is present. As soon as defect height approaches 2 mm this geometric signal disappears. This signal could therefore be used as an additional tool to discriminate between significant and non-significant fusion defects, even in manual UT. The same goes for the transmission signal to the other side of the weld, which could be picked up on the pipe wall if a pitch-catch technique in mechanized UT would be used.
- Fig. 8 shows a simulation on an underbead crack at the weld's toe under an angle of 45°, detected through the weld using a 70° probe placed on the sleeve. The beam intensity is visualized. Fig. 9B shows, as an example, the situation that the wave front has just passed the crystal after having been reflected on the defect (captured image of moving wave front simulation). The A-scan (second echo, black) shows an amplitude that is approx. 6 dB lower than the reference echo (first signal, red), which is equivalent to 80% screen height on a 2 mm high notch using corner effect (captured before at the optimum probe position for that particular reflector). In fig. 9A, the wave front is about to hit the defect. This type of simulations showed that this is a good way to detect underbead cracks at the weld's toe, without significant influence of the (varying) weld geometry as long as it is within visual inspection acceptance limits. Sensitivity has to be slightly higher than 80% FSH on a 2 mm notch.

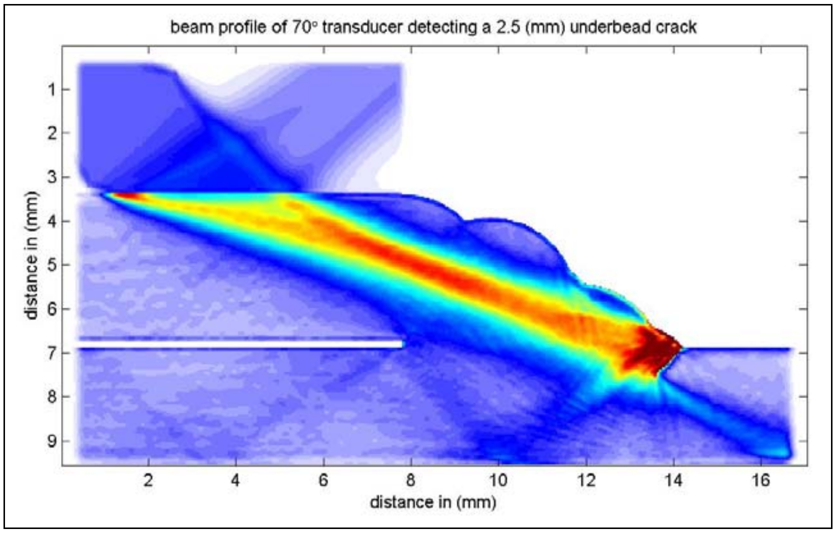

Fig. 8: Beam intensity on underbead defect

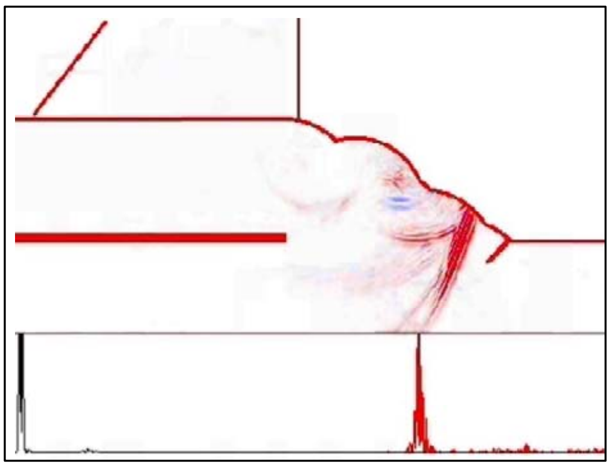
Fig. 9A: Wave front just about to hit defect

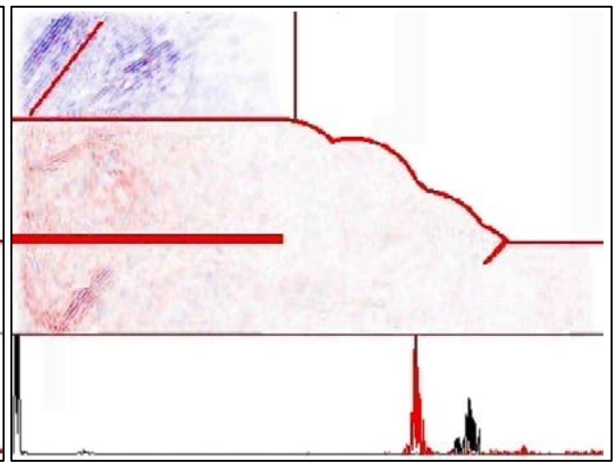
Fig. 9B: Reflected wave front just hit crystal

Round robin test results: On the thinner sleeves, fusion defects with a height of 4 mm and up were detected with a PoD (Probability of Detection) of 92%. Length was, on average, overestimated by 23 mm, standard deviation of length inaccuracy was +19%. On the thicker sleeves, defects with heights of 8 mm and up were detected with a PoD of 80%, with a considerable length overestimation. From the results it became clear that the PoD decreases with increasing sleeve thickness and defect height.

Apart from defect length overestimation, it became clear (from comparison to the fabrication and RT data) that UT detected a significant amount of non-relevant welding-related imperfections. These appear at the extremity of the gap between pipe wall and sleeve, mostly as a consequence of gas trapped between sleeve and pipe wall. Discrimination between defects with significant heights and these small imperfections appeared to be far from reliable. In practice, this could have resulted in many unnecessary repairs.

Defect sizing was fairly accurate for defects with heights up to 4 mm within ±1.7 mm, compared to the fabrication data of the intended defects. These practical results were in unison with the simulations.

Fig. 10 shows a typical example of the round robin test results on one of the welds.

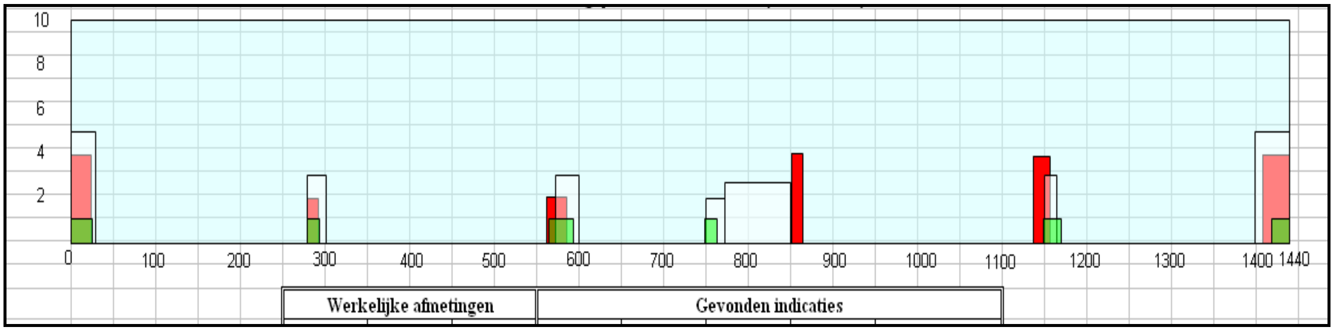

Fig. 10: Example of round robin test results on 10 mm thick sleeve (weld B)

Legend:

Real defect position Detected UT Detected RT
(note: indicated defect height is shown as measured, except for RT results).

Discussion: When comparing the round robin results with the simulated results, the following can be concluded:

- The sensitivity used in the current procedure for manual UT on perpendicular fusion defects is too high. For fusion defects it is recommended to use a 2 mm notch rather than a 2 mm flat bottom hole (DGS) as a reference. This is a sensitivity approx. 12 dB lower than the current sensitivity.
- The round robin results confirm the simulated results in the sense that large defects can not be discriminated from small, insignificant anomalies on the basis of corner effect amplitude alone.
- The possibility of using geometrical signals as an additional tool for discrimination between large and small defects was confirmed by the round robin results.
- Another additional tool to discriminate large defects from small imperfections is, to have the complete area of the defect contribute to the signal. This can be done by introducing tandem technique in a zonal concept on the sleeve, using a phased array.
- Underbead defects can reliably be detected through the weld, with the probe on the sleeve surface. Sensitivity should be a 2 mm notch + 6 dB.

Consequences for future phase 2 work: At the time this paper was filed, phase 1 was completed. Phase 2 was in its definition phase. Therefore, no phase 2 modeling results were available yet.

From phase 1 it became clear that there is far more information available in the ultrasonic signals than a single manually scanned angle probe can pick up. The use of combinations of receiving angles, even tandem technique, which is possible if phased array probes are used, is expected to increase POD as well as discrimination of large from small defects. Based on the results of phase 1, phase 2 will include the following investigations directed to the use of phased arrays:

- Increase of the PoD of perpendicular fusion defects by using a combination of corner effect, tandem technique (only practical when phased arrays are used) and pitch & catch.
- Use of a combination of parameters to asses defect height:
  - defect amplitude using a combination of corner effect and tandem technique
  - use of information from the weld's geometry
  - use of pitch and catch method.
- For detection of underbead cracks at the weld's toe (of which the orientation is hard to predict) a combination of pulse-echo from two sides will be modeled, using a variety of angles at shifting index points; in addition, it will be investigated how the screening effect of an underbead defect on an ultrasonic beam (e.g. creeping waves) can be used as an additional detection and sizing tool.
- For detection of voluminous defects in the weld body, volumetric inspection using a phased array will be modeled whereby the weld's varying geometry is used as a reference rather than a disturbing factor.
- Simulations with ToFD will include the use of multiple transmitters and receivers and optimization of their beam characteristics and location, in order to arrive at an optimized combination of positive detection with diffraction signals and screening of geometric signals (lateral wave, bottom reflection, mode converted signals).

- In Gasunie, a study is going on to establish specific acceptance criteria for the different types of defects that can be expected in a repair sleeve fillet weld. These will have influence on the modeling parameters in the phase 2 study.
- Finally, a written procedure will be drafted that uses the optimized inspection parameters established in phase 2. With this procedure, the existing and additional fillet welds with artificial and natural defects will be inspected, followed by radiographic and destructive examination.

Conclusions: Phase 1 computer modeling of ultrasonic testing of circumferential fillet welds of split-tee and repair sleeves on pipelines has shown that, using manual UT, discrimination between relevant fusion defects and welding-related small, non-relevant imperfections is far from reliable. Large defects can give signals similar to those of small imperfections.

This result was confirmed by a Round Robin test on four welds, using five operators.

Phase 1 modelling study showed that this performance can significantly be improved by making better use of reflected and diffracted signals generated by defects and geometry. Although the current manual UT procedure gives room for improvement, significant improvements can be expected from the use of mechanized techniques using phased array and TOFD. This will be done in phase 2.

References:

1 Advances in Imaging of NDT Results; Niels Pörtzgen, Dries Gisolf and Gerrit Blacquière; paper no. 611, 16 WCNDT, Montreal, Canada, August 30 – September 3, 2004