Trusts and Beliefs in UT of Girth Welds

Helmut HECKHÄUSER, SGS Gottfeld NDT Services GmbH, Herne, Germany

Abstract. In the German pipeline industry ultrasonic testing (UT) has been and still is the method favoured over radiographic testing (RT) for the inspection of girth welds. However, in the internationally widely applied Standard API 1104 (Welding of Pipelines and Related Facilities) till the nineteenth edition, September 1999, UT was of secondary importance when compared to RT. The NDT requirements in API 1104 are contrary to the NDT requirements in API 5L (Line Pipes), which are applied in pipe mills for the longitudinal and spiral welds, specifically for the continuous and uninterrupted inspection of welds by ultrasonic means (Automatic respectively mechanized UT). Common line pipe specifications like API 5L and EN 10208 (Steel Pipes for pipe lines for combustible fluids) include clear definitions about the reference standards used and define clearly the acceptance criteria for the applied ultrasonic inspection. As long as the NDT of girth welds is based on European Standards, the testing parameters including reference criteria and acceptance criteria for the ultrasonic inspection are also clearly defined. Depending on the quality requirements of the pipeline girth welds, a quality level, a testing class and an acceptance level are to be specified and on that basis reliable and reproducible UT results can be maintained. If UT is to be applied in accordance with API 1104 a qualification of the testing procedure is required prior to application. Basis for the acceptance of UT is the capability of the UT technique to circumferentially and axially locate imperfections, size for length, determine the distance between pipe surface and the imperfection and to compare the results with RT on defects and acceptable imperfections. In addition, the UT procedure must accurately determine the acceptability of welds based on the imperfection type, length and distribution, as cracks, linear surface, linear buried, transverse, volumetric cluster, volumetric individual, volumetric root and aggregate lengths. Many papers and inspection procedures reflect much belief in the UT capabilities to determine imperfection types and to locate and to size imperfections. From comparison reports on purposely made weld imperfections and from SGS in-house research work it can be shown to what extent UT results are trustable when inspecting girth welds in pipes made from thermo mechanically rolled plates.

Introduction

Pipelines for the transportation of oil and gas must be designed and constructed such, that leakage or rupture can be excluded during operation to avoid any environmental or personal danger. The pipeline acts as a pressurized container, where circumferential stress is generated by the operating pressure and cyclic loading effects occur due to loading and unloading of the product transported and influenced by pump activities. A critical part of any pipeline is the welds it contains, whether the longitudinal or spiral welds from the pipe mill or the girth welds. As standard practice for pressure vessels and also for pipelines the welds are subject to non-destructive testing (NDT). In both cases the ideal NDT will reliably detect and judge all weld defect types and sizes as unacceptable, which may cause weld failure and will judge those weld discontinuities types and sizes as acceptable, which will definitely not cause failure. It must be however considered, that NDT provides only indirect information about the size of a discontinuity respectively an unacceptable defect. This is recognized in the majority of inspection codes and specifications by specifying the acceptance and rejection criteria of "indications" (responses from the defect) rather than the size of the defect. The indication as the result of the physical interaction with the defect is the only observable quantified information gained and often not well correlated with the defect size, because the indication is rarely dependent on defect size alone. However the defect size and not the physical defect response is the major information required in assessing the fitness for purpose of the product inspected.

Most of the codes and standards specifying requirements for the applicable NDT methods and techniques do not refer to actual defect size, others require the determination of the defect type and/or an estimation of the defect size from the indications observed, a process that is likely accompanied by a number of uncertainties. It is likely, that this uncertainty depends considerably on the type of defect observed and a detailed and thoroughly knowledge of physical interaction mechanism.

NDT methods and techniques

The selection of the appropriate NDT method depends mainly on the product to be tested, the types of defects which may occur and the ability of the NDT method applied to reliably detect and evaluate those types of defects. To gain comprehensive information about the quality of the product tested, it is generally required, to cover the complete volume (surfaces and body) of the product. For this the product thickness and the products metallurgical condition are to be considered, when selecting the best suited testing method. Therefore, except for thin wall products (i.e. heat exchanger tubes) which are often tested by Eddy Current or Stray Flux methods, either RT or UT are selected to gain the complete volumetric information. Although stressed in many publications, no NDT methods provides a one to one picture of detected discontinuities, the responses from the observable discontinuity are purely the physical interactions with the discontinuity. It is therefore likely, that the RT response from a discontinuity is generally different from the UT response of the same discontinuity. The main demand on any NDT whether performed on new products in mills or during construction or service is therefore primarily, to reliably detect all discontinuities which by nature, position and size may be relevant and then classify them by an approved method as detrimental (harmful) or acceptable, in view of mechanical engineering criteria. It has been a long road, developing appropriate component specific acceptance criteria for the observable indications, so as to guarantee that all discontinuities which may cause failure are judged unacceptable and all discontinuities which definitely will not cause any problem are judged as acceptable. The extensive experience of the application of NDT on many component forms (tubes, plates, forgings, pipes, bars, welds etc.) however has shown, that a clear cut off level between harmful and non-harmful discontinuity responses cannot be justified in practice. If a hundred percent probability of segregating harmful discontinuities is a required, then it is automatically associated with a number of component specific wrong classifications of non-harmful discontinuities. The techniques developed over the years of NDT application from manual operation to mechanized and automatic operation as well as developments in data acquisition and data analysis are tools to improve the meaningfulness of the obtainable responses but it still has to be considered that those responses are physical interactions. Limits in correlation between NDT indications and actual defect sizes have been observed in many instances and must still be considered.

Weld NDT

Product welds are generally judged as more critical than the base or body material. Depending on the thickness of the weld and the weld structure RT or UT or both may be chosen to provide a full body non-destructive testing. Weld NDT is performed during manufacturing, i.e. in pipe mill for longitudinal and spiral welded pipes or at apparatus manufacturers, but also during construction of power stations, chemical and petrochemical plants, shipbuilding and offshore platform erection and onshore and offshore pipeline constructions. The development of appropriate codes, standards and specifications for the various types of welds involved and the selection of the best NDT method to maintain optimum segregation between harmful and non-harmful weld discontinuities has been an empirical process. It must always be considered that the types of weld discontinuities, which may occur, the thickness and the grain structure of the weld, the weld shape and accessibility are the demanding criteria for the selection of the most appropriate NDT testing method and technique. On the other hand the process requirements of the welds shall determine the quality level, the testing technique and the acceptance criteria to be applied. Both RT and UT have advantages and disadvantages when applied to weld testing. Historically RT has been used for weld inspection since around 1930, driven by the need to test pressure vessel welds to avoid failure and resulting personal injuries. Ultrasonic flaw detection started also around 1933 but the first applications were on solid metals, bars, plates, rails etc.. Weld inspection with UT started in the early 1950's driven by the demands of inspecting pipe system connections in chemical plants and power stations, weld connections in vessels, on ships and on bridges and last but not least longitudinal and spiral welds in pipe mills. UT had demonstrated advantages in testing time and no need for radiation protection. The advantage of RT was, to gain a document (film), which experts could evaluate and interpreting. The considerable lengths of longitudinal and spiral welds to be UT tested in the mills led already in the 50's to the development of mechanized UT of welds to cover the production needs. [2] Although many improvements in mechanics, electronics, data acquisition and data presentation have taken place, the modern automatic UT weld inspection systems in pipe mills all over the world are still following the weld inspection principles using the line scan approach already realized in the 50's.

Codes, Standards and Specification for weld NDT

The aim of codes, standards and specifications is to describe requirements of component properties and requirements of process parameters such, that whenever and wherever a component is manufactured or a process is performed, nearly identical quality results can be anticipated. The valid codes, standards and specification for weld inspection differ considerably with regard to component type and region. A number of codes, standards and specifications deal with the weld inspection of pressure vessels. A summary with regard to the European application of the Pressure Equipment Directive (PED) is given in [16]. Whether working to German regulations [1], European or ASME codes, standards and specifications [2] in case of UT in [16] it has been summarized: "The acceptance criteria are based on the amplitude, which is to be well known not to be representative of the defect importance. The acceptance criteria of the EN are similar to those of ASME BPV Section VIII or other national codes. All are based on historical background, not related to the techniques to be used and without any significant technical support" In [16] it is further summarized: "In general, it was concluded, that inspection procedures based on ultrasonic and X-rays can meet the inspection objectives required by safety".

A recommended specification for NDT of welds in metallic material is EN 12062 [3]. For all NDT mentioned the technique respective testing class and a corresponding acceptance criteria is specified for the three possible quality levels. For volume inspection both RT and UT are generally accepted, while for RT the acceptance criteria are specified in EN 12517, the acceptance criteria for UT are specified in EN 1712. In case of UT the testing technique respectively the testing class shall be selected in accordance with EN 1714 [4] [5]. The application of EN 12062 can assure comparable testing results for the method selected, the technique and the acceptance criteria applied.

Weld NDT requirements in pipeline products differ with regard to the product form and also with regard to regional differences in standardisation. The majority of pipes used in the pipeline industry are longitudinal or spiral welded pipes. For line pipes, whether API or EN is applied [6] [7], in case of UT, which generally is required for submerged-arc and gas-metal-arc seams a reference standard and acceptance limits (signal heights) are specified. UT is generally performed by automatic means and the signals are judged automatically. For structural pipes for offshore API Recommended Practice 2X may be applied, which specifies the type of reference reflector and acceptance criteria with regard to signal height and length of reflector [15]. For girth weld NDT considerable differences in codes, standards and specifications can be noted. In Germany, specific regulations (DVGW – GW 350) for weld connections in steel pipes for gas distribution are applied as demanded and accepted by authorities [9]. In addition client's specifications were established and must be met [11]. While previously the NDT requirements have been based on the requirements for pressure vessels as per HP 5/3, the actual regulations are based on the actual EN 12062. A worldwide known and applied standard for girth welds is API 1104. Till the 19th edition in 1999 UT was of minor importance versus RT, while RT requirements are thoroughly listed over many pages, UT requirements are covered in less than half a page. For UT ASTM E 164 was valid [14] and signals in excess of 20% reference level had to be investigated to determine location, shape, extent and type of reflector. For linear indications (surface open or buried) a length criteria was specified. In the API 1999 edition many more details with regard to UT were specified.

- At first the contractor shall produce a detailed UT procedure which requires final written approval by the company.
- A qualification of the testing procedure is mandatory: "The company shall require the contractor to demonstrate the application of the procedure and ultrasonic system." This includes the testing of a minimum of two welds per welding procedure containing defects and acceptable imperfections with RT and UT, compare the results and documenting differences in detection result.
- The use of the UT procedure on production welding shall be based on the capability of the implemented UT method/technique/systems to:
    - 1) circumferentially locate,
    - 2) size for length,
    - 3) determine depth from O.D. surface, and
    - 4) axially (weld cross section) locate required imperfections/defects in the test samples.
- In addition, the procedure must accurately determine the acceptability of welds in accordance with the criteria listed in 9.6 and 11.4.7. This meant that indications shall be classified and sized for maximum length dimensions at the evaluation sensitivity as described in 11.4.7.

In the 1999 edition both manual and automatic UT are covered. The manual UT sensitivity shall be based on a DAC from N10 notches, for automatic UT N10 notches plus flat bottom bore holes in diameters equal to the thickness of one welding pass are required [13]. Contrary to the API 5L Standard for Line Pipes or European Standards for welds, the UT results are not related to a reference standard and signal height respectively signal height and length but based on classification and sizing capabilities, which beside other factors are considerably influenced by operators ability.

Pipeline Girth weld NDT

Worldwide the conclusion can be drawn that the majority of girth welds have been inspected by radiographic methods, either by Gamma rays or X-rays. For the mainline production Gamma Crawlers and X-ray Crawlers are applied to perform panoramic exposures of the girth welds. RT is ideally suited for the detection of voluminous discontinuities and provides a permanent record in the form of a film, which allows off-line interpretations through different experts. Planar discontinuities however must be favourable aligned to the radiation beam other wise they may not be detectable at all. UT is most sensitive to planar discontinuities, but requires in the case of manual UT a skilled operator and a permanent record is not supplied. In Germany however, the operating companies as well as the authorities did trust UT more than RT to detect and evaluate planar type weld defects which are more detrimental for the weld performance than voluminous weld defects although a permanent record was not produced. The standard procedure in the German Pipeline Construction was and still is, to inspect 70% of the welds through manual UT and the remaining 30% through RT. The acceptance criteria were similar to those to be applied on welds in pressure vessels. Because skill of the UT operator may have a considerable influence on the results gained, all “Pipeline UT Operators” had to pass successfully an additional qualification test through the operating company, to be accepted for the pipeline job. The UT acceptance criteria had already been discussed in 1966. [18]

Mechanized and Automatic Girth weld UT

The driving force for the application of mechanized or automated UT for girth welds was the demand of the nuclear power industry to perform remote operated UT in-service inspections (ISI). Because the girth welds in nuclear power stations had been inspected by manual pulse/echo UT during construction, the main requirement for the mechanized remote controlled ultrasonic systems was to duplicate the conditions during construction so as to determine any possible process dependent deterioration. The equipment applied in the 80’s was of the P-scan type or comparable and all using contact probes in the raster scan mode so as to match manual UT as closely as possible. The safety requirements in the nuclear industry led also to the development and application of various UT methods and signal analysing methods, such as TOFD, ALOK etc., to describe type, shape and position within the product and the three dimensional sizes of the reflectors detected during UT inspection. Raster scan techniques are time consuming and not a commercially viable solution, if considerable lengths of welds have to be tested by ultrasonic means in a restricted time frame. Therefore line scan type arrangements for the ultrasonic inspection of welds in the mill or welds in the field were already applied in the 50’s. Since the 70’s mechanized and line scan UT equipment has been offered for girth weld inspection in the production stage or as an in-service tool. Such line scan equipment use several contact probes on each side of the girth weld arranged in quantity and angles such, that the complete volume of the weld is covered. The line scan technology cannot provide identical results compared with manual raster scan UT, since the dynamic signal distribution data in the direction perpendicular to the weld is not available. In our group SGS Sonomatic produced and applied their UPS 1108 (Universal Pipe Scanner), and RTD offered their Rotoscan for service. The advantage of those line scan units over are manual UT was the provision of a permanent record, because they were equipped with recording devices (respectively later with data storage devices). Proof could be supplied that the complete lengths had been covered and all signal information was recorded. At that time the International Pipeline Industry was not ready to accept such mechanized ultrasonic equipment on a project base as an alternative to the common applied inspections on girth welds. The application of line scan UT equipment for pipeline girth welds was initiated in the Canadian market where NOVA applied the automatic CRC welding technique and decided that UT was the best inspection option for the CRC weld bevel. [19] Research work had been performed and a report of the development was presented by NOVA in 1988. [20] Selecting UT rather than RT for the mechanized gas metal arc CRC weld was simply based on the fact, that the typical type of planar type defects which may occur in the CRC welds are in many cases not detectable at all with RT, but are most reliably detectable through UT. Due to the production rates of girth welds during construction of a pipeline it was likely to select a mechanized type of UT. Already at that stage, NOVA specified in detail the arrangement and type of probes (Focussed transducers, pitch/catch arrangements and creep wave transducer) applied as to avoid problems with missed reflectors or false calls being encountered during field trials. The first application on a project base using the NOVA approach was realized in 1989 and reported by TransCanada Pipelines in 1990. [21] Further reports about the performance of mechanized UT using RTD's Rotoscan were presented in the same year. [22], [23]. From those papers it can be summarized:

- The use of standard contact probes and amplitude gating resulted in false calls.
- The use of focussed probes and most proper incident angles will improve signal-to-noise ratio.
- Utilizing specific beam widths at target positions allows the maximum defect depth at the target imperfection to be defined (Zonal Discrimination).
- The design of the ultrasonic approach gives specific information about the defect depth in any region and Engineering Critical Assessment (ECA) criteria can be applied.
- The use of ECA reduced repair rate by an average of 49 % compared with workmanship clauses of CSA Z184.
- The comparison between RT and mechanized UT repair rates did result in the anticipated differences with regard to the type of defect needing repair.
- UT has proven more effective than RT in locating lack of fusion defects.
- Defect acceptance criteria based on fracture mechanics was possible because flaws were reliably located by depth and circumferential length.
- Porosity remains a significant defect in terms of its rate of occurrence, requiring continued use of radiography.

It must be highly appreciated, that the Canadian Pipeline Owners initiated all the efforts to gain an acceptable method of girth weld inspection which fulfil their needs. It is certainly an exceptional case, that all inspection details are precisely specified in the clients specification. The requirements on UT used in mainline construction in Canadian pipeline projects were already very stringent in 1991. A typical example:
FIND

- indicate reflectors greater than 250 microns in diameter,

POSITION IN THREE DIMENSIONAL SPACE

- locate the reflector width relative to the internal and external diameters within the cross section of the pipe wall,
- locate the reflector up or down stream, relative to the centre line of the weld,
- classify the reflectors by width in units of 500 microns,
- locate the reflector's circumferential position on an arc relative to the top of the pipe (angle to a vertical reference point such as the centre of the top weld button),
- calculate the total circumferential length for all reflectors exceeding 1000 microns in width,

DETERMINE ORIGIN

- determine within which weld pass and at which weld station the reflector originated,

CLASSIFY

- classify the defect as ID or OD undercut, a crack, lack of fusion (LOF), or porosity in the specific weld pass.

N.B. Lack of cross penetration and burn-through will be considered a specific LOF

A typical example of mechanized girth weld acceptance criteria is listed below.

MECHANIZED GIRTH WELD ACCEPTANCE CRITERIA
(Based on Appendix K, CSA-Z184-M92)

Feature	Depth assumed for analysis [mm]	Acceptable length [mm] for WT < 12.5 mm	Acceptable length [mm] for WT > 15 mm
External Undercut Low Cap (LFS)	0.5 - 1	250	335
External Undercut Low Cap (LFS)	1.1 - 2.5	100	195
Surface Porosity / Pinholes	2.5	2.5	2.5
External Weld Reinforcement	> 2.5 (height)	None allowed	None allowed
Lack of Fusion in one Fill Pass or the Cap Pass (LFSS)	2.5	100	195
Lack of Fusion or Porosity in Multiple Fill or Cap Passes	≤ 5.8	25	25
Lack of Fusion in Hot Pass: Both Zones	3.8	65	120
Lack of Fusion in Hot Pass: One Zone (LFSS)	1.9	100	200
Lack of Fusion or porosity in Root Pass (LFS) / Misfire	2	100	200
Lack of Fusion in Both Root and Hot Pass / Burn Through	5.8	25	25
Lack of Cross Penetration	1	250	335
Spherical Porosity	1	250	335
Piping Porosity	Unacceptable if piping porosity continues through 3 or more passes		

The outstanding solution of quantifying porosity by the ultrasonic method was presented in 1993. [24] At that time two inspection companies were qualified in Canada, both following strictly the owners specification. Our company, SGS Gottfeld NDT Services, experienced in national and international pipeline inspection during construction since more than 40 years, decided late in 1992, to extend their services to the pipeline industry beside X-ray and gamma ray RT, manual UT and MT with automatic UT. We could rely on tube mill experience of advantages and limitations of automatic UT [25] and the experience with the first commercially available TOFD

equipment, the Zipscan from SGS Sonomatic which we applied in German nuclear power stations [26], and had access to the considerable experiences with mechanized UT in nuclear power stations from other SGS affiliates (i.e. SGS Qualitest in France).
The main goal of our development was to serve the German, respectively the European market rather than the Canadian or North American market where local inspection companies were already serving the needs. Krautkrämer with the proven long term capability in the production of turn-key units for automatic ultrasonic weld inspection and theirs worldwide competence in ultrasonic physics was selected as partner to supply the UT electronics including software and support us in the physical design. Because in Germany and Europe manual welding rather than automatic welding was still widely applied, it was clear, that first of all the German and European UT inspection requirements would need to be met both for manual and automatic welding and the German pipeline owners and the authorities would need to be satisfied with the equipments performance. Because the results gained through manual UT were not questioned in the German pipeline industry, but the influence of UT operators skill had proven to play a large role and no positive prove of complete UT scan data could be supplied, the design parameters of the SGS girth weld ultrasonic unit differ from the Canadian approach and can be summarized as:

- Due to practical cycle time requirements a raster scan solution was not selected. Approval must be obtained, that the line scan arrangement covers the complete weld volume compared to the raster scan manual UT. Confidence must be provided that the complete weld length is covered.
- The signal evaluation shall be performed automatically on-line and a testing report in the form as presented during manual UT shall be created automatically. Practice had shown, that the main information to be provided to the owners representatives, the authorities and the contractor is the proven result of acceptance, repair or reject.
- The mechanical design of the unit and the physical concept must be selected such, that the unavoidable pipe and weld shape tolerances, thickness, mismatch, rectangularity and others shall have only minor influence on the test results. Also the environmental conditions, i.e. temperature or rain shall not result in notable differences in the test result gained. The goal is the improvement of reliability against manual UT.
- Although encouraged by a possible simple probe array, TOFD as a stand alone method for the application in mind was not selected. In the as welded condition of girth welds, TOFD is limited in defect detection both in the root and the cap area, whereas root defects are those of real concern. For automatic inspection TOFD has another limitation, because TOFD signals cannot be automatically evaluated.
- Testing results must correlate to testing results of manual UT with regard to detection (detection probability) and evaluation of signal gained during scanning. Applying the same acceptance criteria, automatic UT results and manual UT results must match within an anticipated and unavoidable tolerance band.
- Automatic testing must be cost competitive with manual ultrasonic inspection and ideally also with radiographic inspection.
- The testing unit shall be automatic and not just mechanized, to eliminate human error interpreting ultrasonic signal responses.
- Due to the scanning lengths to be covered during girth weld inspection within a project, we did not like the idea at all, to perform scanning with contact probes with the anticipated wear caused through the scan friction process and the anticipated variations in coupling. It has to be considered, that the testing of an average daily production of for instance

approximately 100 girth welds of 42” diameter will result already in around 340 meter scan length.

- If a positive application approval can be maintained, immersion probes shall be used instead of contact probes. In mill application, where huge quantities are to be scanned ultrasonicly, the use of immersion techniques is a standard procedure. Beside the absence of probe wear through scan friction, immersion probes offer the advantage that the nearfield zone is within the water and not in the product to be tested and the mechanical effort to adapt to a pre-established incidence angle is less than for contact probes. If focussing is required, that can be easily provided on immersion probes. Immersion probes are ideal suited for wall thickness thinner than 8 mm, where contact probes had limitations due to nearfield properties.

The automatic ultrasonic test equipment for girth welds developed in a joint venture of Krautkrämer and SGS Gottfeld NDT Services was named MIPA, for **M**ultiple **I**mmersion **P**robe **A**rray.[26], [27] A similar inspection technique is actually applied in modern pipe mill automatic UT. [28]

Physical Considerations of Girth Weld UT

With the introduction of mechanized UT on girth welds on a project site in 1989 in Canada, the physical concepts behind it had been published thoroughly. In general, all line-scan arrangements require a definite number of probes, to cover the complete weld volume. In the case of manual weld preparations (i.e. 30° bevel angle) other probe arrangements are applied than for the CRC or the SATURNAX automatic welding design. According to Canadian Owner specifications (NOVA – Specification for the mechanized ultrasonic examination of pipeline welds made by the metal arc welding process, TransCanada PipeLines TWE-01 – Total Weld Evaluation of Mechanized GMAW Pipeline Girth Welds) all physical and dimensional requirements are specified in detail. This includes:

- Target description
- Description of the reference reflectors for fusion defects and reference reflectors for porosity detection and its machining tolerances
- Transducer requirements, nominal values and tolerances – beam angle, beam size vertical and horizontal, overall gain, index point, squint, longitudinal angle beam, side lobes, subsidiary maxima, pulse shape, frequency, pulse length and signal to noise
- Transducer Positioning
- Gate settings relative to weld preparation and weld centreline
- Reference Sensitivity, recording threshold and scanning sensitivity
- Maximum Scanning Velocity
- Positional Accuracy
- Calibration sequence
- Coupling Monitoring
- Transducer Wear Measurement
- Reference line and ideal positioning including tolerances
- Temperature Control on wedge material
- Re-examination requirements
- Recording requirements
- Evaluation of indications and acceptance criteria

Schematics showing incident angles, sound paths and target points are prepared by the owner or the UT inspection contractor in a similar form as shown below being typical for a CRC weld bevel and a Saturnax weld bevel are to be approved prior to inspection performance.

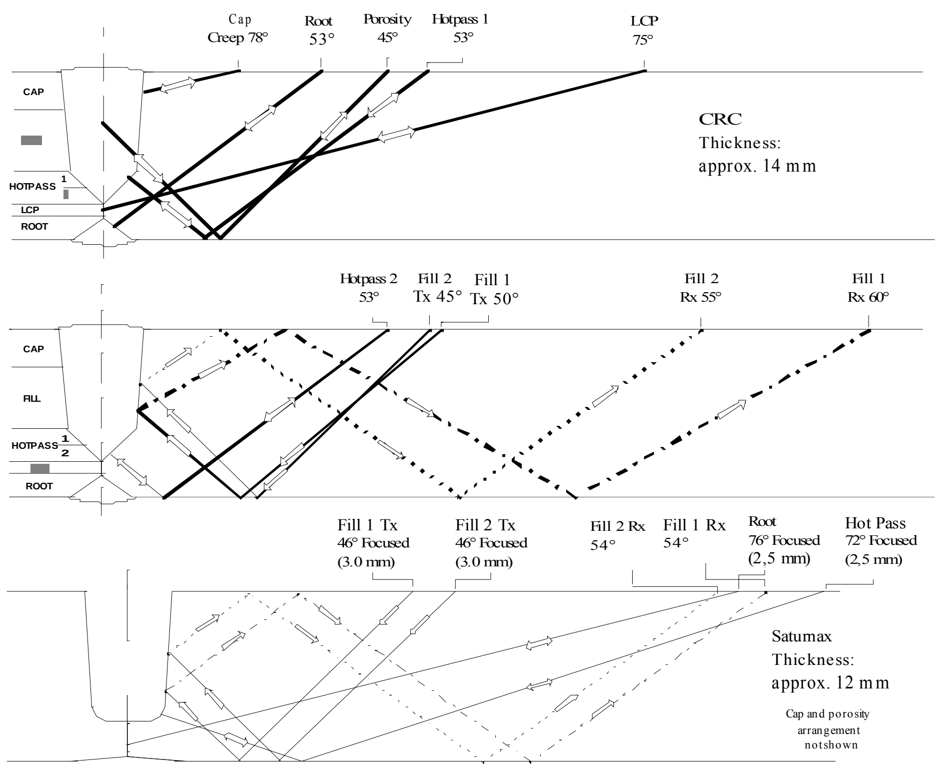


Figure 1: Schematic showing transducer placement, sound paths and target positions on welds

To maintain the specified beam size at the target position, focused transducers must used. The measurement of beam spread (-6 dB) in the vertical plane along the axis relies on amplitude readings from targets at different depths, i.e. side drilled holes in the IOW block and interpolating results by connecting the points. It shall be considered, that the focal plane in a given distance from the transducer determined in a straight direction will change shape when reflected under a given angle at the back wall (see i.e. Fill transmitter probes), because Snell's law is valid for any point of the beam field. Also the curvature of the reflecting wall influences the shape of the beam field. There is no doubt, that focused probes result in improved signal-to-noise ratio, however it shall be considered, that the directivity influence of the reflector is increased. Specifically for reflectors in the range of the focal size, the tilt and surface irregularities can lead to scattered reflections in unwanted directions, which may reduce or even prevent the detection of the reflector.

There is a direct relationship between the achievable accuracy of zone definition and the dimensional variables. According to the Canadian owners specifications the inspection company has to produce a scribe line with a tolerance of +/- 0,5 mm and the tolerance of ideal positioning shall not exceed +/- 0,5 mm. Unfortunately line pipes are a standard industrial product with unavoidable manufacturing tolerances. Diameter and thickness tolerances of the line pipe as well as the rectangularity of the pipe end have to be considered. The CRC driving band as well as the weld preparation can only be provided with tolerances. Typical line pipe tolerances are: API 5L – Welded pipes ≤ 20" Grade X42 and higher - Wall thickness +17.5% / - 12.5% of specified wall thickness – Rectangularity < 1.6 mm, EN 10208-2 – Welded pipes for T nominal 10 mm – 20 mm – Wall thickness +10% / - 5% - Rectangularity < 0.005 * diameter max. 1.6 mm. Because it is not possible to fix the CRC band exactly parallel to the pipe end in case of deviation from the 90° angle and considering the mechanical tolerances of drive unit relative to band and the tolerances of transducer carriages it is most likely that the ideal positioning tolerance of probes relative to the target position cannot be maintained at the construction site. It is obvious, that independent from the positional variances of the sound entrance point the unavoidable thickness variations do have considerable influences on the beam field position within the weld area. Below the situation is sketched, just using the central ray and the calculated transit time to target position for a wall thickness tolerance in accordance with EN 10208-2 (API 5L allows even greater variations). Although it is not anticipated that those thickness limits will really be found within a project, if approved pipe and plate mills are involved, however such variations may occur and do fulfil the contract requirements.

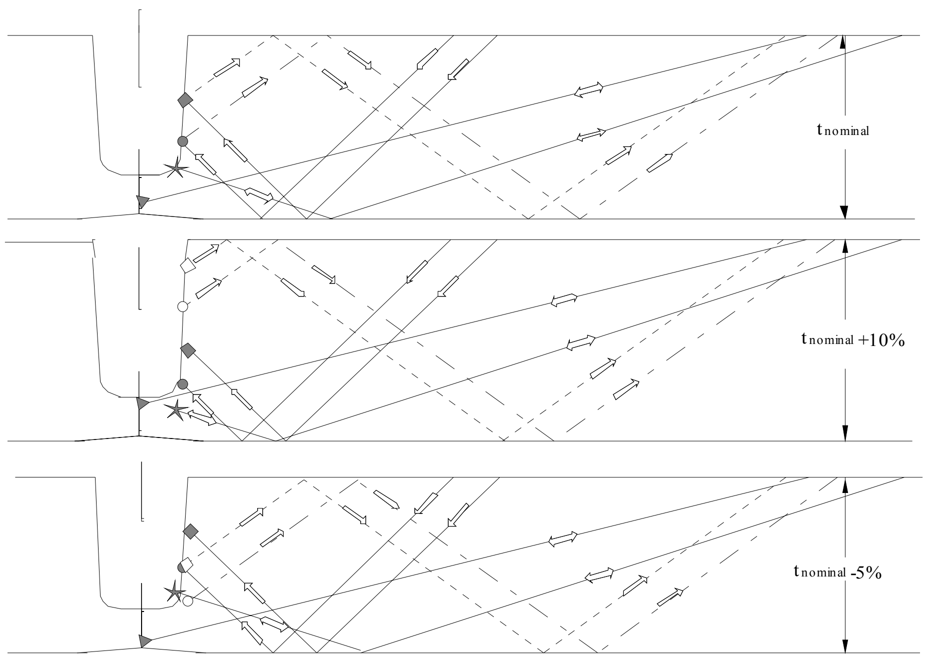


Figure 2: Variations of sound paths for different wall thickness

From the trigonometric laws valid for the sound paths it can be followed, that minor variations do occur in ½ skip and do show maximum after 1 ½ skip. Any other positional variation, variation of incident angle as well as coupling and temperature variations can increase the mismatch between theoretical calculated and practically achieved target positions.

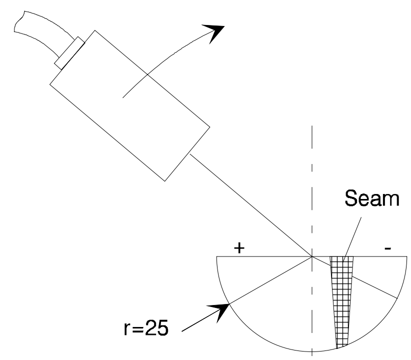
As for the application of ECA it is required, to reliably locate weld flaws by depth and circumferential length. ECA requires applying the containment rectangle approach. Girth weld discontinuities are rarely of simple geometric shapes, they rather vary considerably in height over their length. The sizing capability of the ultrasonic methods has been investigated since the construction and in-service inspections of nuclear power plant components. Independent from any possible applied ultrasonic method or technique a basic law remains: Sizing can only start if a defect is detected. That means that the applied method must achieve a 100% probability of detection for defects in excess of a critical size. Whatever report was published, it can be concluded: A reliable flaw sizing, based only on one method, may be a very dangerous task. The manipulating system must be able to carry out scans with different parameters, for instance tandem technique with different probe distances and apply several techniques, for instance focusing probe, acoustic holography. [29] A review of nuclear studies, the PISC II round robin test showed results with considerable sizing and location errors, although all type of probes, scanning methods, UT techniques and data analysing approaches had been applied without any time frame limit. [30] Early reports about the characterization of flaws in pipeline girth welds using four different techniques on seventeenth actual flaw sizes from 0,8 mm up to 7,5 mm concluded: Based on the best results obtained the sizing errors were such, that merely 1,3 mm need to be added to the depth estimate in order to be almost certain. [31] Even if artificial reflectors with clear sizes are used, the UT results are not free of tolerances. The paper [32] concludes: A comparison of non-destructively assessed artificial weld defects with their actual characteristics (revealed after destructive testing) has demonstrated a very wide variation both between defect sizes predicted by different operators and between predicted and actual defect sizes. If pipeline inspection is applied in accordance with API 1104 an ACCURATE determination is required and in case of the application of ECA length allowance shall be based on definite height values in wall thickness proportional steps. Information about allowable tolerances respectively sizing errors is not obtainable from API 1104. That means in practice, that from the UT response gained either by the manual UT raster scan method or by the mechanized UT line scan method the defect height must be determined for each and every weld discontinuity and no undersizing is permitted. The pipeline girth weld automatic or mechanized UT approach is based on the line scan concept. Considering that a discontinuity is hit by an ultrasonic beam under optimum geometrical conditions, you can gain a signal proportional to the reflected ultrasonic energy and information about the transit time of ultrasound at an individual circumferential position. The signal height obtained depends on the geometrical influences, the relationship of beam field size to discontinuity size and the reflectivity properties of the discontinuity surface. Signal heights are normally evaluated in terms of comparing them with the signal height of artificial reference reflectors. During the circumferential scan signal height responses do vary, whereas the cause of such variations is not observable from the inspection result. In the case of identical reflectivity properties of discontinuities signal responses are proportional to the hit area as long as the size of the discontinuity is smaller than the beam size. It is obvious, that the physical responses which can be gained from a discontinuity during line scan UT are less comprehensive than for raster scaning and it is not anticipated, that sizing errors of the line scan approach are smaller than for raster scan. It is unfortunately a matter of fact that from the signal distribution along the girth weld during practical testing a very limited conclusion about the discontinuity properties can be drawn because there is not much of a linear relationship between the physical interaction of ultrasound with weld discontinuities and the signal response. From the physical point of view there is no basis for to the description of the shape, type or appearance of a defect from the ultrasonic linear signal response distribution.

Specific Physical Considerations of Pipeline Girth Weld UT

Any NDT operation is sooner or later faced with the situation that the products requiring inspection are not designed for simple and reliable NDT. Therefore it is unavoidable, that limited accessibility may occur or that non-destructive testing cannot be applied at all because of material properties (i.e. grain size). Since the seventies the plates used in the manufacturing of longitudinal and spiral welded pipes for the pipeline industry are thermo mechanically rolled, which better fulfil the mechanical properties required. From UT experiences in pipe mills where longitudinal and girth welds require inspection, it is known, that there are considerable differences in sound propagation behaviour when testing in rolling direction or perpendicular to the rolling direction.

This does not really matter as long as line pipe standards, i.e. API 5L are applied. UT signals are evaluated through comparison with signals from calibration reflectors and sound path knowledge is of negligible concern. Because any physical interaction of ultrasound with weld discontinuities is influenced also by variations of material properties, any variation from the homogeneous state makes the interpretation of ultrasonic results more complicated. In a very early stage of the application trials of our MIPA system (1993) we applied probes with the same crystal size but with operating frequencies of 5 MHz and 10 MHz to verify the resulting beam field under identical incident angles and possibly improve signal to noise ratio and detectability. During the investigation of artificial reflectors in line pipe sections in two nominal wall thicknesses we were faced with the unexpected result, that the two probes require different beam entrance point distances relative to the reflector to achieve maximum response. The differences noted were found ranging from 3 mm to 5 mm. It became obvious, that the application of Snell's law for the calculation of sound paths within line pipe material was not appropriate, because Snell's formula contains no frequency value. The result also indicated, that there are differences in sound propagation comparing line pipe material with standard steel material, i.e. IOW block. It is also known, that there are considerable differences in sound velocity notable when comparing pipe materials of the same size and grade from different pipe mills. A study was made and concluded that detailed velocity determination of the pipe material is necessary prior to machining wedge angles and that angle calibrations can not be made on standard blocks, i.e. IIW. However in that study the applied calculations are still based on Snell's law. [33] Our own observations led to the in-house instruction, that calculated beam angles and sound paths are not to be trusted but instead we set the optimum angles and probe offsets using the artificial reflectors in the original line pipe material. In Germany and Austria, where MIPA first was applied on a complete pipeline project the demand for an automatic UT technique was to be equal to or better than the experienced manual UT. The owners did not specify or require an online defect sizing for the application of ECA because the practical results and the repair rates during pipeline construction did not indicate any need for it. Because detectability was our main goal, we selected probes which generate a nearly homogeneous beam field to minimize signal variations due to the unavoidable probe positioning variances. [34] To extend the range of applications of our MIPA system we performed in 1995 a qualification run on a pipeline section for offshore application (dimensions X65 - 966,4 mm ID x 28.6 mm wall) including a mechanized welded GMAW girth weld with purposely made weld discontinuities. The UT acceptance criteria for the project in question were based on eight different kinds of weld discontinuities, variable in type, position within the weld and size. The validation of the system had to cover: Detectability, Positional accuracy, Sizing capability and accuracy. While the results of detectability were as anticipated, we had to learn, that clear positional values of the detected reflectors within the weld volume could not be precisely gained from the signal transit times data stored and evaluated. Upon measuring shear wave velocity in the 0 degree direction we found different values in dependence of the shear wave polarization and we found that double diffraction occurred, because we detect two signals with different transit times from the same reflector. It became obvious, that there were most likely anisotropic properties present and an explanation for the sound propagation in anisotropic line pipe material was needed. A qualified NDT operation should have considerable knowledge of practical performance data, physical interactions and limitations of all NDT methods applied. To establish and apply an appropriate NDT method. To gain knowledge about the appropriate evaluation criteria for the reflector response data provided UT signals need to be evaluated. SGS Gottfeld NDT Services engaged Krautkrämer to perform an investigation program on original line pipe sections (X65 - 966,4 mm ID x 28.6 mm wall). It is within the nature of the thermo mechanical rolling process, that anisotropic properties of the plates are present and can be described through the texture. The anisotropic condition does not only influence the mechanical properties but also physical properties, i.e. thermal extension, electrical conductivity and unfortunately also the sound propagation. Since in-service inspections of stainless welds required the application of ultrasonic testing, research work showed that anisotropic properties can result in deviations of the ultrasonic beam which can lead to errors in determining both the location and size of reflectors. The phenomenon of beam deviation must be carefully considered in planning the ultrasonic examination and in the interpretation of data. [35] It has become clear that ultrasound propagation behaviour is strongly influenced by the anisotropic elastic properties and phenomena associated with anisotropy. Factors such as variable attenuation and beam skewing must be anticipated. [36] It was therefore the purpose of the Krautkrämer investigation to quantify beam deviations (skewing) and attenuation effects.

To determine the beam properties in question a test sample was prepared from a pipe ring section containing a girth weld. The sample was a half-cylinder with a radius of 25 mm with the weld seam off centered. The half-cylinder was scanned in immersion in 0,5 mm steps (see Figure 3) The water distance to the probe used was set such that the sound entrance point is exactly at the end of the beam near field. From the sound velocity charts (Figure 4, Figure 5) it can be drawn, that the sound velocities in anisotropic material are incident angle dependent contrary to isotropic material and Snell's law cannot be applied. It can be further noticed, that the sound velocity of longitudinal waves in the welded section is lower than in the base material while for shear waves it is the other way around.



Half - cylinder arrangement for the determination of sound velocities
Figure 3

Relationship of sound velocity from incident angle - Longitudinal

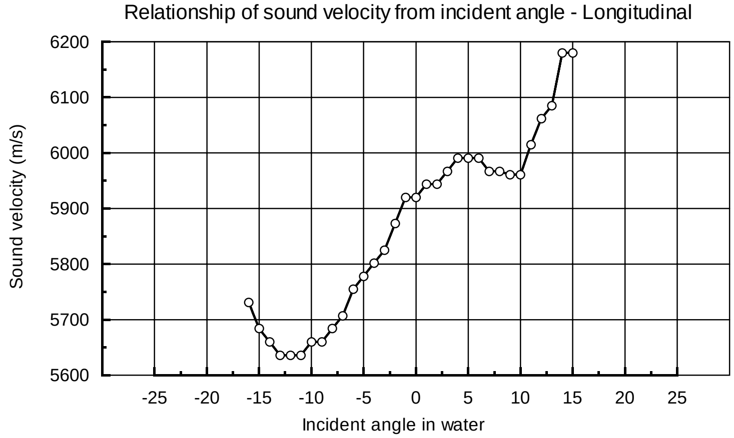


Figure 4

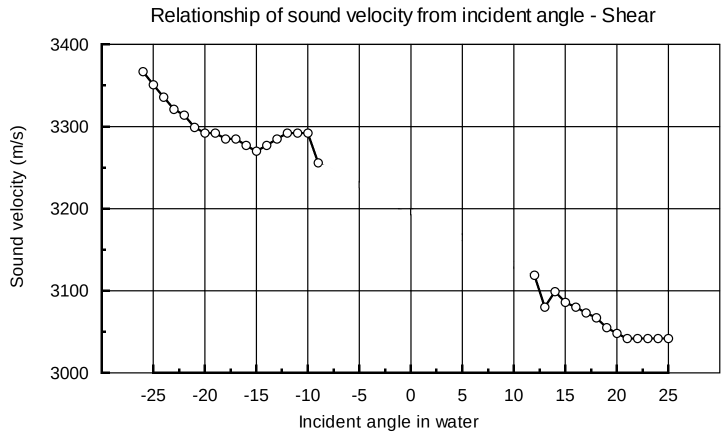
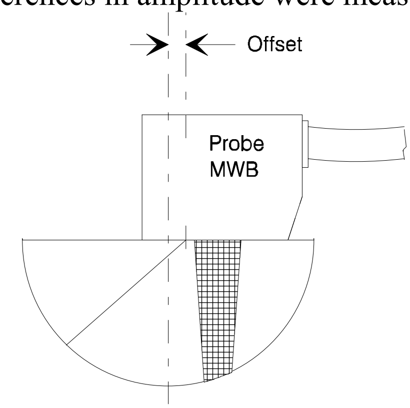


Figure 5

The amplitude variations in relation to the incident angle have been measured and an incident angle dependent maximum response was recorded, which indicates that only for a definite angle the direction of the incident beam fits with the direction of the reflected beam. Between the base material section and the welded section only minor differences in amplitude were measured.

To gain information about beam deviations, respectively skewed beams standard contact probes in angles of 35°, 45°, 60° and 70° were used to determine the positions of maximum responses from the half-cylinder back wall. For isotropic material it is clear that the maximum response is gained with the sound entrance in the half-cylinder center. Not so in the anisotropic sample. To obtain a maximum response, it is required to offset the beam entrance point such, that the reflection direction of the skewed beam fits with the direction of the incident beam. In that position the beam will not hit the half-cylinder wall perpendicularly, but under an angle, which means in practice, that natural reflectors will result in maximum reflection if they are angled to the incident beam accordingly. The offset required has been found as:



Direct contact test on 25mm half - cylinder sample

Figure 6

35°	-2 mm
45°	0 mm
60°	5,5 mm
70°	14,2 mm

while the sound path lengths were measure to be:

35°	24,4 mm
45°	25,6 mm
60°	30,7 mm
70°	37,8 mm

When comparing the measured travel distance with the theoretical travel distance calculated from the geometric position and an isotropic sound velocity of 3255 m/s a relative close correlation has been observed, which means that the differences in travel distance are mainly caused by path variations rather than by sound velocity variations. Beam deviations are therefore most likely caused by the variation of elastic constants within the material and are less influenced by the

shear wave velocity variations. On samples from this material Krautkrämer performed further investigations with regard to detectability and positional accuracy on artificial defects (side drilled holes, flat bottom bore holes, surface notches) and with regard to focusing requirements. From the considerable amount of data gained, we can only offer a briefly summary here.
Pipe material made from thermo-mechanical rolled plates does show a considerable anisotropic behavior (Texture-anisotropy) both for the ultrasound velocity as well as for further elastic constants. Considerable differences of shear wave velocity in the two plate axis directions can be observed, in the actual case 3385 m/s in rolling direction and 3150 m/s normal to rolling direction. The required angle dependent offset of the sound entrance point relative to the sample's center point to gain optimum response indicates, that beside the sound velocity other elastic parameter are also directional dependent. Due to the anisotropic properties the beam propagation direction (direction of maximum energy transport) does not - as common -coincide with the direction of the maximum sound velocity (Phase velocity). Because this coincidence is mandatory for the Snell's refraction law, the application of the Snell's law cannot be properly applied for anisotropic materials. An optimum response of skewed beams requires a different angularity of reflectors than for straight beams. For the practical application of ultrasonic inspection on anisotropic line pipe material the sound propagation within the material cannot be calculated precisely; only approximations can be made. Optimum set-up conditions require experimental investigations on the original material. Dimensional variations within a project as well as variations of the elastic parameter require consideration. The best correlation with isotropic conditions can be gained, if incident angles around 45° are applied. If beam deviations occur and variations in material properties cannot be excluded, then reliable defect detection, positional accuracy and size estimation cannot be provided without a considerable uncertainty. Investigations on artificial reflectors proved, that the incident angles cannot be calculated from the sound velocities of the two media involved and Snell's law is not valid, because all measured incident angles both for pulse-echo and Tandem are smaller than calculated through Snell's law. The highest shear wave energy is provided for incident angles around 45° +/- 5°, while for incident angles over 65° no shear waves could be excited in the samples investigated. An optimum detection in the tandem mode requires individual angle optimization for the transmitter and receiver. The beam deviation and the focusing properties in anisotropic material are approximately identical with isotropic material, as long as angles close to 45° are maintained. With increasing incident angles the focusing properties in anisotropic material are no longer valid. The actual incident angle in anisotropic material is higher than the nominal probe angles, for a 66° focused probe the measurements result in actual incident angles of 72° to 78°, depending on sample. The focusing in a depth of 21 mm was measured to approx. 6 mm in isotropic material and to approx. 16 mm in the anisotropic material. It shall be considered that all the investigation results here are based on properties in samples from one pipe section from one pipe mill. Others pipes from the same mill but certainly same quality and size pipe from other mills may result in differences of the values obtained. Because it is most likely, that the observed anisotropic properties are mainly caused by the forming works applied and the associated temperatures involved, we investigated the sound variations on a representative number of line pipes made from plates from the same plate mill and undergoing the same pipe forming process. In parallel to the measurements of sound velocity we measured the respected wall thickness at the selected points using a wall thickness gauge. On 40 pipes we took measurements at 5 points around the circumference (approx. 10°, 90°, 180° 270° and 350°) and at both pipe ends. Differences were observed both around the circumference as well as from end to end. From the results it can be concluded, that within a production lot manufactured under the same nominal conditions variations occur in wall thickness but also in sound velocity in rolling direction and in

circumferential direction. From the frequency distribution in Figure7, Figure 8 and Figure 9 it can be seen that there are significant variations present.

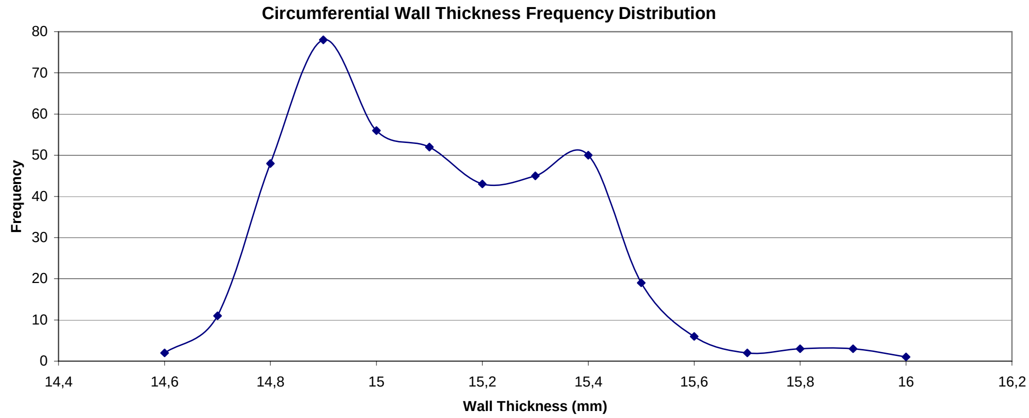


Figure 7

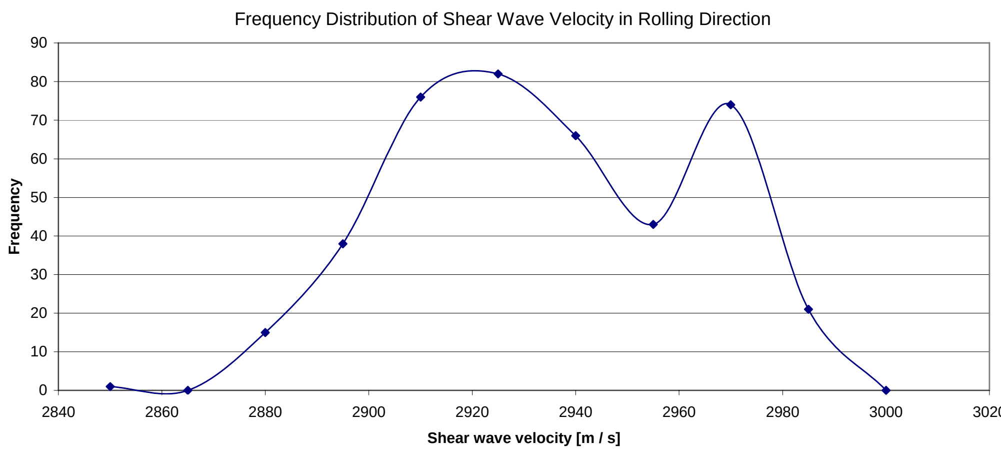


Figure 8

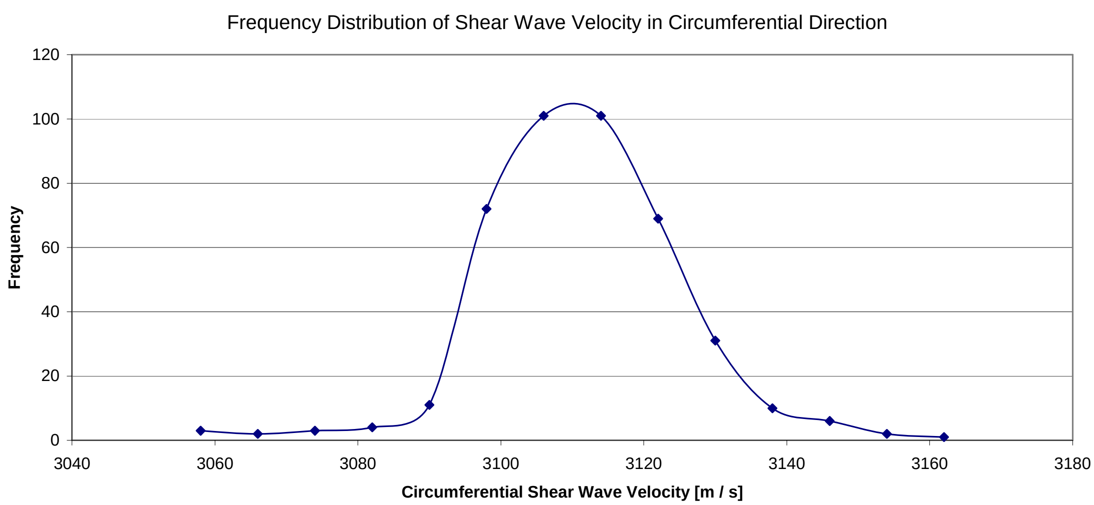


Figure 9

For girth weld inspection the sound velocity variations in rolling direction are of interest and from the values obtained there is an indication notable, that the pipe forming operation may have a greater influence on the velocity variations in rolling direction than in the circumferential direction.

UT Assessing Capability of Pipeline Girth Weld Defects

Because no internationaly accepted code or specification was existent detailing weld acceptance criteria in case of using ECA methodologies, a study had been performed under the commission of the International Pipe Line & Offshore Contractors Association (IPLOCA). On pipe samples with purposely introduced weld discontinuities. Blind NDT inspections using one RT inspection company and two mechanized UT inspection companies had been performed and the dimensions of the discontinuities were determined destructively in Gent university laboratories. The report with a comprehensive amount of data investigated from a total of 168 defects in two pipe sizes were published for a group of sponsors in 2000. [37] The participating AUT companies were entitled to apply the techniques and procedures which, in their view and to their knowledge at the time of inspection (1998) would yield the best / most reliable result. Original pipe material for the production of the calibration blocks was provided. Details of the equipment set up conditions are not reported. The reporting requirements were specified as:

- All linear indications larger than 10 mm in length and having an amplitude height exceeding 40 % must be reported. (Reference reflector and reference height not reported)
- All indications of volumetric discontinuities having an amplitude height exceeding 80% must be reported. (Reference reflector and reference height not reported)
- The length of a reportable discontinuity will be determined where the amplitude has reached a 20 % level.
- Reporting of the discontinuities shall as a minimum include (where possible)
    - Length (when interrupted, this must be indicated))
    - Height
    - Depth
    - Nature
    - Amplitude
    - Location on circumference
    - Location at side of the bevel (upstream, centre line, downstream)

The two participating AUT companies most likely claimed to fulfil all reporting requirements and provide accurate result for the application of ECA. The inspection time and the interpretation time was not limited. One of the major values of interest was certainly the height of a defect and the respective error, because most AUT companies claim as the advantage of their UT over RT, to provide accurate height values for the ECA calculations. If you analyse the results gained, it becomes obvious, that the actual reported parameter of the discontinuities differ considerably from the parameters found in laboratory. Moreover the results reported by the AUT company A do not correlate at all with the results reported by AUT company B. The discrepancies found between actual discontinuity parameters and reported AUT results are difficult to classify or physically explained. Many of the discrepancies are most likely caused by the misleading belief, that UT propagations and the physical interactions follow simple laws. From the 168 defects 29 required no reporting. On the remaining defects nearly any deviation from the claimed capability was observed. In detail:

- A number of defects were not reported, in some cases the same defect was not reported by both AUT companies while for others one reported and the other did not (10 not reported by one company, 16 not reported by the other)

- Defects were reported where no defects exist.
- A number of defects were excluded from analysis, only 107 defects remained
- Length – If the length records of both companies are analysed, considerable mismatches of the start values for individual defects are found in such dimensions, that a physical explanation is not possible. Positive and negative circumferential mismatch is seen which indicates that the signals are likely not caused by the defect and must be classified as false. In the report this mismatch was neglected, only the reported lengths were used for comparison. Defects separated in length distribution were in many cases not reported accordingly. (See Figure 10 & 11 for the 107 analysed defects)
- Depth – Except for the root position, considerable deviations of the reported depth from the actual depth were noted. (See Figure 12)
- Defect type – Except for the defect type LOP at the root position, where the UT defect type reported mostly matched, for all other defects nearly random reporting can be noted.
- Location at side of bevel – Again a good correlation can be found for reflectors in the root area, whereas at the other positions matching was rare.
- Height – For the final analysis of the 107 defects remained the length mismatch, weld positional mismatch and defect type error were neglected. But even, if it is assumed, that the UT signal gained and interpreted was caused by the defect investigated (which must be questioned due to the large mismatches) the heights reported by the two AUT companies differ considerably from the measured heights. For defects positioned in the root the height variations are within an anticipated range, but that result is influenced by the fact that the actual defect heights in that position ranging around 2 mm. For all the remaining defects a defect height sizing capability cannot be drawn.

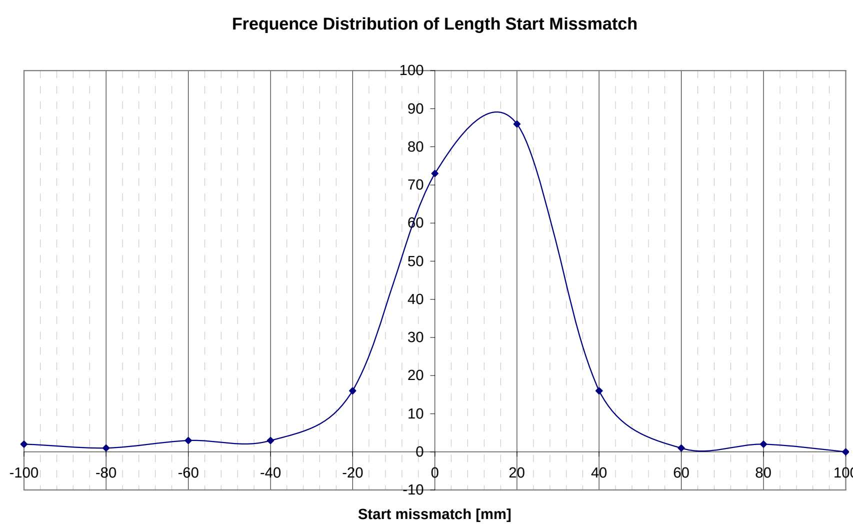


Figure 10

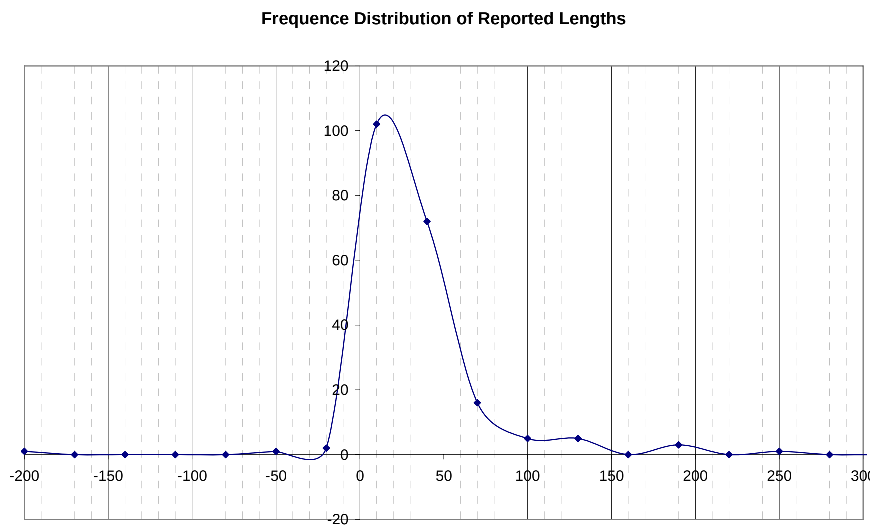


Figure 11

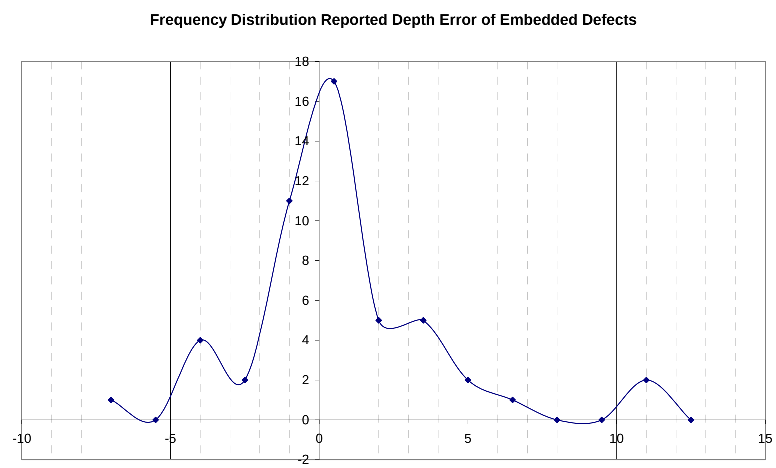


Figure 12

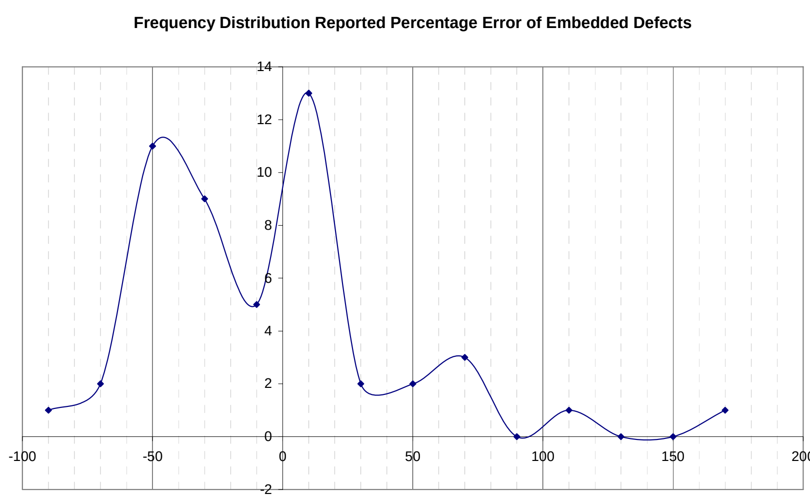


Figure 13

Because there is absolutely no correlation between the reported data of the two AUT companies, it becomes clear, that the techniques applied are not in the position to obtain reliable responses. Whether this is caused by system parameter variations, i.e. probe design and arrangement or by variations between the calibration material and the product, cannot be concluded from the report. But it can be summarized, that the applied AUT technologies are not capable, of providing a reliable record of all defects exceeding a specified acceptance criteria, nor can it be excluded, that false calls occur. Because no accurate positional information of length, depth and position relative to bevel are provided, the data are of no use for gaining information of repair position and a estimation of a defect type based on the position within the weld is useless. It is obvious that the interactions of the sound beam with the reflectors within the weld and the sound beam propagation were not as anticipated by the participating AUT companies, and therefore the focal approach did not supply the information for the estimation of defect height. This became specifically obvious in the case of heights > 3 mm and embedded defects. From the records available it can be seen, that both undersizing and oversizing occurs.

Conclusion

It is obvious that considerable differences exist in the standardization of ultrasound inspection on pipeline welds. Differences in applied techniques, calibration procedures, acceptance criteria and evaluation procedures are noted, when comparing standards for longitudinal welds with those for girth welds, but also if national standards are compared with European or other international standards. With regard to the ultrasonic inspection of pipeline girth welds it is necessary, to consider as well the various owner specific standards, which if applicable on a pipeline project may differ notably from other national or international standards for weld inspection. It must be the goal of any UT standardisation including the ultrasonic inspection of girth welds, to specify the technical requirements (i.e. probes, scanning, frequencies, quality level), the calibration procedure and the acceptance level in such a manner, that definite inspection results can be maintained, when an ultrasonic inspection is performed in strict accordance with the specified requirements. It is advisable to specify only such parameters which can be met reliably. Calibration reflectors should be specified such, that an easy manufacturing within limited manufacturing tolerances can be maintained. To avoid discrepancies in reported results, an unambiguous evaluation of UT signals should be specified and it shouldn’t be the case that individual interpretation leads to operator dependent differences in the results. From the literature analysed it can be concluded that in many cases ultrasonic inspection potentials are being claimed which cannot be met. While ultrasonic inspection has proven its capability to reliably detect and evaluate defects resulting in definite signal response compared to a specified reference response, it failed to be a measuring tool for defect sizes and positional values. Whatever technique was applied and results were reported, it must be expected, that sizing errors are in such a range as to be qualified as not accurate. Decision making based on obtainable size information from ultrasonic inspection requires the comprehensive knowledge of expected defect types and the respective method dependent sizing errors. From literature and research work results reported here the distinct conclusion can be made, that in case of ultrasonic inspections of anisotropic materials the majority of physical laws to predict the physical interaction of ultrasound with reflectors within an isotropic product are not further valid and applicable. For UT line scan techniques applied on unsisotropic materials, the propagation of sound within the product, the beam field characteristic and the associated physical interactions as reflectivity, directivity, scattering, diffraction and mode conversions cannot be based upon research or experimental results on isotropic materials. The inherent variations of elastic properties and the resulting sound velocity changes in thermo-mechanical rolled pipeline materials caused by the process itself and the unavoidable variations of manufacturing parameters does not allow reliable theoretical predictions without practical investigations. Before trusting an UT technique and method, it must be proven, that all reflectors responses exceeding the specified acceptance criteria (signal height and/or length) are reliable and repeatable obtained. If any other property of a signal response such as distribution over distance or associated transit times is specified to be interpreted it is even more necessary, to analyse all influences which may occur under practical conditions. A belief in unproven physical interactions in line pipes may lead to unreliable UT results which are useless for appropriate acceptance decisions. As derivable from the IPLOCA report, the believes created such considerable differences that it is likely, that the applied techniques were not capable of gaining the data required and identical quality levels were not achieved, which means that accept and reject decisions are UT technique respectively UT company dependent. The amount of publications including NDT company brochures convey the impression, that with line scan UT and zonal approach height sizing is a standard procedure and it is no problem, to obtain accurate values. The top requirement found in this area was an allowable height sizing tolerance of 0,3 mm to get accepted as a UT contractor. Such statements compared with the results gained from practical applications are most likely in the position to discredit the application of ultrasonic inspection on girth welds in general. It is advisable, to draw attention to all limits of correlation for a NDT applied, rather than claiming beliefs and not properly proven properties.

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