Automated Ultrasonic Testing Systems for Bars and Tubes, Examples with Mono-Element and Phased Array Probes

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Abstract
This paper presents several examples for ultrasonic testing systems. Solid cross sections (bars and billets) and tubes (seamless and welded) are typical test tasks. The use of mono-element probes and phased array probes is compared.
Systems for bars and billets with linear transportation and with rotational testing concepts (rotating bar/billet and linear probe movement) are presented. Large-scale immersion tanks for aerospace billets (aluminum, titanium, nickel-based alloys) provide the highest possible test sensitivity. The test tanks with high-precision mechanics sometimes use specially focused probes for multi-zone inspection (in accordance with SAE AMS 2628, SAE AMS-STD-2154, SNECMA DMC or MTU MTV 1033). A very large testing system was designed for forged bars with a diameters up to 1 m, lengths up to 10 m and weights up to 35 tons.
The second part of the paper discusses testing systems for welded tubes. The tube welds can be electric resistance welds (ERW) or submerged-arc welds (SAW, longitudinal and helical). Large wall thicknesses and the wide welds (SAW-pipes) lead to large testing volumes, especially if off-bead defects shall be detected. In addition, SHELL and some other test specifications ask for many test angles and probe positions. These requirements lead to a very large number of mono-element probes or suggest the use of phased array probes. Phased array probes with properly adjusted time-corrected-gain (TCG) and angle-corrected-gain (ACG) produce a uniform test sensitivity within the testing volume. This requires a proper design of probes, probe holders and test mechanics, e.g. by means of the CIVA software.

Keywords: ultrasonic testing (UT), phased arrays, steel plant, CIVA, forged steel bars, aerospace bars (titanium or nickel alloys), welded tubes

1. ECHOGRAPH-HRP Testing of bars and tubes in immersion with linear transportation

The activities of KARL DEUTSCH in the area of phased array started as a publicly funded research and development project of the German Federal Ministry of Economics and Technology (BMWi) in the areas of metrology, standardization, testing and quality assurance (MNPQ) together with the Federal Institute for Materials Research and Testing (BAM) in Berlin. For more than 40 years also ultrasonic testing systems (mostly for testing of semi-finished products) are included in the product portfolio of KARL DEUTSCH. In 2009, KARL DEUTSCH became a shareholder of the French company M2M, a well-known provider of PA electronics. This electronics was successfully used for several testing machines so far. In the summer of 2013, a laboratory for ultrasonic systems was established in our testing systems workshop. It contains a 12 m long roller conveyor, which enables testing of bars and tubes with diameters of up to 120 mm and testing speeds of up to 2 m/s. An immersion tank of the type ECHOGRAPH-HRP was installed in the middle of the roller conveyor, where cassettes with either mono-element probes or phased arrays can be inserted. Further cassettes for larger diameters are in preparation. Currently bars and tubes with diameters of up to 60 mm can be tested. The BAM manufactured certified reference bars with different diameters. They contain several flat bottom holes and side drilled holes in different depths (near-surface, center region, near backwall) and diameters (0.7 mm, 0.8 mm, 1.2 mm). These reflectors for the sensitivity adjustment and recording of the TCG-curves needed to be eroded because of the small diameters and the required accuracy. The reference blocks allow for both static and dynamic tests. Optionally, either a conventional or a phased array ultrasonic electronics is applied.

Array setups with up to 512 elements are supported in this testing machine for 100 % coverage of the material cross sections to be tested. In the new test laboratory specimens of interested customers can be examined dynamically and free of charge. There is no plan to offer NDT inspection services: The laboratory will serve exclusively for customer advice. In case of special inspection tasks KARL DEUTSCH is able to manufacture customized array probes. This is based on a prior analysis of the inspection task with the aid of the CIVA software, which provides the specification of test parameters for electronics and sensor technology and allows for precise design specification of the probe with respect to number and size of elements, curvature of the sensor and test frequency.

Figure 1. The 12 m long roller conveyor with ECHOGRAPH-HRP immersion tank in the new laboratory for ultrasonic testing systems

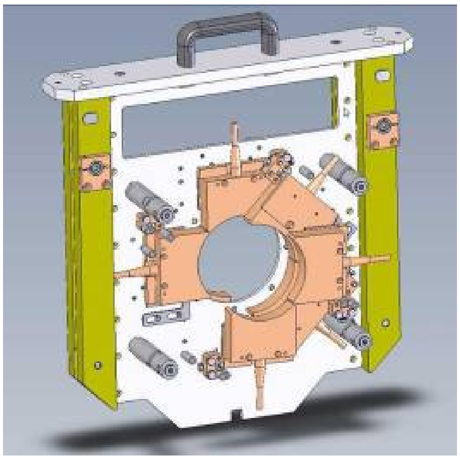

Figure 2. Probe holder cassette with eight phased array probes which cover the entire bar circumference

2. ECHOGRAPH-TTPS Ultrasonic immersion tank testing of aerospace bars

In the German town of Unna, ThyssenKrupp VDM has invested in a new production line for high-grade titanium and nickel-based materials to supply end customers in the aerospace industry. Within this project, a new ultrasonic testing system of bars was provided by KARL DEUTSCH. The duty book described bar diameters between 90 mm and 405 mm, bar lengths between 0.9 m and 6 m, bar weights up to four tons and a high-precision test mechanic. The examination of such bars is carried out in immersion technique and usually with the aid of straight beam insonification. In order to meet the demands of many aerospace specifications the system copes with a very high test sensitivity of 0.4 mm FBH (Flat Bottom Hole Reflector). In order to accomplish this, the bars are subdivided into several depth zones. Four to seven depth zones are specified for four diameter ranges of the bars. Each depth zone is tested by means of a dedicated strongly focused probe, thus enabling such high test sensitivity. Since manufacturing of reference material with flaws of 0.4 mm FBH is mechanically difficult, the sensitivity is adjusted by using 0.8 mm flat bottom hole reflectors. Suitable sensitivity offsets then provide the desired testing sensitivity. For each of the four diameter ranges a reference block is provided with one FBH reflector per depth zone. The system control ensures that all probes scan their relevant reflectors. The maximum echo amplitudes for each reflector are determined in order to automatically create the TCG sensitivity curve (TCG = Time Corrected Gain). The test results are provided as C-Scans with a wide range of representation possibilities. The bars can be evaluated by means of summarized results or individual results for each depth zone. Typical aerospace requirements for the test data evaluation such as ROI (region-of-interest), defect sizing, 3D defect distance computation, tabulated defect list and SNR in ROI (signal-to-noise ratio in region of interest) are taken into account.

Figure 3. View of immersion tank testing system for aerospace bars (titanium or nickel alloys)

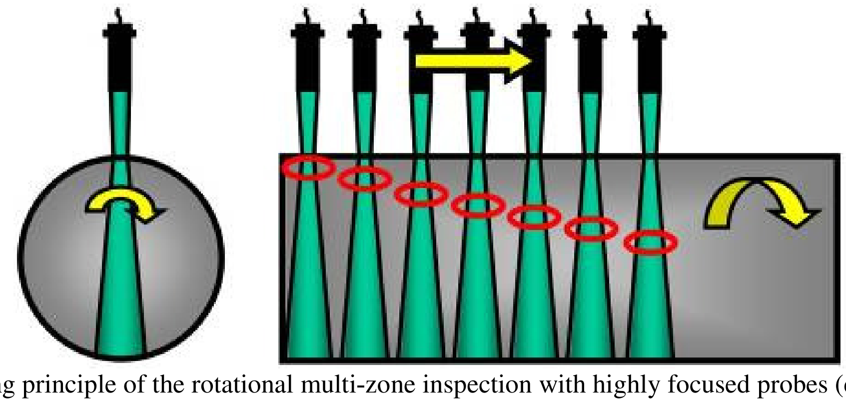

Figure 4. Testing principle of the rotational multi-zone inspection with highly focused probes (example: 7 depth zones are covered by 7 straight-beam probes)

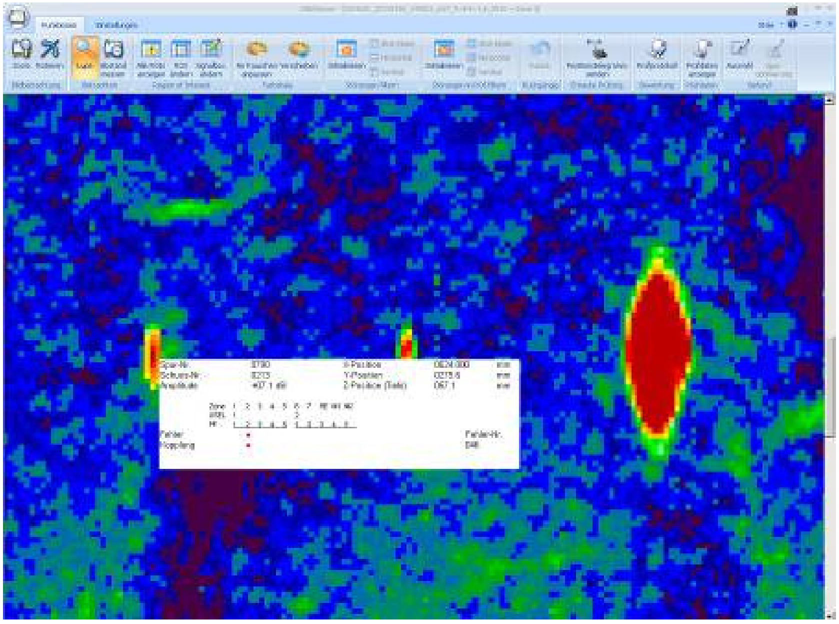

Figure 5. C-Scan test result of calibration bar: Each pixel represents one ultrasonic shot. By a mouse click the respective test data is displayed (defect number, pixel position, ultrasonic amplitude with respect to threshold, etc.).

3. ECHOGRAPH-RPTS Testing portal for forged billets of large diameter

The company BGH Edelstahl Siegen GmbH invested in a new ultrasonic testing system for steel bar diameters between 300 mm and 1000 mm, lengths between 1.5 m and 10 m and component weights of up to 35 tons. In general, the component surfaces are rough-turned with a surface roughness of 25 µm. The forgings are loaded into the testing system by means of a crane. The forging is set in rotation. Typical circumferential surface speeds are 0.15 m/s. The ultrasonic probes operate on the 12 o'clock position and linearly move along the axis of the bar. Thus, the bar is tested in helical tracks.
The new ultrasonic testing system uses two separate testing stations – therefore, a total weight of 70 tons needs to be handled by the testing mechanics. While one station is used for the inspection, the second station can be used for manual post-examination, loading / unloading and service work.

Figure 6. View of the newly developed ultrasonic testing system in the turning shop No III of BGH Edelstahl Siegen GmbH

Loading operations with such high weights are challenging for any testing mechanics. Therefore, the roller devices are equipped with damping modules, which are pneumatically positioned. The floor space of the system is 5.3 m by 14.6 m and the system weight is 40 tons. Prior to shipment, the testing system was fully put into operation at the KARL DEUTSCH systems workshop in order to verify all relevant system parameters. During mechanical construction, a modular design was realized in order to provide fast taking down and fast reassembly at BGH Edelstahl Siegen GmbH. The testing system was successfully put into operation in November 2012.

Special highly sensitive ultrasonic probes with a particularly large test track were designed to achieve a high throughput. The four test tasks comprise straight-beam insonification of the near-surface area with dual-element probes, straight-beam insonification of the core area with single-element probes and angle beam insonification in both circumferential directions (testing for longitudinal flaws) with angle probes. To increase the throughput, eight similar probes for each task are provided, i.e. a total of 32 probes. A helical feed of 32 mm per revolution and per probe could be achieved, resulting in a total feed of 256 mm per revolution. Naturally, defect size, impulse repetition frequency and test speed depend on the material properties. Since sound conductivity in forgings is excellent, phantom echoes might occur. Therefore, two parallel electronic modules and two totally independent probe holder units with a perfectly synchronized ultrasonic shot cycle were realized.

The ultrasonic probes were mounted in a circumferential link chain. The chain was flexibly designed to match all relevant bar diameters. With this probe arrangement, short untested ends and a guaranteed overlap of the test tracks of the neighboring probes are ensured. Overlap is produced for small and large helical feeding per revolution.

Figure 7. Roller devices with damping modules for large component weights

Ultrasonic coupling was achieved by means of a narrow water gap between probe and component surface. For convenient system operation, a motorized gap adjustment was realized, i.e. the gap is optimized in accordance with the curvature and diameter of the bar. Also, the inevitable wear of hard-metal shoes can be compensated.

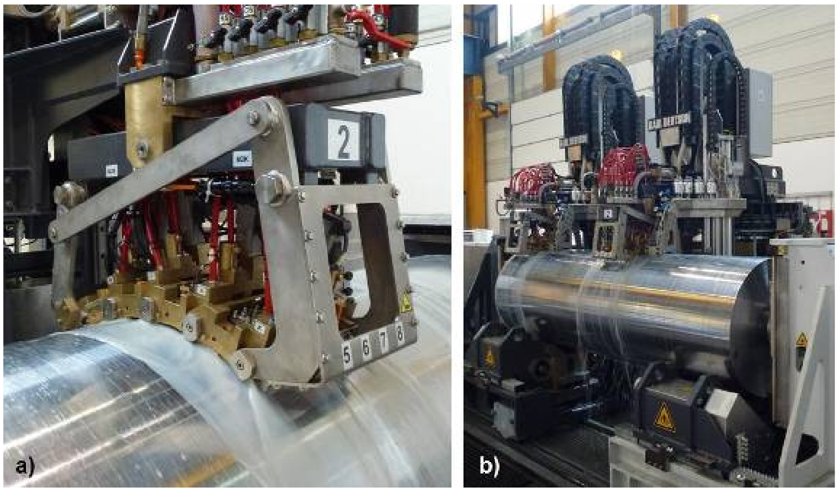

Figure 8. Probe holder for steel bar testing, a) each probe holder contains a matrix of 4 x 4 probes, b) two separate probe holders were used for acoustic decoupling reasons

The required maximum testing sensitivity of the near-surface region could be as strict as 0.8 mm FBH (for a depth of max. 50 mm) and 1.5 mm FBH for the core region. A thorough design of the probes (e.g., roof angle of dual-element probes, near field range of straight-beam probes) was required to provide full overlap in the transition zone (between surface and core). The angle beam probes are calibrated by means of 2 mm surface notches and 6 mm side-drilled holes. Extensive sound beam measurements on samples with artificial defects were carried out to verify full volumetric ultrasonic coverage.

4. ECHOGRAPH-SNHF Ultrasonic testing of ERW pipes

The production of ERW pipes includes several steps of NDT in order to obtain early information about the welding process as a feedback for the production line and secondly, the final inspection of the finished pipe. If the wall thickness gets too large for eddy current testing and if stringent specifications of the oil and gas industries must be fulfilled, ultrasonic testing is the method of choice.

Several ultrasonic systems are encountered during the production process. As a first step, often the strip is tested either with fixed or oscillating probes. In recent projects, a full coverage of the strip was realized with linear test tracks and a large number of fixed probes. Directly after welding, a first online weld test is carried out. This is to check the quality of the welding process as well as the internal scarfing. After annealing, mechanical treatment and hydrotest, the final weld inspection is carried out (offline weld testing). A testing portal with moveable carriage is commonly used. The testing portal shows the advantage that the weld is inspected without pipe movement, thus avoiding vibrations which could degrade the test results. The pipe ends can be tested in the same testing system or in a separate setup. As an alternative to a strip tester, the full-body inspection can be performed in the pipe stage. Either the offline weld testing portal is extended with additional full-body probes or a separate pipe body testing system is used.

The weld test specifications for ERW pipes describe the artificial test reflectors which must be detected (mostly longitudinal internal and external notches or through drilled holes). The reflector size (notch length and depth or hole diameter) is stated in accordance with the requirements. The specifications do not stipulate the use of mono-element or phased array ultrasonic testing (PAUT). The online weld testing with mono-element and with phased array probes is now described in detail.

During the online weld test, the weld seam is in the 12 o’clock position. For an automated weld inspection with mono-element probes, the use of two probe pairs is typical (2 probes for internal defects, 2 probes for external defects). In addition, the inner pipe surface of the tube can be inspected for proper removal of the burr. An oscillating probe movement with straight beam incidence is carried out.

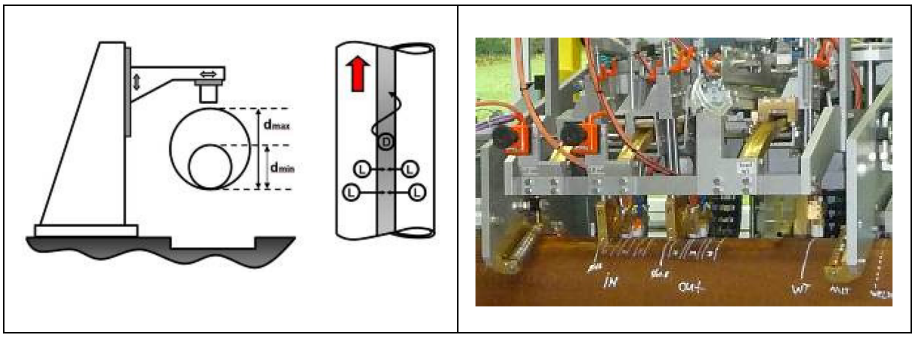

Figure 9. Conventional online weld testing with five ultrasonic probes

Water jet coupling is applied, which means that the water path between probe and tube surface is in the order of several centimeters. This method of ultrasonic coupling results in little wear for the probes and the probe guiding devices. Also, the angle adjustment is carried out within the probe carrier – in contrast to water gap coupling where the testing angle is fixed within the ultrasonic probe. Any required testing angle can be chosen and steplessly adjusted. Even for an uneven pipe surface, stable coupling conditions are achieved because the water path can vary more than with gap coupling. Finally, this method is robust at elevated temperatures as the water flow protects the probes from damage.
The mechanical setup for an online testing system consists of a stable machine frame, a horizontal boom and the probe holders. The boom which can be adjusted in height according to the pipe diameter is attached to the frame by a vertical drive. All probe holders can be moved between the testing position (online), and the calibration position (offline) by means of a horizontal drive. The calibration station consists of a table which is motorized. The table carries a test tube with artificial defects. This enables a dynamic check of the testing sensitivity. An automated seam tracker is provided. A paint line on the side of the pipe (pilot line) is constantly tracked by a CCD color camera. The camera is equipped with a strobe LED illumination for excellent performance also in poor lighting conditions.

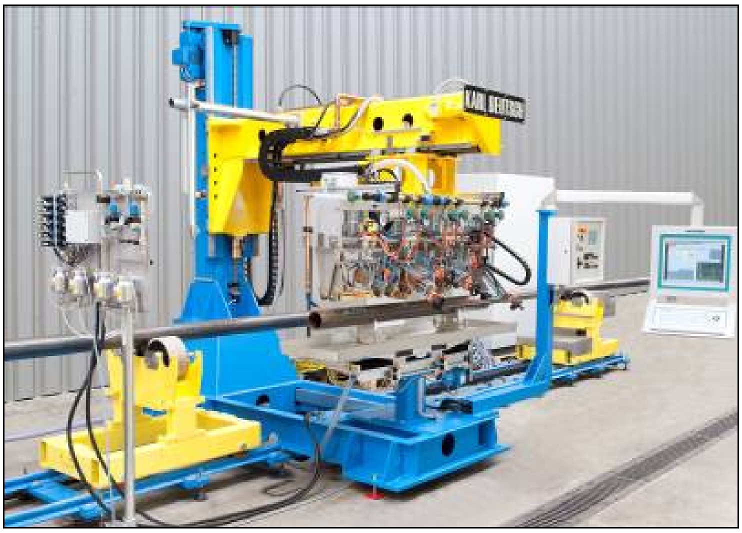

Figure 10. Conventional online weld testing system (this example with 8 probes). The probes are moved offline above a short tube sample for calibration.

The advantages of an ultrasonic testing system using mono-element probes are:

- Small number of testing channels, relatively inexpensive test electronics
- Small number of relatively inexpensive probes
- Long life time of the probes due to the cooling and cleaning effect with water jet coupling (squirter)
- Reliable coupling due to small probe surface and small respective water jet diameter
- Any testing angle can be chosen without changing probe or mechanical parts
- No change of mechanical parts for entire pipe geometry range (diameter, wall thickness), i.e. no curved shoes etc.

Now a PAUT system for a similar test task is described, i.e. angular circumferential incidence and straight beam incidence are required. Instead of five mono-element probes, three phased array probes are used. The pipe diameter range was between 140 mm and 340 mm. It was desirable that the entire diameter range is tested with the same set of array probes to reduce the cost of the system and the respective spare parts. Curved arrays were chosen to reduce the required steering angles and to increase the test sensitivity. In order to design suitable probes with sufficient circumferential coverage, the CIVA simulation software was used. It is interesting to note, that each virtual probe (shot with group of active elements) within the phased array requires a different delay law setting – this requires a powerful phased array testing electronics! In order to avoid very large arrays (which would make coupling difficult), a seam tracking unit is provided (similar to the conventional testing system).

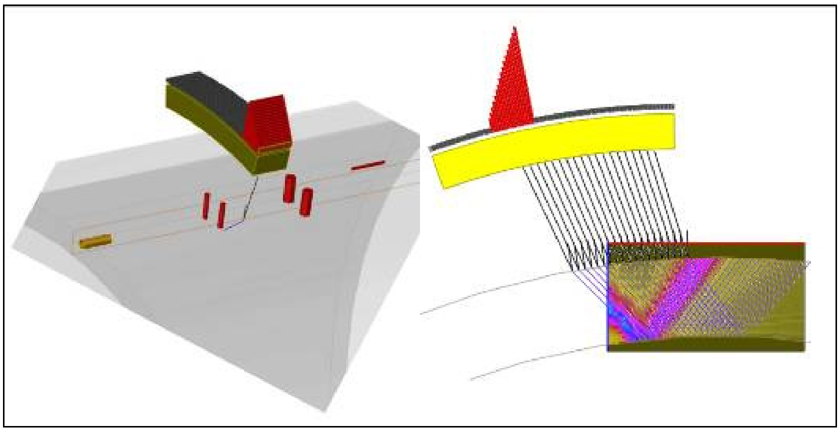

Figure 11. CIVA modelling of angular incidence into the pipe weld cross section

The mechanical setup is kept quite similar to the conventional testing system. A spindle with mechanical drive and position indicator is still provided for optimum array positioning with respect to the weld seam. Ultrasonic coupling is now carried out with a water-filled chamber between array surface and pipe surface. As with conventional water jet coupling, the nozzle design is crucial for proper test results. Sound beam diameters, testing angles and side lobes which might occur with phased arrays must be taken into consideration. The nozzle outlet radius must match the pipe diameter, i.e. the nozzles must be exchanged in accordance with the pipe geometry.

An M2M phased array testing electronics with 320 parallel channels drive the three array probes. The large number of testing channels allows an extremely flexible assignment of the delay laws for each virtual probe, a high testing speed, a good shot index and parallel firing of several virtual probes within one array. Nevertheless, the electronics is very compact and requires only a small cabinet which was mounted to the machine stand. The test electronics allows to visualize several test functions parallel and in real-time (multiple A-scans, B-scans, C-scans). A strip chart representation of the ultrasonic amplitudes versus pipe length (similar to conventional testing systems) is also provided.

Figure 12. Three phased array probe holders with white plastic water nozzles

The advantages of a phased array testing system are:

- Reduction of the size of the test mechanics by reducing the number of probes
- Multiple test angles and tandem method with the same probe
- Large testing area due to large array probes, weld seam wandering is therefore less critical
- B-scan visualization of the test results as cross sectional views
- C-scan visualization of the straight-beam test and therefore good monitoring of descarfing area

5 ECHOGRAPH-SNUL Ultrasonic testing of longitudinally welded SAW pipes

Following the common specifications (e.g., API5L, DNV and SHELL), an ultrasonic inspection is mandatory with the main focus on the weld (weld zone and heat-affected zone HAZ). Some final customers of the pipes also require an inspection of the heavy plates. This inspection is typically carried out in the plate mill and recently with testing concepts which employ enough probes for a 100 % coverage of the plate volume. A first ultrasonic weld testing system is used for the supervision of the welding process. It can be considered as an internal test. The final inspection (after the hydrotester) with a second weld testing system is basically the last production step and ensures a proper pipe quality. The probe configuration is in accordance with the above mentioned test specifications and a test report for each pipe is produced.

Testing systems in pipe mills can use mono-element and phased array probes. For large wall thicknesses and many test angles and calibration defects, the phased array technique has many advantages. Even if the test speeds for LSAW-pipe inspection are not very high, a large number of test channels is typically used. Dependent on the test speeds and the requirements, powerful phased array electronics in multiplexed or parallel architecture are available.

The most important testing task is the detection of longitudinal defects (lack of fusion, mid-seam defects with multiple test angles). Some existing testing machines were recently extended by longitudinal phased probes.

Figure 13. Probe holders for LSAW-pipe weld testing system. Two phased array probe holders are provided for longitudinal defect detection.

Future work will comprise phased array probes for all test functions. A possible probe configuration which would fulfil the highest requirements (SHELL, DNV, etc.) is proposed:

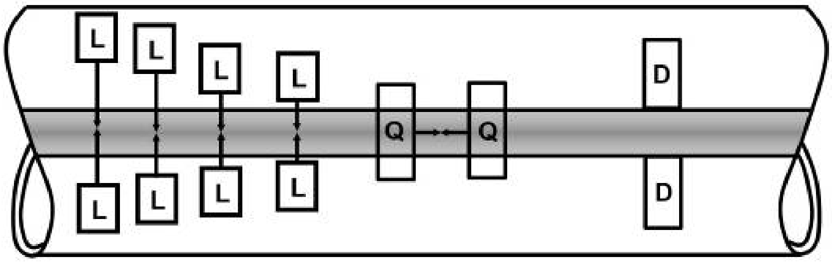

Figure 14. Phased array probe configuration for LSAW pipes.

Many different test angles for the detection of longitudinal defects (L) can be produced in parallel. Linear arrays for transverse defects (Q) are mounted on-bead and cover the entire weld bead. Linear arrays for lamination detection (D) cover the entire heat-affected zone with a width of 50 mm track.

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