In-line Ultrasonic Testing of Welded Stainless Steel Tubes

Presenter:

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1. Abstract
Ultrasonic testing (UT) of heat exchanger tubes made of stainless steel and Titanium alloys is mandatory due to a number of standards. The prerequisite for reliable testing is automated testing equipment which produces documented results. For this purpose Magnetic Analysis Corporation (MAC) offers complete turn-key ready systems including material handling; which allows the user to meet the most widely used UT standards. This article covers the requirements, the basic components, the test procedure, and displays some results of the test equipment at Schoeller Werk, Germany. The first test line (erected in 2009) reached its capacity limits and therefore in March 2011 a second line with enhanced test capabilities was delivered and installed. Schoeller Werk uses the UT equipment not only for fulfilling NDT requirements but as well for a quick feedback for the operator of the welding line. Bad welding quality heavily affects the UT testing. Monitoring of the noise level can be helpful for adjusting the weld line.

MAC designed a unique material handling in order to fulfil the customer requirements to allow the testing and sorting of up to 33m long tubes (dimensional range: 10 to 50 mm OD, 0.5 to 4 mm WT) at the end of the welding line. Typical artificial defects for adjusting the equipment are notches of 12.7mm (0.5”) length and sometimes a depths of as low as 0.1mm. The installation consists of an inlet table with variable length, the test bench with the seven channel UT rotary and automatic centering function and an outlet conveyor of variable length with sorting capabilities. As the testing speed of 30 m/min is higher than the maximum speed of the laser welding line, the system is used as well for testing of tubes manufactured on other production lines. In that case the inlet table creates an ordered single layer of tubes out of the bundles which are supplied by cranes. Depending on the test results the tubes are sorted automatically by the outlet conveyor. Defective sections can be marked with a built in ink marker system. The Testing equipment has proven its capabilities to reliably run 18 shifts a week since mid 2009 and was certified by the TÜV Rheinland Group Germany to be compliant with the main UT standards for heat exchanger tubes. In order to enhance the testing capabilities MAC installed a second testing line in the first quarter of this year. This line is equipped with a 14 channel rotary allowing a testing speed of up to 60 m/min. In addition the rotary allows the measurement of the outside diameter and wall thickness of the tubes in real time with UT.

2. Requirements
2.1 Schoeller Requirements
Schoeller has a history of more than five decades of stainless steel tube manufacturing. Due to increasing customer demands regarding Non-destructive testing requirements of longitudinally welded heat exchanger tubes the company intended to introduce Ultrasonic testing of these products. Schoeller was therefore well equipped except Ultrasonic testing capabilities. As the requirements are well defined (see 2.2 Standards) Schoeller looked to
the market for a partner to install the mandatory UT tube tester. The aim was a fully automated system with in-line testing capabilities. The UT needed to be able to test according to all major standards. Schoeller’s aim was to deliver stainless steel tubes in the outside diameter range of 10mm to 50mm with a wall thickness of 0.5mm to 4mm and a length of 6m to 33m. The desired throughput speed of the line was 0.5m/s.

The design of the test line needed to be flexible in a way that both in-line testing of 33m long tubes at the end of an existing laser welding line was possible as well as the testing of tubes supplied in bundles from other manufacturing lines. These tubes are typically in lengths of 6m to 18m. Due to limited available space some of the components of the test line need to be removable. Additionally the tube ends need to be accessible for deburring and plugging.

Other requirements were the marking of rejected tubes and sorting into accept and reject pockets. Documentation of the test results in electronic form was another request.

2.2 Standards for heat exchanger tubes
The requirements for Ultrasonic testing of heat exchanger tubes are defined in a number of standards. The most commonly used standards in this business and for the given dimensional range are:

The standards required for welded tubes include at minimum the detection of a longitudinal defect and sometimes a transverse defect as well. In order to prove the sensitivity of the test it is mandatory to run reference tubes with well defined reference defects. These defects have to be found by the installed NDT equipment every time the reference tube is tested. Each of the reference defects have to be measured and certified by a NIST traceable procedure. Typically electrical discharge machined notches are used. Table 1 gives an overview of the requirements of different standards.

<table>
<thead>
<tr>
<th>standard</th>
<th>type of reference defect</th>
<th>class</th>
<th>dimension of the reference defect</th>
</tr>
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<tbody>
<tr>
<td></td>
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<td>depth in % of nominal WT</td>
<td>width</td>
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<tr>
<td>SEP 1914</td>
<td>ID and OD notches</td>
<td>U1</td>
<td>3</td>
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<td></td>
<td>longitudinal and transverse</td>
<td>ID and OD notches</td>
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<td>U3</td>
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<td>longitudinal and transverse</td>
<td>U4</td>
<td>12.5</td>
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<td>DIN EN 10893-10, July 2011 replaces DIN EN 10246-6 and DIN EN 10246-7</td>
<td>ID and OD notches</td>
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<td>ASTM – code rules UT in accordance with ASTM E213</td>
<td>ID and OD notches longitudinal</td>
<td>ASTM A495/A495M</td>
<td>12.5</td>
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<td>ID and OD notches long and trans</td>
<td>ASTM A495/A495M</td>
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<td></td>
<td>ID and OD notches longitudinal</td>
<td>ASTM A1016/A1016M</td>
<td>12.5</td>
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Table 1: reference defects for ultrasonic testing of (welded) heat exchanger tubes

A second aspect is the inspection coverage of the tubes by the ultrasonic testing. It is essential to guarantee that the whole material is tested and there are no untested gaps. Schoeller has some advice about allowed rotational speed, maximum throughput speed and minimum pulse repetition frequency in order to guarantee full coverage. Some critical products were successfully tested in advance in pre-acceptance tests prior to the installation of the system.
3. UT Rotary and handling system

Magnetic Analysis convinced Schoeller with the turn key ready solution which covered all requirements mentioned in chapter 2.1. The system consists of:
- inlet table with access to both tube ends for deburring and plugging
- automated inlet conveyor
- automated test table with central tube guiding and height adjustment
- UT rotary with computer based parameter setting, evaluation and result documentation
- closed loop water package for treatment of coupling water
- outlet conveyor with sorting function

3.1 Inlet table

The inlet table serves two main purposes:
- access to both tube ends for deburring and plugging
- storage buffer in the production line

The inlet table allows two modes of operation depending on the use of the installation. If the UT works in conjunction with the laser welding line, the tubes are supplied by a conveyor to the inlet table. The tubes are then transported by motor driven belts in transverse direction to an end stop and thrown into the inlet conveyor. The operators have the possibility to deburr and plug the tube ends during this period. If the UT is used for testing of tube bundles, the bundles are supplied by cranes. On the belts of the inlet table the tubes are separated into a single layer, deburred and plugged and transported to the inlet conveyor. The throw-in mechanics is controlled by a programmable logic control (PLC) which uses a number of inductive sensors to check if the tube is placed over the whole length in front of the final stop. This is necessary to prevent bending of the tubes. If all sensors have detected the tube it is elevated into the inlet conveyor.

Figure 1: Inlet table with motor driven belts for transverse transport and for storage. In in-line operation the tubes are fed by the conveyor belt on the left of the picture to the table. The belts transport the tubes in transverse direction to the final stop on the right hand side. Pneumatic cylinders elevate the tubes into the inlet conveyor, which is integrated into the stands on the right hand side of the picture. The motors of the inlet conveyor line are mounted on the green stands. Each conveyor roll has its own driving motor.

Operators have access to both tube ends between the stands for deburring and plugging.
3.2 Inlet conveyor
The inlet conveyor feeds the tubes to the test table. The line consists of motor driven double V-shaped rolls. It can be operated in automated mode and manual mode. The manual mode is typically used for setting up the UT rotary where the tube often is run several times back and forth in order to optimise the settings. Once the tubes are fed into the inlet conveyor they cannot be transported by the system back to the inlet table.

3.3 Test table
The test table consists of a stiff frame which holds the motor driven triple roll drivers and the slide mechanism for the UT rotary. The frame is PLC controlled and height adjustable to allow the system to run tubes with different diameters out of the conveyor lines. In the V-roll conveyors the height of the centre of the tube is a function of the tube's outside diameter.

The test table is necessary for a stiff and central guiding of the tubes through the UT rotary. The tubes are centred through the triple drivers that automatically open and close at the tube ends. These drivers close to a common central point and guarantee that the tubes are fed to the guiding bushings of the UT rotary. The UT rotary is mounted on a slide table to allow movement to an off-line service position.

The table is equipped with optical sensors and encoders to track the tube throughout the test station. At the end of the system an air knife is used for drying, followed by an ink marker for the identification of defective areas.

Figure 2: Test table with four triple stands, rotary and water system. The water chiller and the water storage tanks are placed behind the test line. The tubes are guided from right to left through the UT rotary.
3.4 Ultrasonic rotary

Figure 3: UT rotary with water retentions, engine (in blue) and lubricator package (mounted on the backside). On the front side the brass connector for the coupling water hose is visible. The retention contains a rubber gland for additional sealing to keep as much water as possible in the water cycle. The rotational part is covered by the black anodized box. The hatch is locked and the lock is controlled by a PLC to satisfy safety regulations according to CE requirements.

The UT rotary holds up to seven different ultrasonic transducers in a stainless steel cube with adjustment capabilities. The whole cube is constantly filled with tempered, degassed coupling water and spun typically at 3000 rounds per minute. The tube is fed through a central hole in the cube at 0.5m/s. In order to allow a precise measurement it is eminent to have a good control of the coupling water and a precise central guiding of the tubes. This is realised by the use of four plastic guiding bushings. In order to allow short untested ends it is necessary to plug the tube ends. Otherwise, water drops on the inner tube surface will lead to reflections of the ultrasonic beams and result in erroneous indications.

The rotary is equipped with several transducers for longitudinal and transverse defect detection. The transducers are capable of testing the whole diameter range which is covered by the rotary without need of an adjustment of the offset distance to the tube's surface. The only adjustment that is needed is the adjustment of the incidence angle due
to the different sound velocities of different materials. This is easily done with an rotational offset of the transducer holder assembly. The bigger the rotational offset the bigger the incidence angle in water.

Figure 4: UT rotary with open cover. On the right hand side the transducer holder with adjustment possibilities for the incidence angle is visible. The whole stainless steel block is spun with typically 3000rpm. It is driven with a transmission belt from an motor on the outside of the covered area.

The transducers are connected to local electronics which are mounted in the rotary (black anodized ring right to the transmission belt) and contain pulsers and pre-amplifiers. These electronics are supplied over an inductive connection with external power and UT signals from the Ultrasonic electronics.

The system is easy to maintain; wear parts like the oil-mist lubricated bearings can be replaced on site within several hours. The typical life time of a set of bearings is more than one year (when used for 18 shifts/week)

3.5 Ultrasonic Electronics
The ultrasonic electronics consists of proprietary FPGA-boards which are installed in an industrial PC. The system is scalable. One PC can be extended to a 32 channel UT electronics. All functions are accessible with help of the MAC software Echohunter. The system runs under Windows.

The main features are:
- individually settable gain, delay time, four gates per channel
- simultaneous display of up to eight A-scans and charts
- freely adjustable distance amplitude correction
- synchronisation of gates and display to initial pulse or interface echo
- pulse repetition frequency of up to 20 kHz
- easy setting of testing line parameters like distance to markers, sorting gates, ...
- easy setting of UT parameters by copying of already adjusted channels
- control of markers and sorting gates based on the test results
- storage of parameter sets
- batch statistics and documentation
- password locking of functions
Figure 5: Setup Screen of the Echohunter-Software
The setup-screen allows full access to all relevant UT parameters for both defect detection and wall thickness measurement like gain, gates, delay time, damping, distance amplitude correction. The effects of all changes can be directly seen in the A-scan representation.

Figure 6: Multi Channel Representation
The multi channel representation allows investigation of problems like crosstalking between two channels and gives some more insight into artefacts which may occur in dimensional measurement. Additionally the interaction of one defect with several channels can be monitored.

3.6 Water Package
The water package contains a chiller in a closed water cycle. The chiller controls the temperature of the coupling water. This is necessary because the sound velocity in water is a function of temperature. Without constant temperature the gates in the UT electronics would need a constant monitoring and readjustment. The water is stored in tanks and is pumped through the chiller and hoses into the UT rotational chamber where the transducers are installed. This is necessary for acoustic immersion, otherwise most of the energy of the ultrasonic pulses could not enter the steel tubes. The chamber is constantly held under a low water pressure. The coupling water leaks through the guiding bushings into retention tanks which are drained into the storage tanks. Due to contamination of the coupling water by process fluids on the tubes a regular change of the coupling water is necessary. From time to time the system has to be cleaned to avoid the formation of foam in the water system. Gas bubbles in the coupling water would lead to a lack of coupling. This is normally prevented by the use of storage tanks of a sufficient size, where the water
can settle after it is collected underneath the rotary and fed in once again into the water cycle.

3.7 Outlet conveyor with sorting
The outlet conveyor consists of segments with motor driven V-rolls and a pneumatic operated sorting gate which is controlled by the UT electronics. When the tube leaves the test table rejected tubes are sorted to one side into a pocket whereas accepted tubes are sorted to the opposite side of the conveyor into the accept pocket. The tubes are then unplugged, bundled, packaged and shipped.

Figure 7: Outlet conveyor with sorting function
The yellow bars below the green stands are moved pneumatically up or down the conveyor line. They raise plastic cones which will sort the tubes into either the accept or the reject pocket – based on the test result for the tube

4 Testing procedure
4.1 Setting up the instrument
The system set-up is a two step procedure: The first step is the mechanical set-up and adjustment of the testing table. The second step is the adjustment of the transducers and UT parameters with the help of a sensitivity check on reference tubes with known reference defects.

The mechanical set-up is done by adjusting the table height by typing in the correct numbers into the operator’s panel of the PLC and changing of the guiding bushings in the rotary.

The adjustment of the ultrasonic test is done with the help of the reference tubes described in chapter 2.2. A reference tube is fed into the rotary and stopped with a reference defect underneath a transducer. Then a rough adjustment of gain and gate position is done. As next step the Echohunter-software helps with a value for the offset for the longitudinal defect detection transducer. With the still standing rotary the signal of the reference notch is then peaked up and a fine adjustment of the parameters is done. This is done for all UT transducers. Finally the rotary is started, the gate positions are checked once again and a test run of the reference tube is accomplished in order to check the settings and adjust the gain. When the detailed order and batch information is fed into the UT electronics the testing can be started.
Figure 8: Test run of a reference tube (reference tube #62) using an Echomac® with Echohunter® Software

Tube dimensions: 22.22mm OD x 0.51mm WT, material: 3.7035, longitudinal notches inside and outside, notch dimensions: 12.7mm x 0.787mm x 0.102mm (length x width x depth)
Figure 9: Test run of a reference tube (reference tube #93) using an Echomac® with Echohunter® Software

Tube dimensions: 16.00mm OD x 1.50mm WT, material: TP439, longitudinal and transverse notches inside and outside, notch dimensions: 25mm x 0.375mm x 0.1875mm (length x width x depth)

The indications in the transverse channels on the left side and on the right side are of the joints between the reference tube section and the guiding tube that is necessary to guide the reference section through the rotary.
Figure 10: Test run of a reference tube (reference tube #117) using an Echomac® with Echohunter® Software

Tube dimensions: 19.00mm OD x 1.65mm WT, material: TP439, notch dimensions: 12.7mm x 0.40mm x 0.20mm (length x width x depth)

4.2 Testing
The testing is done in automatic mode. The inlet table feeds the deburred and plugged tubes into the inlet conveyor. The inlet conveyor passes the tubes into the test table where they are tested. The outlet conveyor sorts the tubes based on the test results. The system can operate without operator interference as long as there are tubes on the inlet table and space in the sorting pockets. Nevertheless due to the deburring and plugging of the tubes an operator is needed. Typically every four hours a sensitivity check with a reference tube has to be done and the result has to be stored.

5 Experience
The typical first call rate is in the low one digit percentage range that is: only a few percentages of the tubes have an indication that will cross a threshold. However there are possible reasons for indications and natural defects but most of the time the UT is used as a mean for process control. In case the welding or scarfing is not running smoothly the UT often suffers from an increased noise level. Therefore the UT is a perfect tool to close the feedback loop quickly after the last production step thus preventing production of more bad quality tubes.

Possible causes for indications are:
- quality issues related to the coil (e.g. laminations or inclusions)
- height and volume of internal weld seam
- misalignment of coil edges
weld defects like lack of fusion, irregular shaped welds
- transportation marks (in material supplied as tube bundles)

Additionally it has to be mentioned that there is an influence of the material on the ultrasonic testability of tubes. Different alloys with different sound velocities and different grain sizes and especially with different gradients of the grain size in the heat affected zones lead to a variation in the noise level. Some welds can all the time be detected due to a reasonable amount of reflection of the ultrasonic energy in parts of the welding or heat affected zone. Sometimes the use of a different set of optimised UT probes is the only way to test products, sometimes a review of the production process is needed to establish a quality level that is sufficient to be tested by UT.

The installation is running as of mid 2009 in a three shift operation scheme for a minimum of five days a week. The system is used for testing LASER-welded and TIG-welded stainless steel tubes and titanium alloy tubes in- and off-line.
The line is certified by the German TÜV Rheinland Group to be compliant with the main UT standards for heat exchanger tubes.

Due to Schoeller's success in the new markets the system reached it's capacity limits. As a result a second line with some modifications and additional features for off-line testing was erected in March 2011. The new system will in its final state be equipped with up to 14 probes for longitudinal and transverse defect detection, as well as wall thickness transducers.

6 Conclusion
Based on its more than five decades of experience, Schoeller has successfully expanded the range of products about ultrasonic tested heat exchanger tubes. Magnetic Analysis provided the necessary missing equipment in the form of customised, cost effective, automated ultrasonic test equipment.

The system not only fulfils the requirements of the main UT standards for the mentioned market but is additionally proven very useful as a means of process control. It closes the feedback loop and helps to maintain the highest possible quality level. The installation is highly customised, with flexible usage for in- and off-line testing and allows quick change over times. The reliability and long term stability allows the system to run up to 18 shifts a week and is able to handle tubes up to 33m in length.

7 Standards
For this article just a reduced set of standards was taken into account. Nevertheless the below mentioned standards are most often used as requirements for the Non-destructive testing of welded heat exchanger tubes made of stainless steel and Titanium alloys. The standards are:

1) Stahl-Eisen Prüfblatt 1914 (SEP 1914) edition 1983-08: Non-destructive testing of fusion-welded seams in pipes of stainless steels
2) DIN EN ISO 10893-10, July 2011: Non-destructive testing of steel tubes - Part 10: Automated full peripheral ultrasonic testing of seamless and welded (except submerged arc-welded) steel tubes for the detection of longitudinal and/or transverse imperfections (ISO 10893-10:2011); German version EN ISO 10893-10:2011
3) ASTM E213-09: Standard Practice for Ultrasonic Testing of Metal Pipe and Tubing
4) ASTM A450 / A450M: Standard Specification for General Requirements for Carbon,
Ferritic Alloy, and Austenitic Alloy Steel Tubes

5) ASTM A999 / A999M - 11 Standard Specification for General Requirements for Alloy and Stainless Steel Pipe

6) ASTM A1016 / A1016M - 11a Standard Specification for General Requirements for Ferritic Alloy Steel, Austenitic Alloy Steel, and Stainless Steel Tubes