Automated Ultrasonic Testing of Large Casted Cask Bodies using Phased Array Techniques

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Abstract. Large casks of the type CASTOR® by GNS are used in Germany as well as internationally for transport and storage of highly active nuclear waste. The body of these casks is made of nodular graphite casting. During manufacturing it is subject to NDT in an intermediate production state with almost cylindrical shape using UT in a variety of directions. The task of this project is to provide an automated ultrasonic testing machine which is capable of performing these tests with increased efficiency and reproducibility as compared to manual testing.

This contribution will show the design and realization of an AUT machine which comprises 13 phased array probes for insonification in different directions into this large (approx. 6 m length, 2.5 m diameter, 0.5 m wall thickness) component. Due to the size of the cask body the acoustic paths partly excess 3 m.

A reference body was provided with 54 flat bottom drill holes (diameter 6 mm) which represent the different flaw orientations. We will demonstrate the capability of the newly designed ultrasonic testing system using this reference body. Furthermore, several design aspects are discussed in more detail, e.g. coupling, probe and wedge realization.

The phased array system makes intensive use of sector scans in order to increase the tested volume and testing directions. The implications on particular testing directions will be discussed. Also the calibration using the above mentioned reference body will be demonstrated.

The probes were designed using simulation methods which will be presented in a different contribution to this conference.

Introduction

CASTOR® by GNS is a trademark design of casks for the dry transport and storage of high-level radioactive waste. The high quality and safety standards of CASTOR® casks require the use of various inspection procedures, including the ultrasonic testing (UT) of the complete CASTOR® body. Until recently, this requirement has been fulfilled by manual UT-inspection. New regulation standards and the reduction of testing periods have motivated the development of a fully-automated UT-inspection system.

In this contribution, we present a fully-automated ultrasonic testing (AUT) system for CASTOR® cask bodies. The UT-inspection is performed on a well-defined cylindrical cask, in an intermediate production state, with approximate length of 6 m, diameter of 2.5 m, and wall-thickness of 0.5 m. The cask body consists of nodular graphite casting

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therefore sound frequencies around 1.5 MHz are used to reduce sound attenuation and scattering. 13 phased array (PA) probes are used by the AUT-system to insonify the complete body volume in different directions. The PA-probes are grouped into 8 different inspection tasks, each corresponding to different flaw orientations. The main advantages of automated ultrasonic testing (AUT) as compared to manual testing are the increased reproducibility and reduction of testing duration. In the present case the AUT-system is also used to overcome limitations on probe size and weight, which otherwise would prevent the realisation of several inspection tasks.

The sensitivity requirement for the inspections of CASTOR® cask bodies is the detection of circular disk reflectors of 6 mm diameter in the complete volume under different orientations. The testing is performed in an intermediate production state in which the cask body is basically a simple cylinder with a closed bottom. The proof of performance of the AUT system to inspect the cask body is done by inspection of a specially designed reference body with a number of several flat bottom holes (FBH) which are designed to represent the requirements. Therefore, the design of the AUT system is done along groups of different FBHs in the reference body. The first task is thus to separate the inspection into several groups, each group represented by one or two UT probe and a set of FBHs. Afterwards a suitable probe has to be designed and tested. It will become clear that only phased array technique is able to provide the different necessary directions of inspection. Only after this work has been done successfully, the design of the complete machine could be started. This work relied heavily on simulation tools, such as CIVA [1, 2].

This contribution is thus organized along these lines and starts with the reference body and probe design. Subsequently, measurement examples and the realization of the AUT system will be discussed.

1. Reference Reflectors and Resulting Probe Configuration

A drawing of the reference body is given in **Figure 1**. There are 54 drill holes with 6 mm FBHs. The directions of the drill holes are radial, axial and tangential in different depths and partly with additional tilting in different directions.

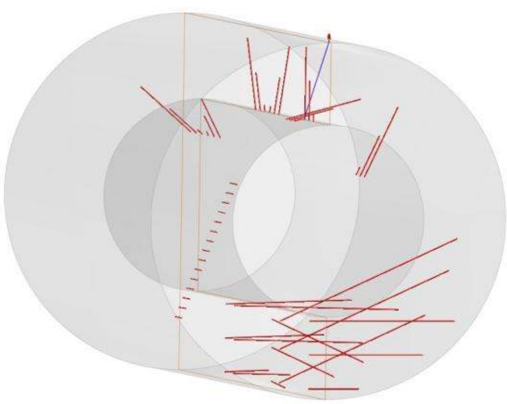

Figure 1: The reference body with indications of the different reference reflectors (6mm FBHs).

1.1. Inspection tasks utilizing compression waves

1.1.1. Inspection in mainly radial direction

In the case of standard inspection of casted materials, the inspection with perpendicular incidence with compression waves is of high importance. Therefore, the reference body exhibits 15 of its drill holes in the mainly radial direction. There are three drill holes in different depth for 0° incidence, a set of six drill holes tilted additionally in axial direction and another six drill holes tilted in the direction of circumference. The tilt angel is + or – 25° and different depths are also realized. Using conventional UT probes this would lead to five probes, one with 0° incidence, two tilted + and –25° in axial direction and two tilted + and –25° in circumferential direction. In the present design these inspection tasks are solved using two linear phased array probes both without wedge performing a sector scan from + to –35°. One of the arrays is oriented with its active axis along the axial direction and the other is oriented in circumferential direction.

Simulations and trials lead to the conclusion that a testing frequency of 1.5 MHz and an array with 64 elements is optimal for this inspection task.

1.1.2. Inspection in axial direction

There are 18 FBHs in axial direction. A series of them is located almost on the front surface of the reference body. Another three drill holes are located in different depths when viewed in axial direction. This inspection is realised by a large 128 element phased array which is located at the opposite bottom surface of the cask body. The scanning is done with a combination of electronic scanning and sector scan from sub-apertures of the array. This inspection was already reported in [2] and therefore will not be discussed in depth here. From simulations and experiments a phased array was designed with testing frequency of 1 MHz and a large pitch in order to cover an aperture of almost 400 mm. 6 mm FBHs can be detected with sufficient S/N at a sound path of more than 3m.

1.2. Inspection tasks utilizing shear waves

1.2.1. Inspection in circumferential direction

There are nine drill holes representing reflectors in tangential and additionally tilted directions – all oriented in a plane perpendicular to the cylinder axis. These FBH can be detected with one phased array sector scan where the array is performing an approx. 35° to 70° scan with shear waves in the plane perpendicular to the axis of the cylindrical cask. If these directions would have to be inspected using conventional probes at least four probes would be necessary.

In this case there are partly sound paths from more than 1 m. A sufficient S/N can be established using a 1.5 MHz, 64 element array mounted on a matched wedge. There are two probes of the same kind in order to inspect clockwise and counter-clockwise insonification directions.

Figure 2 displays a simulation for the detection of three of these FBHs. The direction is tilted by 25° with respect to the tangential direction. The simulation displays the maximum amplitude in a gate as function of circumferential position of the probe (x-axis) and sector-scan angle (y-axis). This kind of simulation was used to design and verify the necessary probes and focus settings (focus is 800 mm in this case). Real measurements show only minor deviations from these simulations.

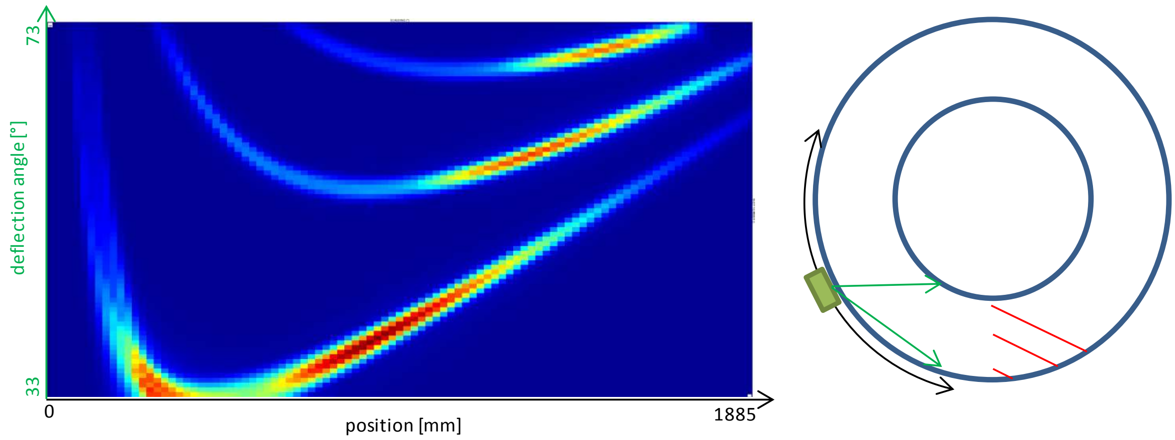

Figure 2: simulation results for the case of shear wave inspection in circumferential direction. The max. amplitude of the simulation is plotted as function of is deflection angle (green, y-axis) and circumferential position (black, x-axis). The three reflectors (red) are 6 mm flat bottom holes. The damping of the material (supposed to be isotropic) has been considered, too.

1.2.2. Inspection in axial direction

There are two probes using the same wedge as in 1.2.2. but oriented perpendicularly in order to perform a sector scan in axial direction towards the bottom and towards the top of the cask body (only the matched surface is different). The corresponding FBH are tilted 45° in different depths and can be detected using the same probes.

1.2.3. Inspection in oblique directions

Another set of reference reflectors are oriented tangentially in three different depths and are additionally tilted in axial direction by 25°. I order to establish an inspection in these directions wedges are used for the three different tangential depths and sectorial phased array scanning is used to tilt the beam in the desired axial direction. In order to perform the inspection clockwise and counter-clockwise a total of six probes are necessary. The same 1.5 MHz 64 element probe is used as for the other shear wave inspections.

2. Test Concept and Realisation: MUSI-C

The complete setup is shown in **Figure 3** and **Figure 4**. The system has been named MUSI-C (Multichannel UltraSonic Inspection of Casks) and is realized as a portal moving in x-direction with the probe holder attached. The portal can be used to scan the rotating reference body which remains in the testing system permanently or to scan the testing object itself. Therefore, the calibration can be performed before and after the inspection without the need of transportation of cask bodies.

Probes with or without wedge are in contact to the surface of the cask body but exhibiting a small gap which is filled with coupling medium. This system uses oil as coupling medium due to corrosion prohibition.

The 12 probes used to scan from the cylindrical surface are arranged in two sets of six probes each on two probe holders which can be used for separate scanning. Details of the two probes holders can be seen in **Figure 5**. The probe holder for the axial insonification is a copy of what was reported in [2].

The UT electronics consists of 7 systems of type MicroPulse5PA [3] with 128 phased array channels each. The system is able to operate all 13 probes in parallel. Due to physical limitations (recurring echoes) the pulse repetition frequency is limited to approx. 0.7 kHz.

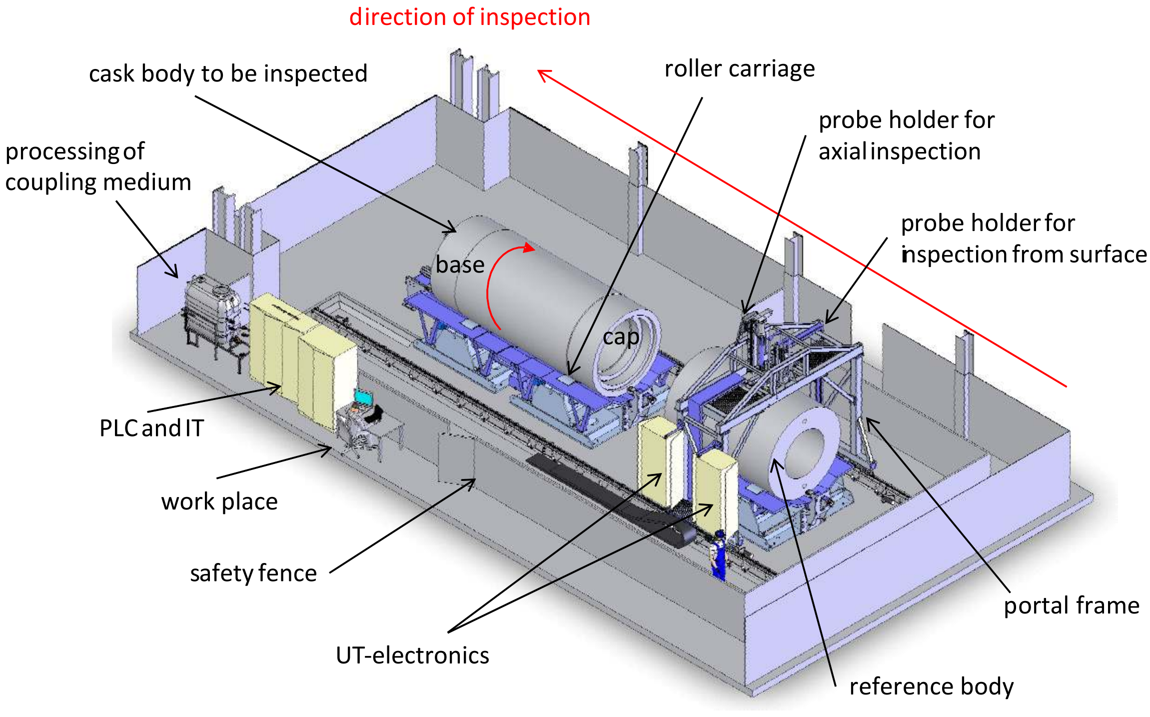

Figure 3: Overview of testing machine MUSI-C

Figure 4: Side view of testing machine MUSI-C – operator control desk in the centre.

Figure 5: Detailed views of testing machine MUSI-C

2.1. Calibration

Using the 54 reference reflectors, DAC curves for all of the probes are derived. The DAC curves are depending on sound path and steering angle. Intermediate values are interpolated linearly. The calibration is checked frequently by scanning of the reference body. The calibration is scaled to 80% FSH for the 6 mm FBHs which corresponds to the acceptance threshold. At 40% FSH a detection threshold is established.

2.2. Coupling check

Coupling check is performed by evaluation of additional firings, electronically steered towards the inner surface of the cask body. This data is stored and evaluated in order to provide coupling quality information as a function of circumferential or length position.

2.3. Software / Interface

The complete setup is automated by a PLC system and UT software. The UT software runs on a high performance industrial PC which is capable of displaying the sector-scans and A-scans of three probes simultaneously. The standard display of UT data is a combination of uncorrected sector scan and a pseudo A-scan derived as the maximum of all A-scans of the corresponding sector-scan. Thereby, the user receives a quick overview of indications in the currently probed region. During runtime the software displays C-scans of all probes simultaneously. The C-scan information is organized in three hierarchical display modes:

a) Maximum amplitude in gate over circumferential position (x) and steering angle (y)
b) Maximum amplitude in gate and steering angle over circumferential position (x) and axial position (y).
c) Projection of max values in a 3d-grid on the cylindrical surface. This is calculated by taking information from b) and mapping this into the 3d grid of the cask body taking angle and sound path into account.

All three types of C-scans can be displayed of all inspection tasks; furthermore, the calculation is performed in real-time. The software is parameterized by a database driven setup catalogue and delivers test reports automatically. A-scans of detected indications are stored together with complete C-scan information to enable off-line analysis.

In addition to C-scan information a simplified linear display of maximum amplitudes over circumferential or length position is also given.

3. Example Results

As examples reflections of the calibration FBHs in the reference body are reported here. The uncorrected sector-scan in **Figure 6** displays the situation for one probe with 0° incidence performing a sector scan of +/–35° in circumferential direction. The calibration is done using 6 mm FBH in three different depths and under 0° and +/–25°. The indication displayed here is the 6 mm FBH under 0° located in the middle of the wall thickness. The figure also shows the backwall reflection under 0°. The same calibration is used in the following **Figure 7** but using the probe rotated by 90° and thus performing the sector scan in circumferential direction. A side drilled hole of 10 mm used here as test reflector results in an indication larger than the calibration reflector although measured only at 35° deflection angle.

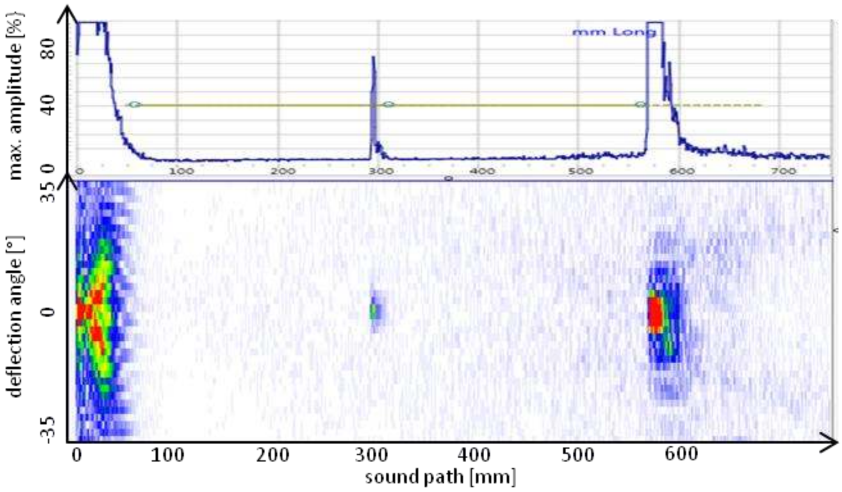

Figure 6: Example measurement of one of the compression wave probes in circumferential direction. The lower panel displays the uncorrected sector scan; the upper panel is a pseudo A-scan derived as the maximum over all scans in the sector-scan. The indication at 300 mm is a 6 mm FBH reflector.

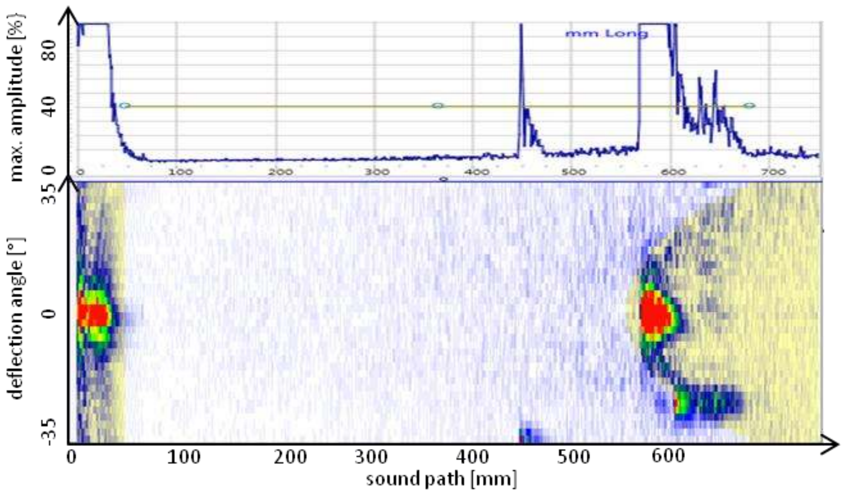

Figure 7: Example measurement of one of the compression wave probes in axial direction. The lower panel displays the uncorrected sector scan; the upper panel is a pseudo A-scan derived as the maximum over all scans in the sector-scan. The indication at 450 mm and -35° is a side drilled hole reflector with 10 mm diameter. The yellow overlay indicates the gated region.

The movement of the probe around the cask body results in a C-scan as displayed in **Figure 8** (type a) C-scan). A reference indication is clearly detected with very good S/N ratio. The other indications in this figure stem from geometrical indications.

An example utilizing shear waves is given in **Figure 9**. In the same manner as described above an uncorrected sector-scan is displayed and an indication resulting from a 6 mm FBH reflector is demonstrated. This shear wave sector-scan is oriented perpendicular to the cask-axis thus the deflection angle is in circumferential direction. The reference reflector in a distance of ~ 1m still proves a sufficient S/N ratio. However, the noise in the A-scans is seen to increase for larger sound paths and steeper angle.

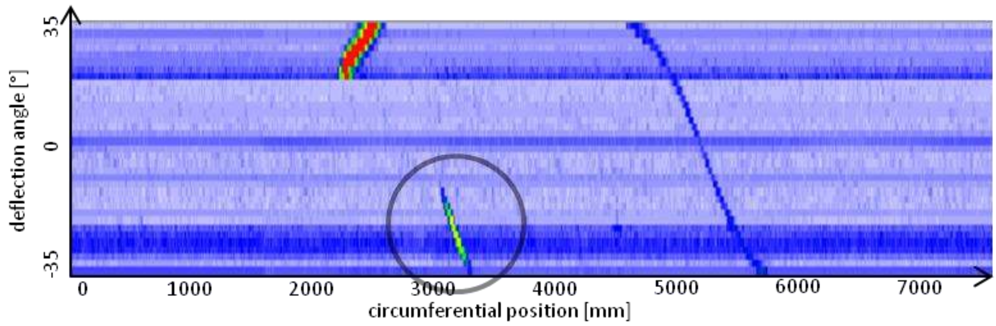

Figure 8: Example C-scan: compression wave probe with sector-scan in circumferential direction (angle is on y-axis). The maximum amplitude in the gate is displayed as function of deflection angle and circumferential position (x-axis). The marked indication is a 6 mm FBH at ~-25° and ~385 mm sound path.

Another interesting case is the inspection in oblique directions. As an example Figure 10 demonstrates a C-scan resulting of a measurement with a phased array probe mounted on a wedge with an angle in steel of approx. 35° in circumferential direction. The active phased array axis is rotated such that the sector scan is performed in axial direction in a range of +/–25°. The indication detected again results from a 6 mm FBH. The S/N ratio is excellent over the complete measurement range.

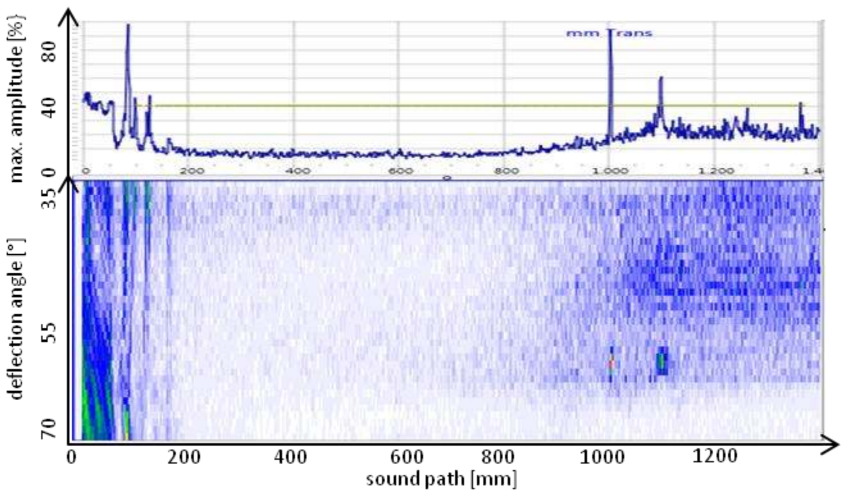

Figure 9: Example measurement of one of the shear wave probes in circumferential direction. The lower panel displays the uncorrected sector scan; the upper panel is a pseudo A-scan derived as the maximum over all scans in the sector-scan. The indication at 1000 mm is a 6 mm FBH reflector at an angle of approx. 60°.

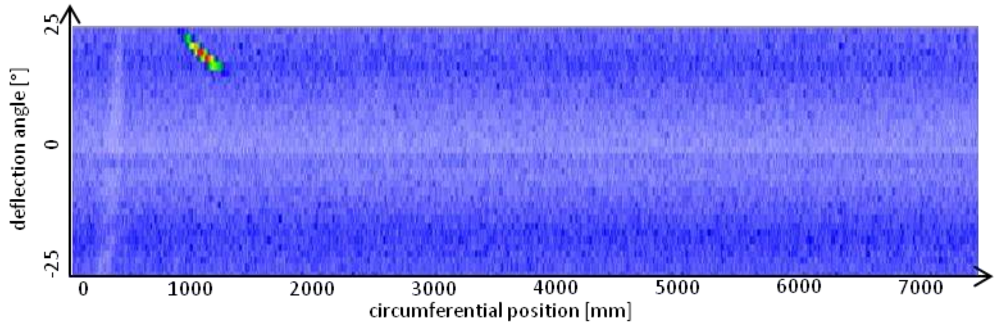

Figure 10: Example C-scan: with a shear wave probe mounted on a wedge in circumferential direction and the active phased array axis in axial direction. The indication is a 6 mm FBH at ~ 750 mm sound path.

4. Conclusion

The system MUSI-C is operational since beginning of 2016 and delivers very reproducible results. The typical statistical error derived from many subsequent calibration scans is less than 1 dB and the spatial localization of defects is typically better than 5 mm. The S/N ratio is sufficient although the sound paths used are long as compared to standard UT applications. The fast measurement results in an increased inspection throughput.

References

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[3] MicroPulse5PA is a product of PeakNDT Ltd. see www.peakndt.com