

PERFORMANCE AND RESTRICTIONS OF NON-DESTRUCTIVE TESTING (NDT) WITHIN THE QUALITY SURVEILLANCE DURING MANUFACTURING OF TYPE B- PACKAGES

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ABSTRACT

The Competent Authority BAM (Federal Institute for Materials Research and Testing) is responsible for the supervision of quality assurance and quality control of Type B-Packages in Germany.

BAM is supported by independent experts of TÜV Rheinland. The main work scope of these experts is the surveillance of the manufacturing process of components or whole packages for transportation of radioactive materials.

Today the required material quality and in particular the acceptance criteria for indications are in many cases determined according to fracture mechanical standards or new analysis concepts. The present paper describes several important aspects for working out agreed concepts in respect to the package design analysis and the quality assurance.

In scope of quality assurance the unacceptable material defects in Type B-packages must be sufficiently sure excluded by means of non-destructive testing. Thus the NDT gains in importance for quality control and design safety assessment of packages.

The paper presents following examples of ultrasonic NDT practice:

- Ultrasonic examination of thick-walled cask body made of ductile cast iron
- Ultrasonic examination of bottom to shell weld of forged flask

The perspectives and limitations of NDT as well as novel development approaches to catch the state-of-the-art technology are presented.

INTRODUCTION

The German Competent Authority BAM (Federal Institute for Materials Research and Testing) is responsible for the acceptance and supervision of quality assurance measures for the design manufacturing and use of transport packages. The goal of the quality assurance and quality control while manufacturing of packages is to guarantee the specified boundary conditions of the Safety Analyses Report (SAR).

Depending on the cask material used the theoretical assumptions in the SAR and the corresponding requirements of the ultrasonic examination on the cask body can be changed. The concept for the theoretical safety analysis depends on the material used too.

One part of the SAR is the assessment of the fracture mechanics. As a result of the numerical analysis stress and strain distributions and the amount of them were determined. In case of a thick walled cask body made from ductile cast iron the concept of fracture mechanics analysis is based on the normal stress in the critical parts of the cask body under estimation of an artificial flaw in the cask body.

Under these assumptions the stress intensity factor for the critical part of the cask body can be determined and compared with the fracture toughness. The stress intensity factor depends amongst others on the geometrical dimension and the orientation of the artificial flaw in the cask wall. Therefore it is very important to know, how and in which direction such a flaw has to be excluded in the cask body. For detecting a flaw, Ultrasonic Testing (UT) is an available method on thick-walled cask bodies. This non-destructive testing method must be able to

detect a flaw with specific geometrical dimension in the material reliably. In this way it is possible to guarantee that appeared material defects are in accordance with the assumptions made in the theoretical safety analysis and inadmissible flaws can be excluded.

THE CONVENTIONAL ULTRASONIC TESTING (UT), PERFORMANCE AND RESTRICTIONS

The ultrasonic testing of thick-walled cask bodies is typically a manual procedure regulated by special codes, which is reasonably conform to common state of the art in ultrasonic testing of steel and cast iron components.

While ultrasonic examination the operator manually scans the inspection object with prescribed overlapping and speed. Thereby he is responsible for complete coverage of inspection volume without gaps and simultaneously he have to register and evaluate all the relevant indications from the screen of flaw detector.

Evaluation of UT indications is carried out based on echograms (A-Scans) obtained in pulse-echo mode. An A-scan represents the amplitude of reflected ultrasonic wave along the sound path in material (Figure 1).

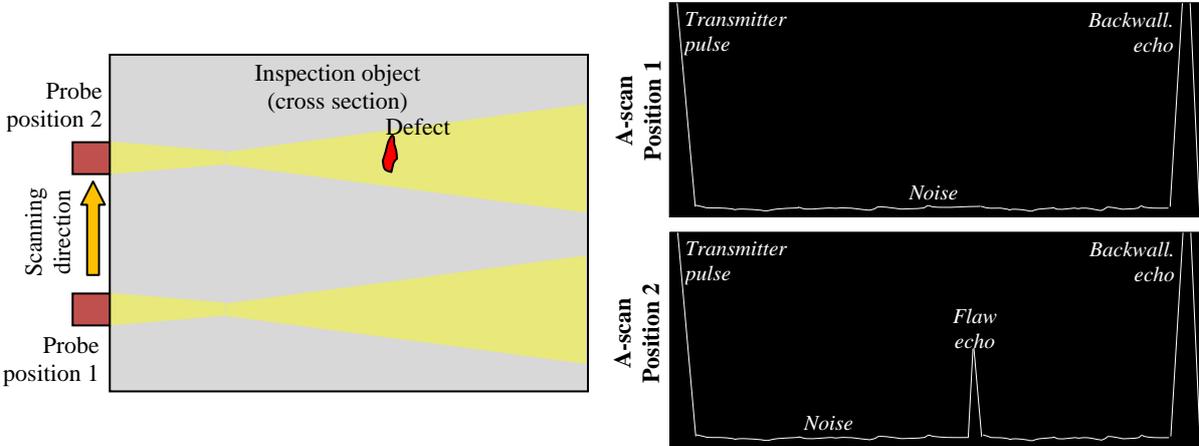


Figure 1. Principles of flaw detection by pulse-echo UT

By interpretation of A-scans the operator is able to estimate position and size of the ultrasonic indications [1].

For *position estimation* so called *distance calibration* must be carried out. Thus in case of pulse-echo probe the UT flaw detector directly shows the distance to a possible material flaw. The *estimation of a possible flaw size* occurs by evaluating the defect echo amplitude. A sensitivity calibration must be carried out that allows operator classifying the UT indications. The concept behind the sensitivity calibration of ultrasonic instruments is so called *Equivalent Defect Size (EDS)*.

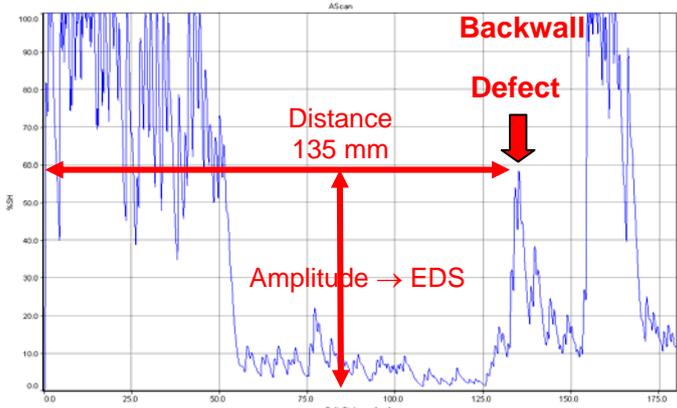


Figure 2. Estimation of defect position and Equivalent Defect Size

In order to have universal references for evaluating the UT indications the reference reflectors for sensitivity calibration have been introduced, such as *Flat Bottom Holes* (FBH) or *Side Drilled Holes* (SDH).

There are two commonly used methods applied for sensitivity calibration on steel and cast iron components:

- 1) DGS diagram method
- 2) Calibration block method

DGS diagrams represent interdependence of three values: Distance to reflector, Gain value required for getting echo signal to certain amplitude and Size of a flat bottom hole on the basis of theoretical models.

Figures 3 and 4 show the DGS diagram of a normal beam transducer and corresponding A-Scans while practical calibration and testing.

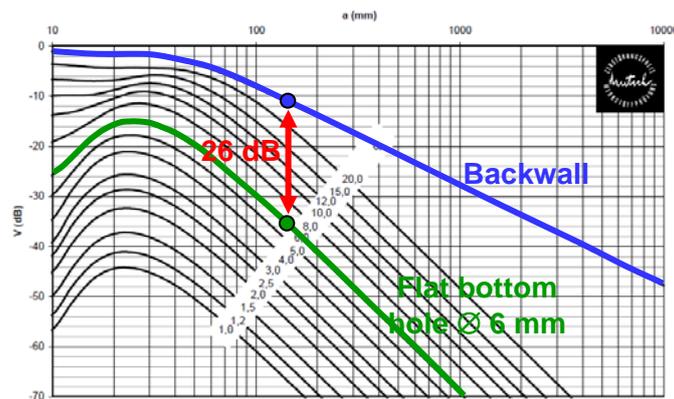


Figure 3. DGS diagram of UT transducer S24W1 from Karl Deusch

Distance Amplitude Correction (DAC) mode in modern digital flaw detectors allows adjustment of gain value depending on the sound path according to DGS diagrams. Thus reference reflectors of the same size provide echo signals of the same height independent of sound path.

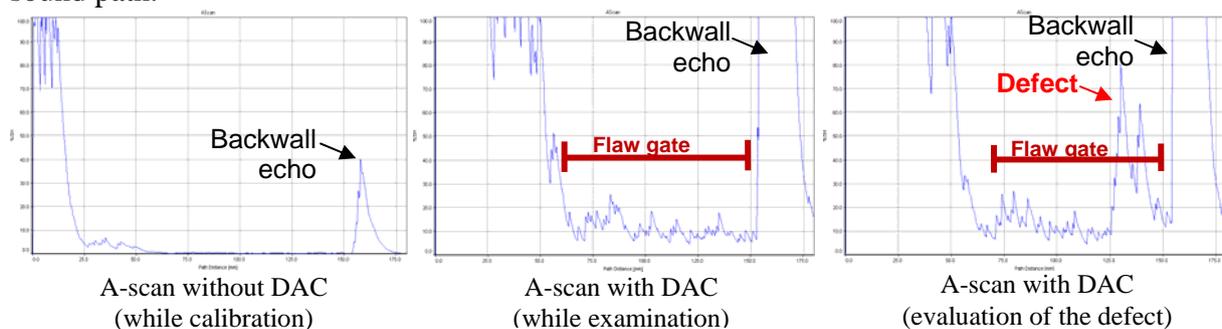


Figure 4. Typical A-scans while calibration and examination by DGS method under using the Distance-Amplitude-Correction (DAC) mode

The alternative calibration method by means of reference block implies sensitivity setting on a reference block with reference reflectors, which is comparable to inspection objects.

Both methods DGS and reference block provide evaluation of UT results in terms of *Equivalent Defect Size* (EDS).

A *Flat Bottom Hole* (FBH) with particular diameter as an Equivalent Defect Size can have a better informational value compared to the *Side Drilled Hole* (SDH) in respect to fracture mechanical consideration in particular of plane defects like cracks. So it is the usual acceptance criterion for the quality assurance for this defect type.

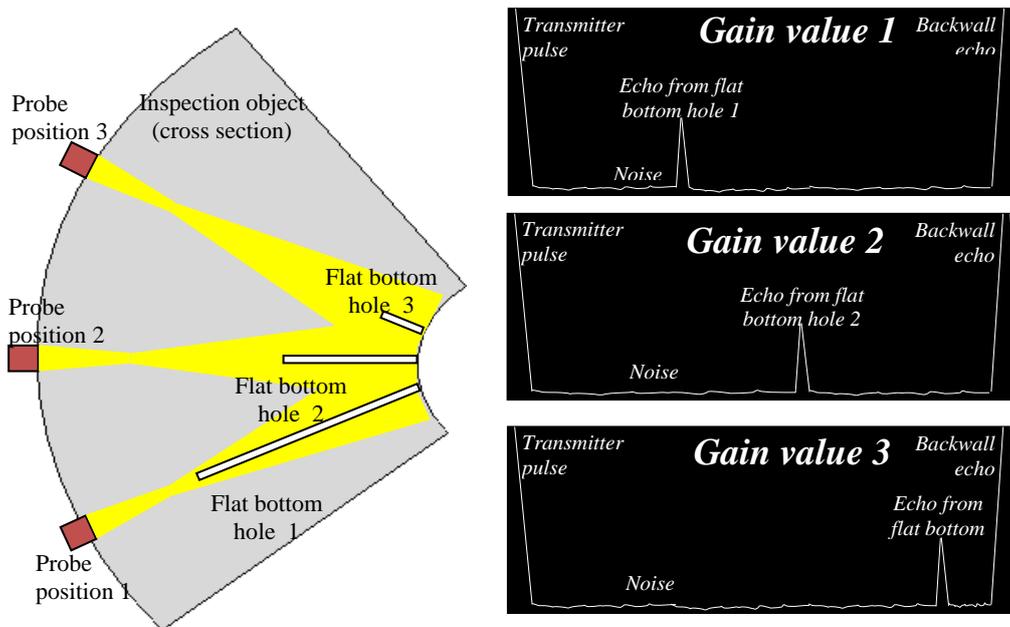


Figure 5. Principle of sensitivity calibration on reference block by using DAC

ORIENTATION DEPENDENCE OF PLANE DEFECTS AND RELIABLE FLAW DETECTION

Nevertheless material flaws like cracks, lack of fusion, inclusions, cavities, etc. have characteristic reflectivity, i.e. ability to reflect ultrasonic waves, and directivity, i.e. spatial intensity distribution of reflected waves. These have influence to the echo amplitude and the estimated flaw size.

Plane defects are normally characterized by relatively high reflectivity and distinct directivity which causes a strong dependence of UT indications on flaw orientation, while voluminous inclusions and cavities are normally weak reflectors with wide directivity (Figure 6).

Thus the orientation dependence of plane defects requires optimal insonifying the defect, especially if single beam ultrasonic transducers are used. Mismatch of angle of incidence and directivity of the reflector can lead to significant amplitude drop and wrong estimation of inspection results. So the estimated EDS could be much less compared to the real defect size and the reliability of flaw detection decreases.

One of the challenges in practical application of conventional UT is therefore optimizing the insonification schemes in respect to particular inspection task.

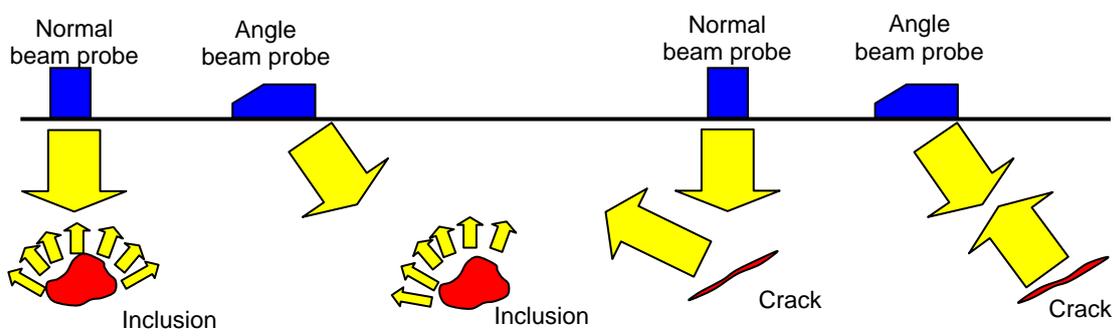


Figure 6. Schematic representation of reflectivity behavior for cavity-like and crack-like defects

Example 1: Inspection of weld joint of bottom to shell on the forged cask body

For reliable detection of material flaws the insonification directions must be aligned with orientation of longitudinal defects (e.g. lack of fusion) and transversal defects (e.g. transverse crack) in accordance with manufacturing risks and fracture mechanical needs.

For this reason more than 20 different manual scan positions with angles of incidence 0° , 45° , 60° , 70° are used in scope of UT on weld joint to ensure optimal insonification.

SPECIFIC CHALLENGES OF UT ON DUCTILE CAST IRON CONTAINERS

Ultrasonic testing of ductile cast iron components is characterized by limited inspection sensitivity in comparison to carbon steel components due to high sound attenuation.

There are two sound attenuation mechanisms in solid bodies: scattering and absorption. In last decades quality of nodular graphite cast iron was significantly improved in respect to advancement of its mechanical properties.

The optimized spheroidal graphite has reduced the scattering component of sound attenuation and reduced the structural noises. Nevertheless the absorptional part still leads to high energy loss of ultrasonic wave in those materials.

Low frequency transducers are typically used for UT on cast iron to overcome attenuative material properties. This compulsorily reduces flaw detectability by UT. Large dimensions of cast iron casks enhance the problematic of high sound attenuation.

Figure 7 shows that high structural noise can lead to poor flaw detectability due to low *Signal-to-Noise-Ratio* (SNR).

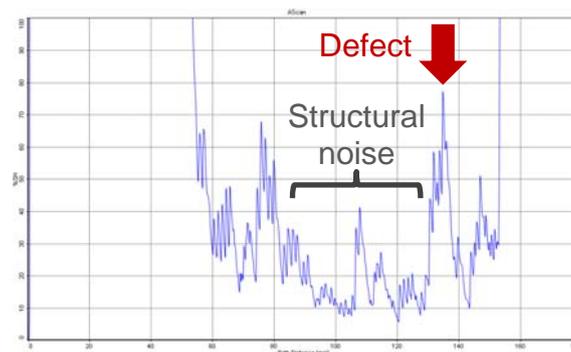


Figure 7. Poor flaw detectability due to low SNR

Example 2: UT of a testing thick-walled cast iron cask body

Due to poor reflectivity of typical defects like cavities and structural disaggregation in cask iron the *Equivalent Defect Size* approach is questionable. Large discontinuities can be classified as very small EDS. So the concept considering the back wall echo reduction must be additionally applied to increase the flaw detectability.

Only a few insonification positions are essential for detecting defects typical for cast iron.

The main task for the UT is excluding of the fracture mechanically relevant inadmissible defects. Thus insonification positions must be optimized for relevant plane flaws under consideration of the sufficient SNR.

Therefore more than 90% of about 60 manual scan positions are focused on this target and cause a big effort of inspection.

INNOVATIVE UT TECHNIQUES FOR IMPROVING FLAW DETECTABILITY AND RELIABILITY OF INSPECTION RESULTS ON CAST IRON COMPONENTS

The main potential for enhancing the reliability of ultrasonic inspection consists in mechanization of testing procedures for supporting UT operator in combination with introduction of novel inspection concepts for improving the flaw detectability. Two examples of these methods will be shortly presented in the current paper.

eRDM technique for improving inspection sensitivity on high attenuative materials

By mechanized or automated scanning of inspection object ultrasonic signals are acquired in every inspection position. Structural acoustical noise contained in neighbored positions can be considered as statistically incoherent, while the echo-signal from reflector is a stable event, represented in every A-scan, correlate with each other.

Unlike classical spatial averaging methods (e.g. SAFT technique), the novel Energy Rejective Diviative Method (eRDM) applies principles of so called “weak statistics”. Its advantage is that even with very few statistically composed amplitude values (Figure 8) an enormous improvement of SNR can be obtained.

Hereby both electrical and acoustical noise can be effectively suppressed without distortion of the signal form defect.

A flat bottom hole reflectors \varnothing 5mm and \varnothing 3mm at distance of 250 mm can be hardly distinguished due to acoustical noise. After signal processing by eRDM method near to unlimited SNR can be obtained.

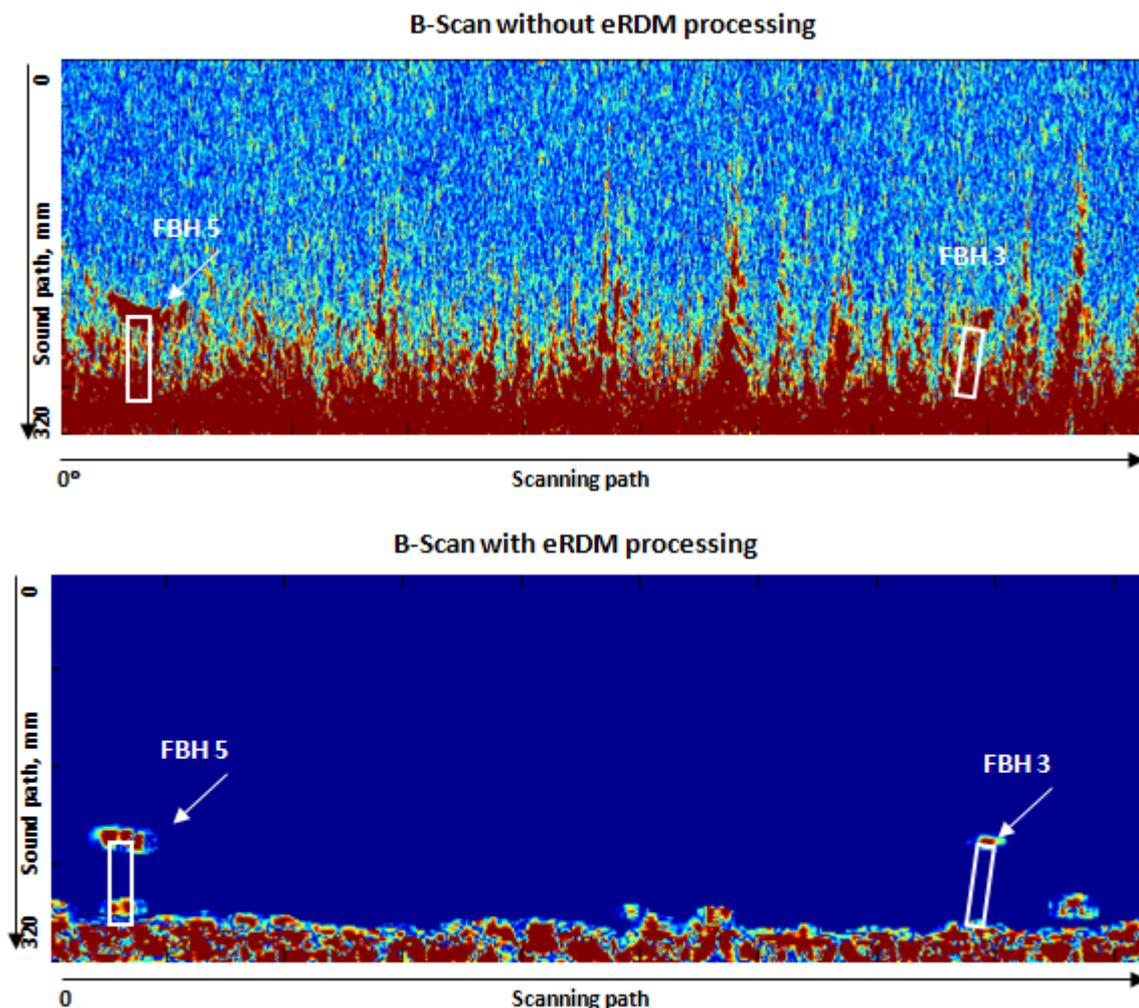


Figure 8. Results of ultrasonic testing before and after eRDM signal processing

(Source: I-Deal Technologies)

Sampling Phased Array Technique as a quantitative approach for defect size evaluation

Phased Array probe is an ultrasonic transducer consisting of several elements (typically >16), arranged at defined distance from each other. An important feature of phased array is its ability of sound field steering. I.e. the angle of incidence of phased array transducer can be changed by applying different time delays to array elements.

Thus by electronic steering the sound beam any arbitrary angle of incidence can be realized (Figure 9). This provides higher flaw detection reliability in comparison with single element transducers due to complete coverage of inspection volume.

The inspection results can be represented in common manner as A-Scans for particular angle of incidence or as two dimensional images, where operator can easily recognize flaw indications and perform their estimation according to appropriate sensitivity calibration.

The Sampling Phased Array (SPA) is an advancement of Phased Array technique, which principle makes use of the measurement of elementary waves generated by individual elements of the sensor array to reconstruct the composite phased array signal for any arbitrary angle or focal depth. The use of special signal processing and image reconstruction algorithms allows the simultaneous generation of A-Scans of all physically realizable angles of incidence and/or two dimensional images, which can be implemented in real time. Thus the principle can be used for automatic testing systems at a very high inspection speed.

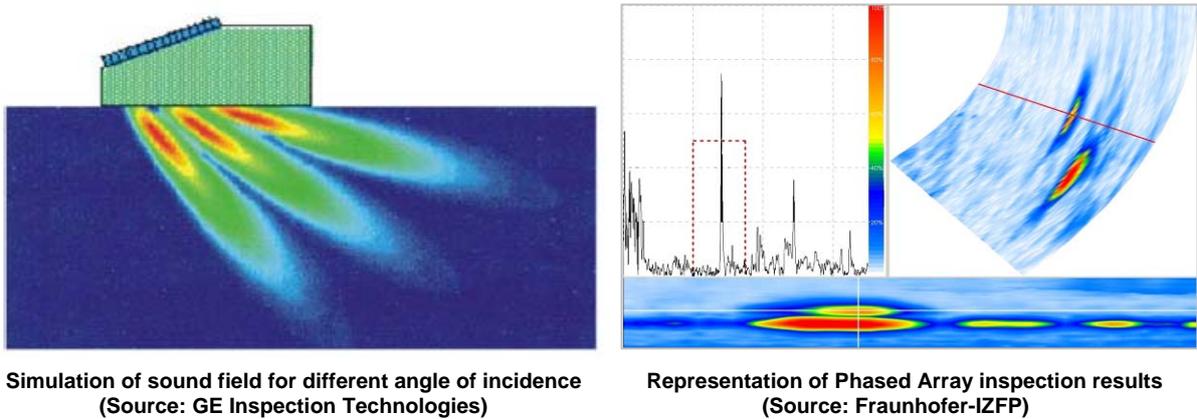


Figure 9. Coverage of inspection volume with all-over beam steering

Sampling Phased Array technique with its tomographic 3-dimensional representation of material flaws allows quantitative evaluation of defect size and offers direct bridge to fracture-mechanical consideration of ultrasonic inspection results.

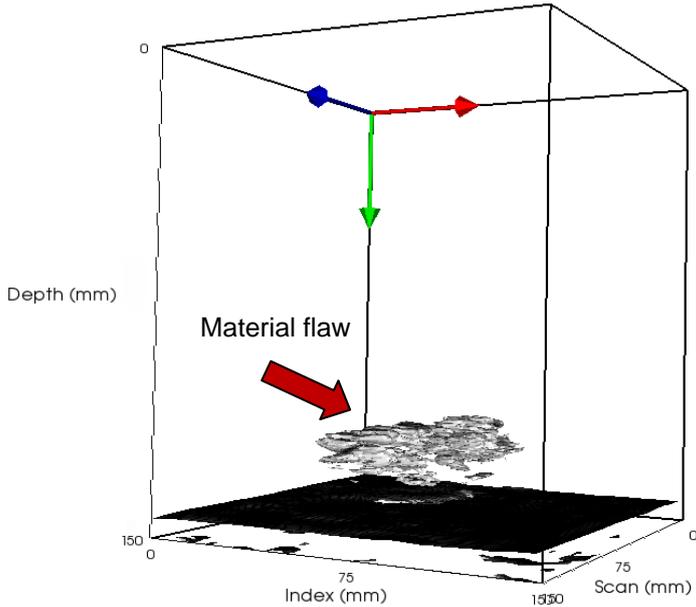


Figure 10. Quantitative 3D tomographic representation of material flaw in cast iron
(Source: Fraunhofer-IZFP)

CONCLUSIONS

UT inspection was from the beginning an important quality assurance measure in manufacturing of forged and cast components for Type B packages.

The proof of safety for container bodies are nowadays based in many cases on fracture mechanical analysis methods. Thus the fracture mechanical approach defines demands on fracture toughness of the material as well as on maximal acceptable material defects in respect to their size, orientation and position. The sufficiently safe exclusion of those unacceptable flaws in scope of quality assurance in manufacturing is a challenging task for non-destructive testing. For thick-walled container bodies ultrasonic testing (UT) only comes into consideration as an examination technique.

As long UT is the most suitable method for detection of plane defects, the problem of optimal insonification of all fracture mechanically relevant flaw orientations arises. Without this optimization the evaluated equivalent defect size strongly deviates from the real defect size and the detection reliability decreases.

For materials with acoustically disadvantageous properties like cast iron the problem of short sound paths due to strong attenuation accrues. Traditional UT methods can provide only limited solutions by enormously high efforts. The manual scanning with its subjective effects is a problematic aspect for the reliability as well.

Therefore improvements towards mechanized scanning of inspection objects in combination with innovative testing and evaluation techniques should be taken into consideration. The examples presented in this paper like eRDM-technique for inspection of highly attenuative materials or Sampling Phased Array show the potential and advantages of latest developments in respect to improvement of flaw detectability and reliability of UT results.

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