NDT Controlled Production in Steel Industry

Vasiliy A. Klimenov[a], Michael Kröning[a], Paul Kröning[b],
Friedrich Mohr[c], K.M. Reddy[d], Helmut Wolf[e]

[a]Tomsk Open Laboratory for Material Inspections, Tomsk Polytechnic University; Russia
[b]Q NET Engineering GmbH; Saarbrücken, Germany
[c]intelligeNDT Systems & Services GmbH; Erlangen, Germany
[d]Lucid Software Ltd; Chennai, India
[e]Anna University, Dept. Mech. Engineering, Chennai

ABSTRACT

In this paper we present Nondestructive Testing (NDT) systems and instruments used in steel industry for the quality control of production processes. We present real-time multi-channel ultrasonic inspection systems with advanced array transducers for the inspection of bars and other semi-finished parts. The equipment is designed for fast inspection in the production flow. For the control of heavy parts we discuss mobile high energy Betatron radiography that can be upgraded to tomography. The control of special processes like surface hardening can also be performed nondestructively based on the evaluation of ultrasonic backscattering. Thermoelectric phenomena are applied for sorting of mixed-up metal parts.

For all these types of NDT systems that are used in quality controlled steel production computing and related software solutions are the key for advancement. Further, inspection data are integrated into company's asset management system that immediately informs the management about the performance of production processes and may also serve as a good show case for clients. Software solutions support stand-by maintenance with immediate trouble shooting by off-site experts that guarantees highest possible operational availability of the inspection system.

Introduction

The steel industry is applying Nondestructive Testing (NDT) methods for quality control of products at different stages of production with the objective of sorting out parts not in compliance with the specified quality standards. Most often, the inspection is mandatory according to customer specification or technical regulations. However, advanced quality management takes advantage of NDT as a production integrated tool that controls and monitors the process for defect free output (1). Advances in key technologies of measurement physics like computing, micro-electronics, sensor physics, and automation (robotics) have contributed significantly to the development of automated NDT systems matching the requirements for quality production in steel industry (2). IT asset management solutions have become standard industrial practice and support the management for immediate and adequate response (3) when integrated into the company's management process.
We discuss current developments of ultrasonic testing equipment and high energy radiography as a special but challenging opportunity for the control of heavy components. We structure the presented examples according to application aspects that comprise fast in-line inspections and also as replacement of destructive tests by 100% nondestructive control of the material condition and microstructural state.

Ultrasonic Testing Systems

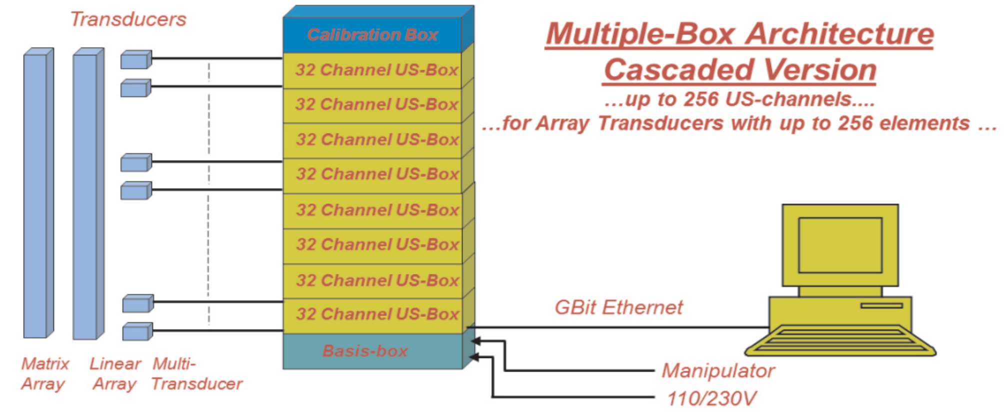
Ultrasonic instruments with improved features for automated inspections are available on the market. Advanced computing and instrument micro-electronics but also robot based scanning systems are pushing the ultrasonic inspection technology towards faster inspection including real-time flaw evaluation by reflector imaging. The NDT industry is offering multi-channel inspection systems and Phased Array equipment that has already become state-of-the-art. The drive for further advancement leads to a very dynamic situation. We present the latest result of instrument development together with inspection solutions that have become viable for industrial use.

SaphirQuantum® Ultrasonic Instrument

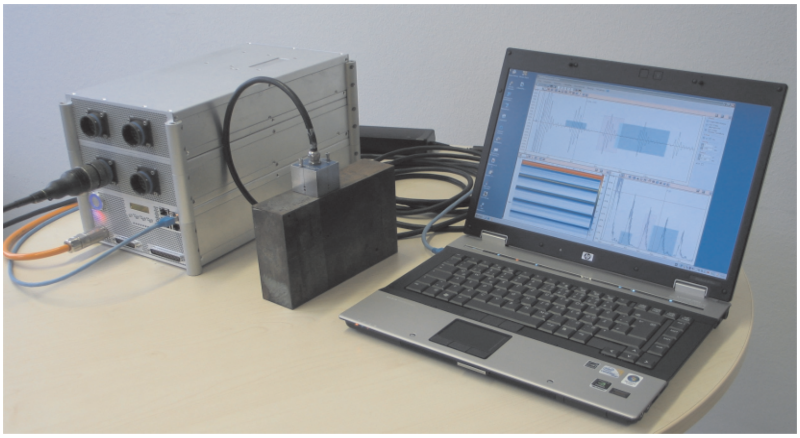
The instrument has been designed in compliance with existing standards for multi-transducer and phased array systems with modular 32 parallel ultrasonic channels (fig. 1a and 1b). The add-on is the parallel measurement and processing of the high-frequency A-scans of each array element. Fast data links have been designed for real-time processing of the full array A-scan and element position information (4) but in consideration of standards for easy future upgrades.

The system can be used in all common operation modes of a multi-channel ultrasonic instrument: as a standard multi-transducer inspection system, as a conventional phased array system with up to 16 phased array linear transducers with 16 elements each. Further, the system may be operated in any hybrid operation mode, for example as a multi-transducer system with additional one or more phased array transducers.

Special emphasis was put on amplifier features including high dynamic range and extreme low noise even at highest amplification settings for the operation of array transducers with small element apertures for future matrix arrays. In addition, we plan to implement smart signal processing algorithms for improving contrast and/or resolution sensitivity or for filtering acoustic noise. Examples will be discussed in this paper.



a: System Architecture



b: Photograph of the 64 channel version

Fig. 1: Advanced Ultrasonic System Saphir Quantum[1]

[1] Saphir^{quantum} is a development of AREVA intelligeNDT System and Services GmbH, Erlangen, Germany.

The automated ultrasonic inspection systems consist of a (multi-channel) ultrasonic instrument, a transducer system, a manipulator and software. Each of these components challenge the designer to meet specific industrial demands like operational availability in the production line, the inspection of complex component geometries, automated flaw detection and evaluation, and data management for quality assessment and reporting. Therefore, we have developed a modular multi-functional instrument architecture that allows optimised systems for a large variety of automated ultrasonic inspection tasks. At the same time, the specific systems developed are not only in compliance with relevant codes and standards and meet in-house customer requirements, but may also solve specific inspection problems, for example the inspection of anisotropic or coarse grain material, that require new and even innovative techniques.

In this paper we discuss two features of advanced systems - multi-transducer inspection of railway wheels and high resolution flaw imaging for quantitative flaw evaluation.

Railway Wheel Inspection

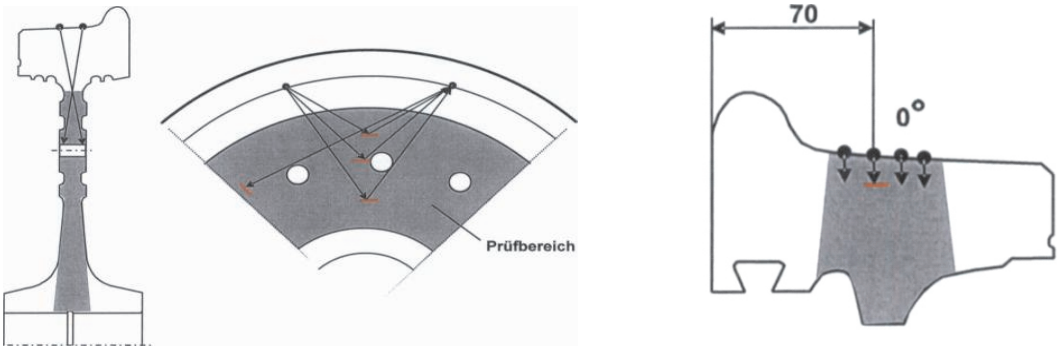
Figure 2 shows the complexity of the automated ultrasonic inspection system of railway wheels. Only when many very specific transducers are applied all the flaws to be detected can be scanned on the shaped wheel geometry. However, there are limitations with respect to the size of the transducer system mechanics when the wheel should be inspected by one scan only to achieve reasonably short inspection times. The phased array technique allows the reduction of number of transducers by the electronic control of the transducer sound field, i.e. the angle of incidence and focus distance. However, there are still scan positions where standard transducers offer the optimal solution. Therefore we designed a multi-transducer system with phased array and common transducer that allowed the design of a robust and reasonably small transducer system mechanics with optimal flaw detection according to the applied procedure.

Fig. 2: Automated Railway Wheel Inspection (5)

Figure 3 illustrates the complexity of the ultrasonic transducer system as a function of the multitude of assumed flaws to be detected in the wheel, figure 4 the transducer arrangement in the carriers for tread and rim scans.

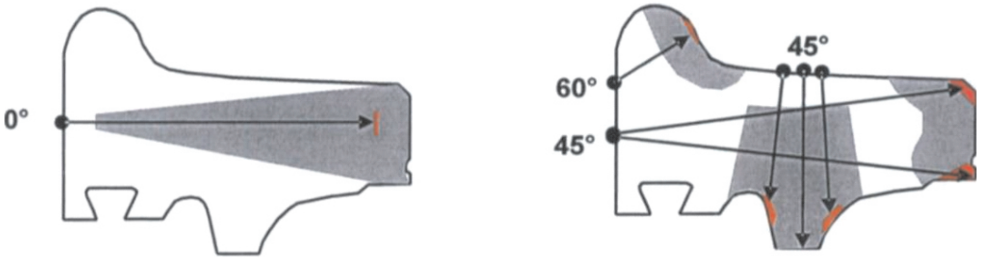
The circles at the edge of the tread carrier indicate eddy current coils applied for sensitive surface crack inspection.

The hybrid technique enables robust handling mechanics of relatively small size but with full coverage of the inspection task by one scan. The multi-channel instrument operates eight phased array transducers and seven standard transducers simultaneously. The complexity of inspections as outlined by this example explains the need but also the advantage of the high number of channels that may be operated in parallel mode. As a result the inspection time for one wheel is less than 3 minutes.



a) Transducer System Carrier for Wheel Tread Scan

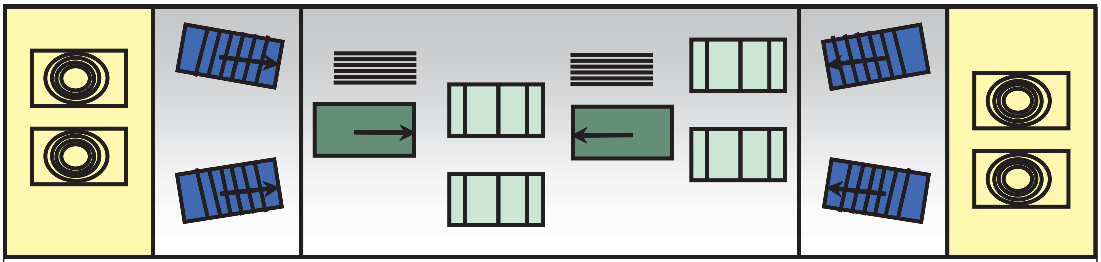
b) Transducer System Carrier for Inner Wheel Face Scan (Rim and Flange Inspection)



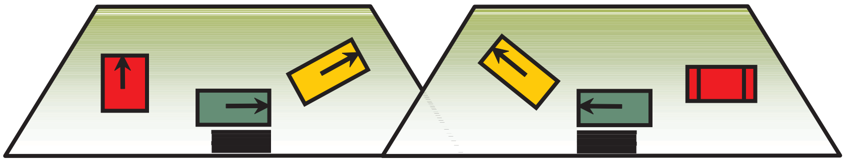
c) ET Transducer 0°

d) Four Phased Array Transducers 45° with vertical sweep and two ET 60° SW

Fig. 3: Required Scope of Wheel Inspection



a) Transducer System Carrier for Wheel Tread Scan



b) Transducer System Carrier for Inner Wheel Face Scan (Rim and Flange Inspection)

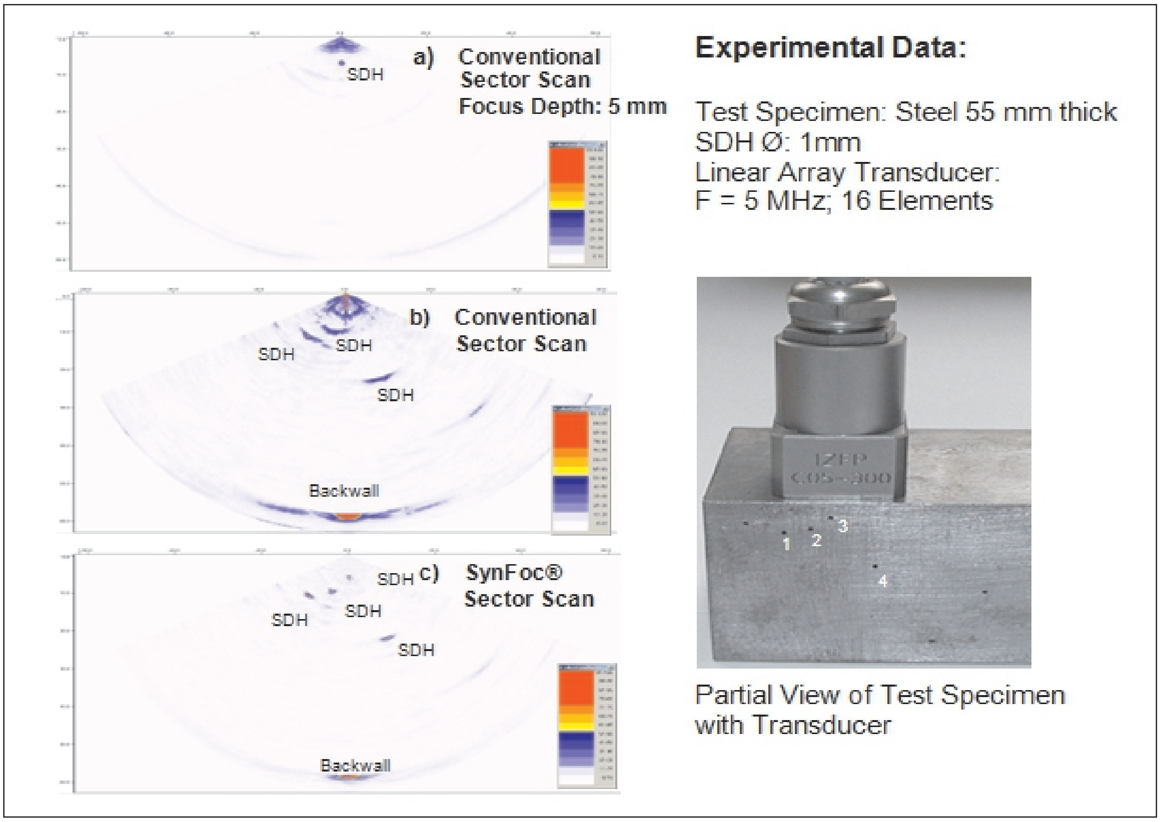
Fig. 4: Hybrid Transducer Systems

Quantitative Ultrasonic Testing

Quantitative Ultrasonic Testing (QUT) implies the evaluation of flaw type and dimension for the assessment of further usability of material or structure. QUT methods are imaging the reflecting material discontinuities. The reflector image is evaluated by experts for flaw sizing. Important features of primary reflector imaging are contrast and resolution sensitivity. Good resolution contrast is the key for imaging the individual contributions of the reflecting compound of the discontinuity including reflector artefacts caused for example by multi-scattering or mode conversion. Good contrast sensitivity is necessary for the imaging of contributing small and planar but misaligned reflectors.

Acoustic imaging physics has provided applicable principles of measurement that meet the addressed needs of reflector imaging for flaw evaluation. When an array of suitably arranged acoustic transducers measures acoustic wave field data on the surface of the specimen we can reconstruct the acoustic sources of the wave field. The high-frequency A-scan data of the transducers measured simultaneously are used for the reconstruction of the wave field - a process called migration (6). This type of reflector reconstruction includes inherently synthetic focussing into the near-field of the array arrangement with resolution given by the aperture of the array element. For long distance reconstruction we may distribute the elements to limit the number of array elements (or channels of instrument). This type of aperture is called sparse. The optimized arrangement of elements but also special data filtering techniques can be applied for the elimination of reconstruction artefacts that may appear when sparse apertures are used since the sampling theorem is violated. If required by product specification we may design arrays for reflector imaging with resolution close to the Raleigh criterion of half a wavelength (7) by applying point-like element transducers. The principles of migration measurement and the resulting ultrasonic system specification are discussed in (8).

Each phase array transducer can be considered a migration array when we keep the simultaneously measured A-scans of the array elements available for further processing (9). They offer already high resolution imaging of half a wavelength in the sector scan plane but a limited one perpendicular to it. Therefore, matrix arrays are one objective of current development. However, array elements of very small aperture are very poor acoustic transmitters and receivers. For that reason, the ultrasonic instrument has to meet specific requirements to be used as a tool for advanced QUT. Most important are the quality of amplifier, its dynamic range with minimum noise, the parallel architecture of ultrasonic receiver channels and the adjustable control of transmitter channels. We are using Saphir Quantum instrument for current pioneering development of acoustic migration inspection systems. Figure 5 delivers terse insight into results achieved already (9). We compare Phased Array Sector scan images with migration images of same measured data that illustrate the improved resolution but measurement time for migration imaging would be less than 1% compared with Phased Array sector scan imaging.



Experimental Data:

Test Specimen: Steel 55 mm thick
SDH Ø: 1mm
Linear Array Transducer:
F = 5 MHz; 16 Elements

Partial View of Test Specimen with Transducer

Fig. 5: Comparision of Phased Array Sector Scans with Migration Image (8)

The Phased Array sector scans are composed each of 141 measurements (angle increment 1°) between -70° and +70°. For the upper sector scan we focused the ultrasonic pulse on the reflector close to the surface. In this case even the backwall of the test specimen has disappeared. The sector scan in the middle of figure 5 was measured without focussing. The near surface reflector is not imaged and we have to encounter the rather deep dead zone of the phased Array transducer. The third sector scan was measured with one transmitter signal only but by processing all simultaneously measured A Scans of the Array elements. All the specimen reflectors are imaged with resolution close to half the wavelength. Because of the dominant transmitter/receiver information the dead zone has almost disappeared. We consider the high sensitivity of migration measurements close to the scanned surface an additional important advantage of migration measurements.

Until now, results have been achieved for linear arrays only but we will present 3D images in the next time. 2D migration measurements allow fast scanning of the array with up to 1m/sec or higher when special measures are implemented. This fast scanning makes the system applicable to most of the industrial inspection problems like bar or shaft inspections. Current work is directed to understand prominent advantages the system may offer for industrial applications such as cost savings, inspection of specific materials and geometries, and real-time quantitative assessment of findings.

Material State Characterization

Nondestructive material characterization is still considered a challenge for research and development. However, there are common applications that demonstrate the benefits of non-destructive material state characterization. Some methods and instruments have been developed successfully based on different physical principles. We present two methods - the thermal test for material sorting and the ultrasonic backscattering technique for hardness depth control.

Ultrasonic Hardness Depth Control

Surface properties are critical features of materials that determine their later technical usability. Surface hardness and the related hardness depth are critical quality parameters of steel components that ask for control.

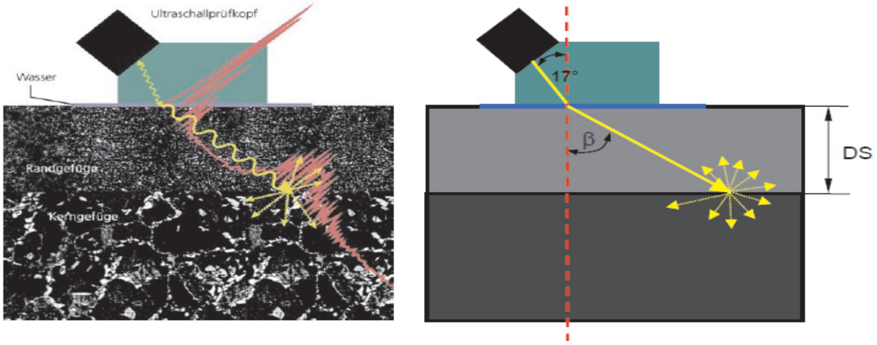


Fig. 6: Typical Microstructure of a Surface Hardened Steel Part

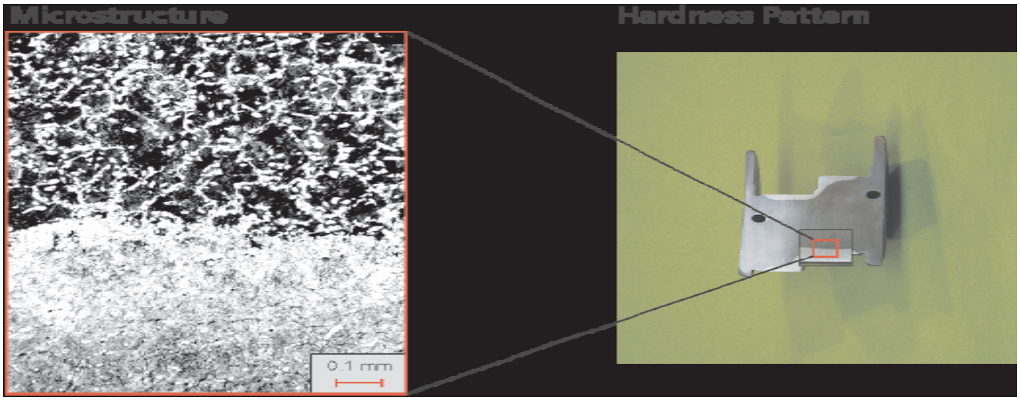


Fig. 7: Principle of Ultrasonic Hardening Depth Control

We present a technique that allows the non-destructive control of hardness depth when the hardening process results in a fine grain hardened surface layer with a pronounced interface line to the non-hardened base material as indicated in figure 6. Most of the inductive hardening processes result in this type of surface micro-structure. The pronounced interface geometry allows the use of ultrasonic backscattering technique for the measurement of hardness depth. The principle of measurement is simple (see fig 7) but its application asks for specific technical solutions facing specific challenges by the multitude of different geometries and critical areas to be controlled.

Nevertheless, the interface backscattering is rather poor because of the minor impedance change. For that reason, the acoustic pulse characteristics have to be optimized and the backscattered A-Scans have to be averaged and processed for hardness depth evaluation. One effective procedure is the averaging of A Scans measured at slightly different positions. Fig. 8 shows the formation of the averaged A Scan comprising about 100 different A- Scans all measured at positions within one wavelength displacement. However, the possible displacement might be much larger as long as hardness depth is not changing.

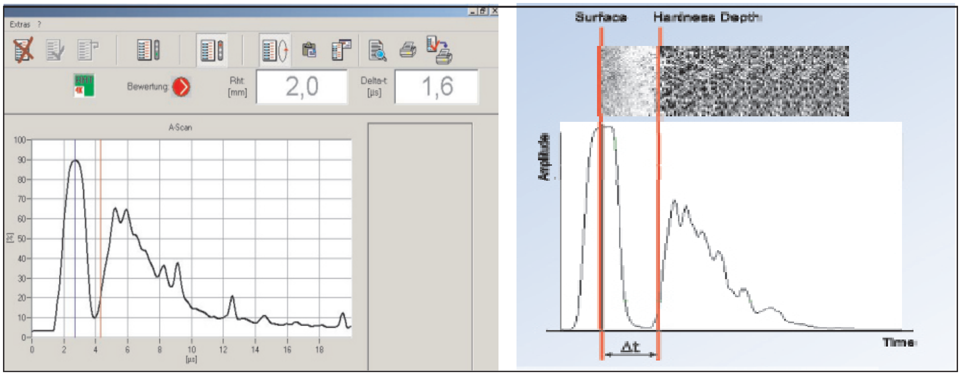

Rht [mm] 2,0
Delta-t [µs] 1,6

Fig. 8: A Scan Measurement for Hardness Depth Evaluation

The acoustic beam characteristics are matched to the inspection problem by the appropriate design of transducer polystyrene wedges for inspection frequencies of 20 MHz. We simulate the inspection for the best customized wedge geometry that guaranties robust and accurate hardness depth data for most of the inspection problems. Figure 9 shows some of many possible inspection solutions for components of different geometries.

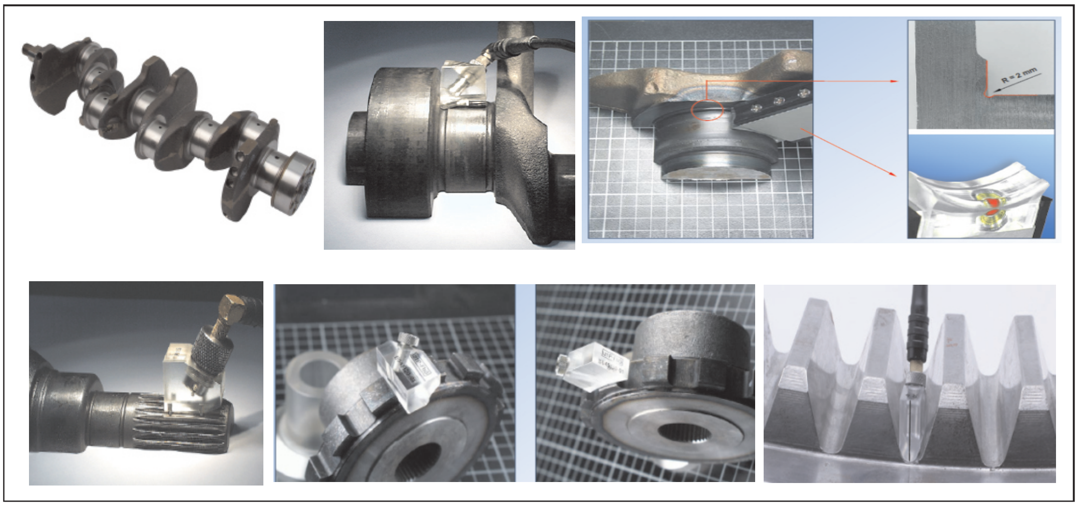
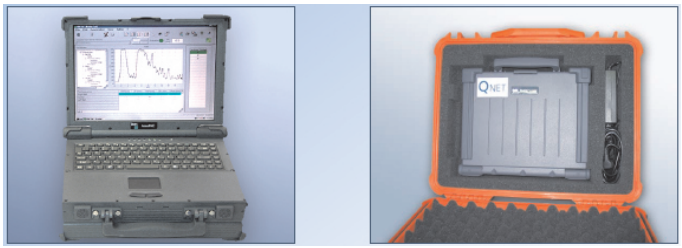


Fig. 9: Inspection Problems and Solutions

The inspection can be performed manually or (semi)automated with appropriate inspection mechanics or robotics depending on customer demands. Fig. 10 shows a standard inspection instrument. The non-destructive control of hardness depth replaces destructive random tests with the benefits of significant cost savings and the opportunity for a complete quality control of the hardening process including data management and reporting.



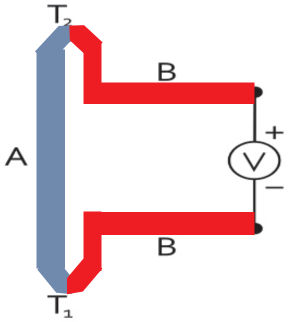
Ruggedized Notebook including:

- Ultrasonic electronics (analogue and digital)
- PINT Rht-software
- Connectors for four transducers
- DVD burner
- Standard PC ports

Fig. 10: Standard Instruments

Thermo-Test for Sorting of Parts

Quality standards demand for the fast control even of small parts of mass production. One quality issue of concern are mixed-up components that have to be sorted in-line of the production flow. We have developed a new inspection device based on the well-known phenomena of thermoelectricity of metals (10). The contact voltage can be used to distinguish between different metals, their alloys and material states when their Seebeck coefficients are different. The Seebeck effect enables the conversion of temperature differences directly into electricity. Seebeck coefficients are material parameters. A simplified explanation of the measurement principle is given by figure 11.



S_A and S_B are the thermopowers or Seebeck coefficients of metals A and B, and T_1 and T_2 are the temperatures of the two contact points. The Seebeck coefficients are non-linear as a function of temperature, and depend on the material and its micro and molecular structure.

Fig. 11: Seebeck Circuit

Fig. 12 shows a prototype instrument for manual testing that also demonstrates the robust and easy performance of measurement.

Fig. 12: Thermo Test Instrument for Manual Part Control

The inspector or the robotic handling mechanics contact the part to be controlled with one element of the split and heated sensor head for a second only; the second element contacts the reference part with the desired properties. The range of accepted difference indicated by the thermal current or voltage can be calibrated according to the inspection task. The thermal test can be applied for almost all metals and alloys including modified surfaces, i.e. hardened components. We could demonstrate that we can distinguish parts from different heats of same grade. We cannot quantitatively characterize the material state but we can confirm it by using a certified reference part.

Inspection of Heavy Components

The manufacturing control of heavy steel components and semi-finished parts and also the functional in-service tests of systems pose problems when standard non-destructive testing methods are not applicable or limited with respect to flaw detection and evaluation, and structure imaging. Ultrasonic scanning is time consuming and needs special manipulators or cannot be applied when material is anisotropic as most of cast components are. The use of high energy radiography is one solution, but mostly X-ray energies between 5 MeV and 12 MeV are needed for good inspection results. In those cases when Cobalt isotopes are no longer reasonably applicable, electron accelerators can be used with good results as it can be seen in the specific contrast diagram in figure 13.

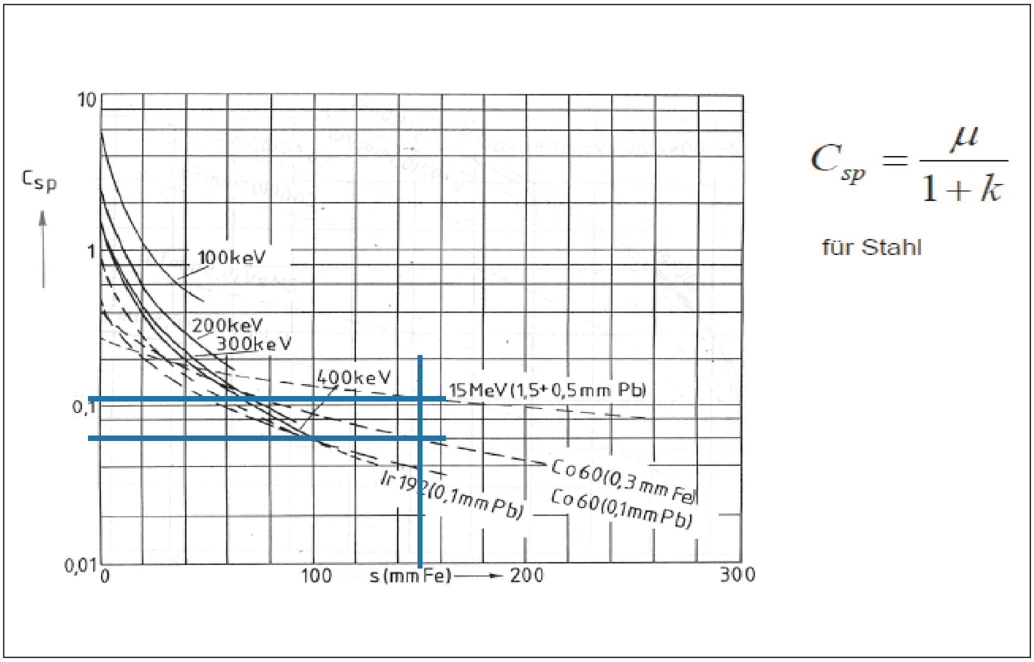
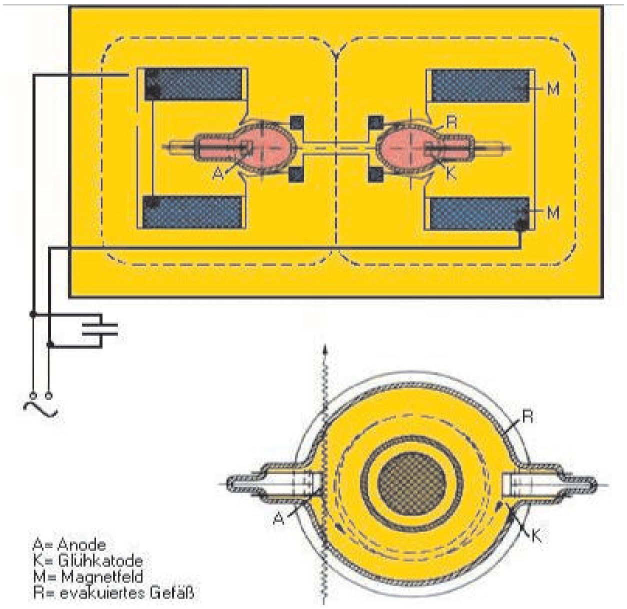


Fig. 13: Specific Contrast Diagram for Steel High Energy Radiography (11)

For that reason, high energy radiation centers have been organized that offer inspection services with linear accelerators. Until now, linear accelerators are expensive stationary radiation sources that can be operated only by qualified experts. We have developed and qualified betatron as a high energy x-ray source for material inspections. Advanced Betatron equipment as mobile sources are designed and built at reasonable costs but with adequate beam characteristics that can be operated by trained x-ray inspectors. The betatron is essentially a transformer with a torus-shaped vacuum tube as its secondary coil. An alternating current in the primary coils accelerates electrons in the vacuum around a circular path. The stable orbit for the accelerated electrons is achieved by the adequately controlled magnetic field. Figure 14 shows the betatron configuration.



Radial Stability Criterion:

$F_c = F_L$

Centrifugal Force: $F_c = m_e v^2/r$

Lorentz Force: $F_L = evB(r)$

as reactive centrifugal force

2.5 MeV **r ~ 25 mm**

300 MeV **r ~ 1m**

Fig. 14: Betatron Electron Accelerator

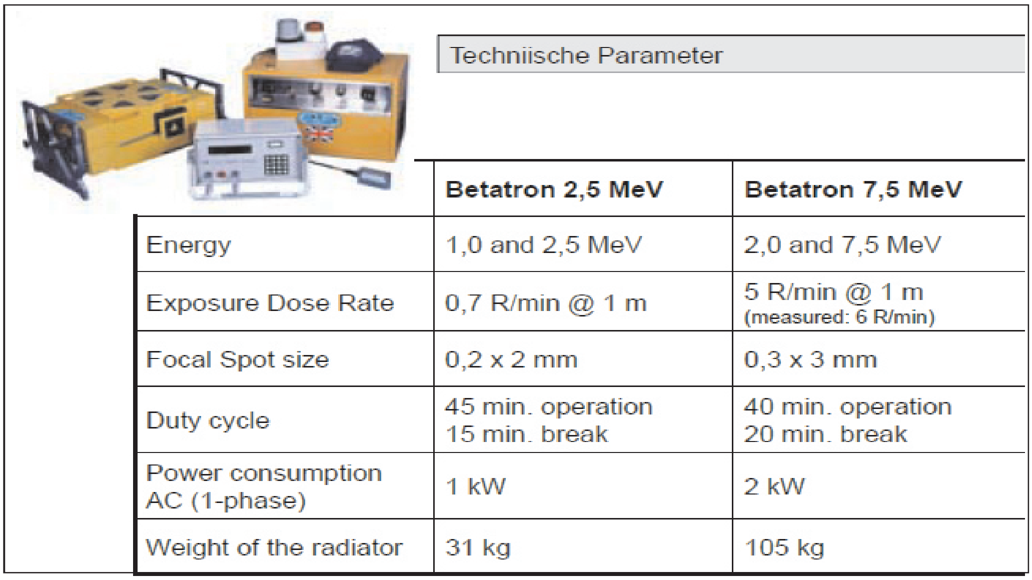
Betatron Equipment

Figure 15 shows as an example equipment developed at Tomsk Polytechnic University, Institute for Nondestructive Testing.

At TPU we have developed customized Betatron equipment with energies in the range from 1 MeV up to 12 MeV for medical applications, material inspections, and structure control. According to our experience the demand for 2.5 MeV and 7.5 MeV Betatron is highest for NDT applications. Table 1 indicates the main technical parameters of these two Betatron systems:

Fig. 15: 7.5 MeV Betatron Equipment

Table 1: Technical Parameter of Betatron Systems (11)



Techniische Parameter

	Betatron 2,5 MeV	Betatron 7,5 MeV
Energy	1,0 and 2,5 MeV	2,0 and 7,5 MeV
Exposure Dose Rate	0,7 R/min @ 1 m	5 R/min @ 1 m (measured: 6 R/min)
Focal Spot size	0,2 x 2 mm	0,3 x 3 mm
Duty cycle	45 min. operation 15 min. break	40 min. operation 20 min. break
Power consumption AC (1-phase)	1 kW	2 kW
Weight of the radiator	31 kg	105 kg

The 2.5 MeV Betatron X-ray radiation replaces equivalent the Co60 γ -source (1500 GBq) that makes the transport and storage of hot isotopes unnecessary. The 7.5 MeV Betatron can be still considered transportable mobile equipment with the advantage that walls thicker than 80mm steel equivalent can be inspected.

Figure 16 shows as an example the inspection station with 7.5 MeV Betatron in the Russian steel plant Volgogradneftemash. A second example demonstrates the use of Betatron for the control of heavy castings in a British foundry (Fig.17).

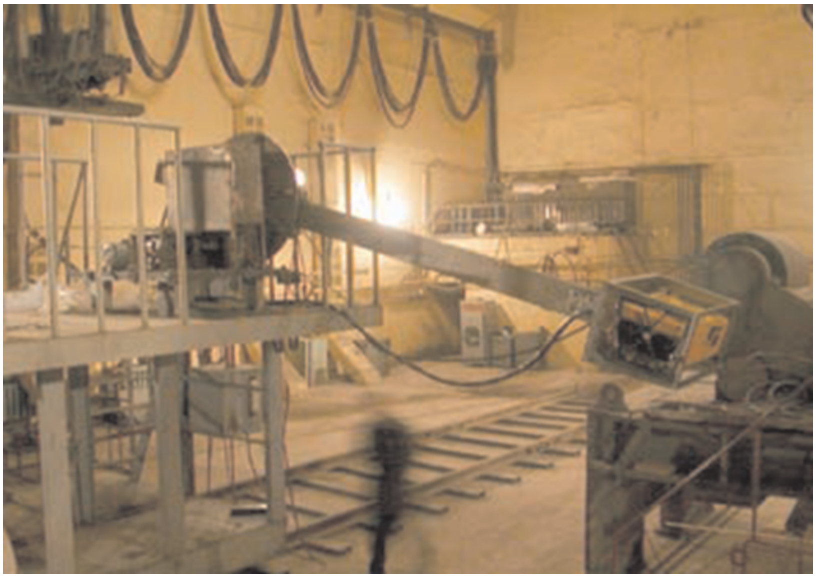


Fig. 16: 7.5 MeV Betatron Inspection Station in Volgogradneftemash production plant, Russia

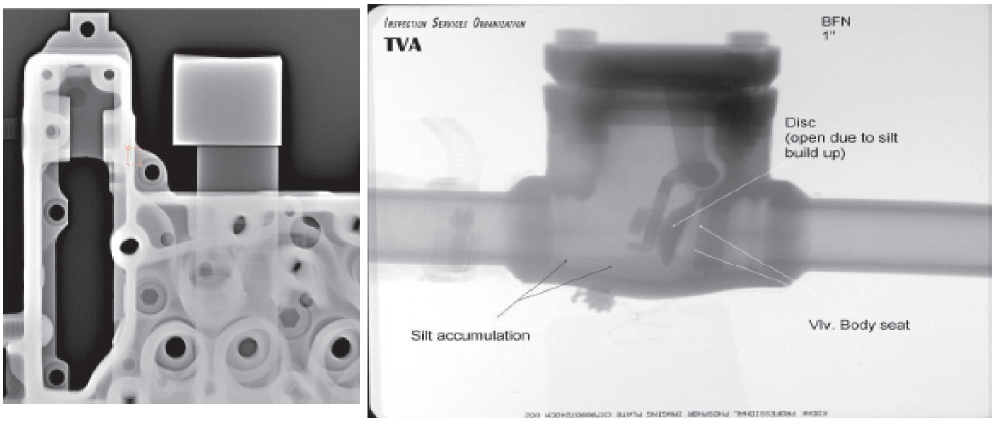
Fig. 17: Inspection of the Casting Process

Betatron Radiographs

The image quality achieved with Betatron radiation complies with relevant national and international codes and procedures. In comparison with isotope inspections the Betatron produces radiographs with better specific contrast and lower ratio of scatter and primary radiation that results in an improved build-up factor. We can inspect with good image quality wall thickness up to 250 mm steel equivalent or 1 m concrete when applying 7.5 MeV Betatron radiation.

The achieved quality of equipment is promising for high energy X-ray tomography with highest contrast and resolution as current results of development have proved.

The following images demonstrate the quality of radiographs that allows the nondestructive inspection of heavy components but also wall thickness measurement and functional control of assembled technical components.



a) Engine Block (Defect Inspection) **b)** Valve Housing (Functional Control)

Fig.18: Radiographs of Heavy Components (11)

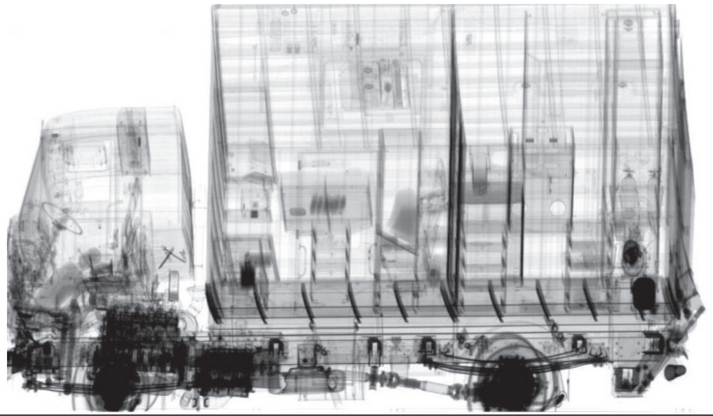


Fig. 19: Lorry Control by Betatron Radiograph

Summary and Outlook

Main stream developments of key technologies like computing, sensors, robotics, and micro-electronics are pushing progress in measurement physics. We present examples of applied developments for new nondestructive testing methods and equipment that demonstrate the opportunities. The examples discussed represent different type of inspection problems that are common in steel industry. We are aware that nondestructive testing as elements of quality and safety policy of industry need specific concern to be applied only following a certified and justified procedure that require statuary approvement and engineering experience. The development of certified new NDT systems need close cooperation between developers and practitioners. This cooperation has enabled the transformation of exciting opportunities provided by up-to-date technologies into new NDT equipment that benefits the industry and the quality and safety of manufactured components and structures.

We continue to build on international partnerships between industry and research institutions to sense the demands and to respond to them by global knowledge and technical opportunities.

References:

1. G. Dobmann, M. Kroening, and B. Wolter, "NDT Aided Production Processes", in: Advances in Manufacturing Technology, IIM-University Press, 2011
2. M. Kroening, R. Pinchuk, and K. Reddy, "Real-time processing of NDT data for in-line control of production processes", in: Advances in Manufacturing Technology, IIM-University Press, 2011
3. http://www.kovidndt.com/CMS/resources/articles/article-2 "Where is NDT Headed in the next 10 Years", retrieved on 11.11.2011
4. M. Kroening, "Realtime Quantitative Ultrasonic Inspection", in: Proceedings of IV Conferencia Panamericana de END, Buenos Aires. 2007.
5. G. Engl, R. Meier, H. Hintze, R. Ettlich, "Advances in On-Train Inspection of High-Speed-Train Wheels by the new Generation of UFPE-Systems", INSIGHT (BINDT), 49 (2007) 337-340
6. N. Bleistein, J. Cohen, and J. Stockwell Jr., Mathematics of Multidimensional Seismic Imaging, Migration, and Inversion, New York: Springer, 2001
7. Y-F. Chang, R.C.Ton, "Kirchhoff migration of ultrasonic images", Materials Evaluation, 59 (2001) 3
8. I. Bolotina, M. Kröning, F. Mohr, Krishna M. Reddy, A. Soldatov, Y. Zhantlessov, "Ultrasonic Arrays for Quantitative Nondestructive Testing-an Engineering Approach", accepted for publication by: Russian Journal for Nondestructive Testing, Ekaterinburg, Russia
9. R. Y. Chiao, L. J. Thomas, "Analytic Evaluation of Sampled Aperture Ultrasonic Imaging Techniques for NDE", IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control. 41 (1994) 4
10. N. W. Ashcroft, and N. D. Mermin, Solid State Physics, International Edition, Saunders College, Philadelphia, 1976, p. 24-25, p. 253-261
11. B. Redmer, W. Przybilla, M. Föllner, H.-J. Malitte, U. Ewert, "Anwendung hochenergetischer Strahlenquellen in der Durchstrahlungsprüfung", BAM Berlin, in: Proceedings of DGzfP Jahrestagung 2011, Bremen, Germany