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Progress in Digital Industrial Radiology Part I: Radiographic Techniques - Film Replacement and Backscatter Imaging

Postępy w cyfrowej radiologii przemysłowej Część I: Techniki radiograficzne - sukcesor błony i obrazowanie rozproszone wstecznie

ABSTRACT

Similar to the success story of digital photography a major upheaval has been observed in digital industrial radiology. This paper is split into 3 parts:
Part 1: Film Replacement and Backscatter Imaging: Computed radiography with phosphor imaging plates substitutes film applications. Digital Detector Arrays enable an extraordinary increase of contrast sensitivity in comparison to film radiography. The increased sensitivity of digital detectors enables the efficient usage for dimensional measurements and functionality tests substituting manual maintenance. The digital measurement of wall thickness and corrosion status is state of the art in petrochemical industry. Photon counting and energy discriminating detectors are applied up to 300 kV and provide increased thickness dynamic and material discrimination by synchronously acquisition of images of the high and low energy part of the spectrum. X-ray back scatter techniques have been applied in safety and security relevant applications with single sided access of source and detector. First inspections of CFRP in aerospace industry were successfully conducted with newly designed back scatter cameras. Numeric modeling is used to design X-Ray optics and inspection scenarios as well as conducting RT training.
Part 2: Computed tomography (CT)
Part 3: Micro Radiography and Micro CT.

Keywords: *Digital radiography, computed tomography, laminography, Imaging plates, digital detector arrays, photon counting detectors, back scatter, numeric modelling, CFRP, welding, corrosion*

STRESZCZENIE

Podobnie jak w przypadku fotografii cyfrowej tak i w cyfrowej radiografii przemysłowej nastąpiły poważne zmiany. Publikacja składa się z 3 części.
Część 1.: Zastąpienie techniki analogowej i obrazowanie metodą rozproszenia wstecznego. Radiografia komputerowa z zastosowaniem ekranów luminoforowych (płyt obrazowych) zastępuje błony. Cyfrowe detektory radiograficzne DDA umożliwiają uzyskanie ponadprzeciętnego wzrostu czułości kontrastowej w stosunku do błony. Zwiększona czułość detektorów cyfrowych umożliwia wykorzystanie radiografii do określenia rozmiarów obiektów i przeprowadzenia testów funkcjonalnych, zastępując obsługę ręczną. Pomiar cyfrowy grubości ścianki i procesu korozji rozwinął się znacząco w przemyśle petrochemicznym. Detektory działające w trybie zliczania fotonów z dyskryminacją energetyczną, stosowane do 300 kV umożliwiają większą, dynamiczną rozróżnialność grubości i rodzaju materiału (akwizycja synchroniczna). Techniki związane z rozpraszaniem wstecznym promieniowania X zostały zastosowane w aplikacjach z dziedziny bezpieczeństwa i ochrony, w których źródło i detektor musiały znajdować się po tej samej stronie. Omawiane systemy obrazowania zostały również po raz pierwszy zastosowane do testowania kompozytów węglowych w przemyśle lotniczym. Modelowanie numeryczne zjawisk fizycznych związanych z radiografią jest wykorzystywane w projektowaniu optyki rentgenowskiej, opracowywaniu procedur kontroli materiałów i szkoleniach RT.
Część 2: Tomografia komputerowa (CT)
Część 3: Mikroradiografia i mikrotomografia komputerowa

Słowa Kluczowe: *Radiografia cyfrowa, tomografia komputerowa, laminografia, płyty obrazowe, cyfrowe detektory radiograficzne, detektory zliczające fotony, rozpraszanie wsteczne, modelowanie numeryczne, CFRP, spawanie, korozja*

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1. Introduction

Industrial Radiography has been dominated by application of special X-ray films with thin lead screens in front and behind the film with double sided emulsion. This technique was the basis for industrial applications since about 120 years. [1] provides related information on film replacement.

New digital detectors substitute the film and improve quality and efficiency of industrial radiography. Film replacement will be discussed for computed radiography (CR) with phosphor imaging plates (IP) and digital detector arrays (DDA). A new generation of photon counting and energy discriminating detector arrays was developed over the last decade to extend the application range of DDAs [2].

The most important advantages of digital radiography [1] are:

- shorter test and interpretation time;
- new application areas by higher inspection quality and higher wall thickness range;
- no usage of chemicals and dangerous waste as film developer and fixer;
- less consumables;
- high accuracy in the measurement of dimensions;
- visualization and evaluation of flaws and internal structures enhanced by image processing.

The X-Ray back scatter technique was discussed since more than 60 years to permit single sided radiographic testing [3].

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Especially after the successful application in the security field, the back scatter imaging returns back to the attention of NDT. First applications for carbon fiber reinforced polymer (CFRP) testing are presented [4].

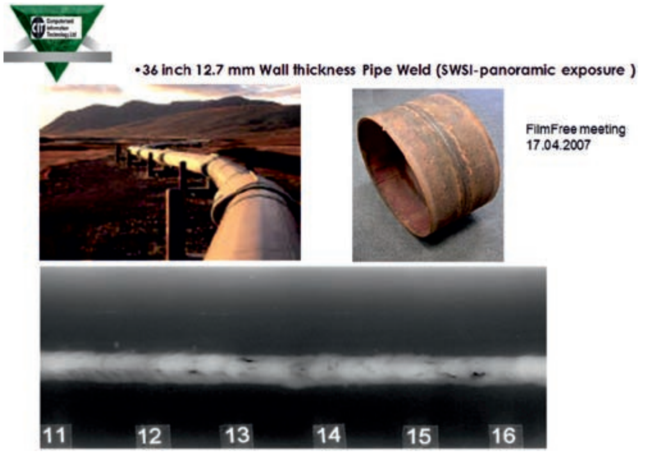

Fig. 1. Inspection of welded pipelines with CR [6]
Rys. 1. Inspekcja rurociągów za pomocą radiogafii cyfrowej [6]

Radiography and CT cover a wide application range, despite upcoming alternative NDT methods as phased array ultrasonics with synthetic aperture focusing for 3D visualization and complex electromagnetic methods, as e.g. THz based inspections. Radiography and CT are used in a range of few keV until 15 MeV for industrial usage and cover applications of objects in the nm to meter range.

Selected radiographic application areas will be discussed.

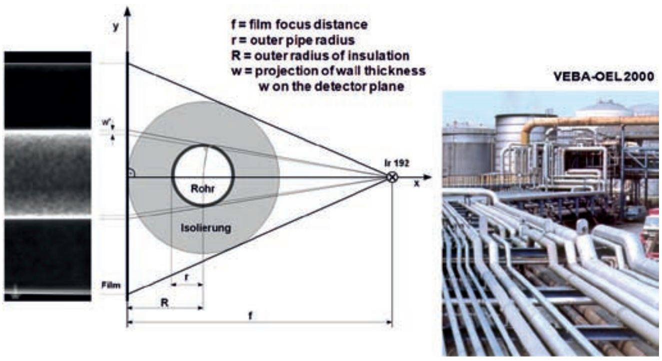

Fig. 2. Inspection of thermal insulated pipes for corrosion and wall thickness measurement with CR [7, 8]
Rys. 2. Inspekcja rur z izolacją termiczną w celu pomiaru korozji oraz grubości ścianek z wykorzystaniem radiografii cyfrowej [7, 8]

2. Filmless Radiography – Film Replacement

2.1 Computed Radiography (CR) with Phosphor Imaging Plates

Imaging Plates (IP) are routinely used in medicine and biomedical autoradiography since more than 20 years. Several systems are also offered for NDT applications [5, 6]. IPs are handled nearly in the same way as radiographic films. After exposure, they are read by a LASER scanner and processed to a digital image instead of being developed like a film [1, 5, 6]. Any remaining latent image can be erased with a light source (e.g. halogen, incandescent). So, the same IP can be recycled up to more than 1000 times if carefully handled. Less expensive CR scanner require manual handling of the imaging plates. This may reduce the IP cycle to less than 100 applications before scratches disturb the digital images.

Tab. 1. Standards for CR and DDA based applications
Tab. 1. Standardy dla aplikacji bazujących na CR i DDA

EN 13068	Radioscopy
EN 14096, ISO 14096	Film Digitization
EN 14784 CR (2005) ISO 16371 part 1 (2011)	Part 1: Classification of Systems, Part 2: General principles, part 2 becomes ISO 16371-2
ISO 10893-7 (2010)	Steel tubes – NDT of welds with DDA and (CR), in revision
ISO 17636-2 (2012)	NDT of welds: CR and DDA, substitution of EN 1435
EN 16407 (2012)	Practice: wall thickness measurement, with film, CR and DDA, double wall and tangential technique
ASME BPVC, S.V, Article 2 (2015)	Radiography with film, DDA, CR, radioscopy, film digitization
ASTM CR (2013) Under revision	Classification (E 2446-15), Long term stability (E2445-14), Guide (E 2007-10), Practice (E 2033-99, reapproved 2013)
ASTM DDA (2010)	Characterization (E 2597M-14), Guide (E 2736-10), Practice (E 2698-10), Long Term Stability (E 2737-10)
ASTM DICONDE (2010) (data format)	Standard Practice for Digital Imaging and Communication ND Evaluation (DICONDE)(E 2339-10, E 2663-08, E 2699-10, E 2738-10, E 2767-10)
ASTM E 2422-05, E 2660-10, E 2669-10	Digital reference image catalogues, light alloy, titanium and steel castings

CR systems are substituting film applications, especially for mobile NDT. A typical application is quality assurance of welds, based on ISO 17636-2. Fig. 1 shows an example of a CR application for radiographic pipeline inspection [6]. CR is applied in chemical industry more and more for corrosion and pipe thickness monitoring [7, 8] (see Fig. 2). More radiographs are taken for corrosion and thickness measurement in chemical industry than for weld inspection. Nowadays, CR is also applied to optimize manual maintenance of valves, fittings and other armatures. Radiographic imaging permits the evaluation of the functionality. Fig. 3 shows the digital radiograph of a unidirectional restrictor valve [9]. It is clearly seen that the valve is not functioning, because the valve flap sticks in the silt deposit. Manual maintenance is required. Imaging plates are especially sensitive for radiation of lower energy (< 250 keV). CR and DDA applications are regulated by standards. ISO 17635 defines the general rules for weld inspection ISO 17636-2 and ISO (Pipes) describe the standard practice for weld inspection. ASME BPVC Section V, Article 2 describes film and digital radiography practices. Most of the standards are taken over from ASTM E07 standard publications. The most important ones are listed in Table 1.

They can also be applied for high energy radiography in the MeV range, if scattered radiation is properly shielded and lead and steel sandwich filters are applied in front of the IP (see ISO 17636-2).

2.2 Digital Detector Arrays (DDA)

Two types of DDA's, also called flat panel detectors, are available on the market: The first design is based on a photo diode matrix connected to thin film transistors (TFT) [10]. These components are manufactured of amorphous silicon and they are widely resistant against high energy radiation. The photo diodes are charged by light which is generated by a scintillator converting the incoming X- or gamma rays to visible light. The next generation of DDA's is based on a photo conductor like amorphous selenium [11] or CdTe [12-14] on a multi-micro electrode plate, which is also read out by TFTs [13]. Currently the typical DDA systems for NDT achieve a resolution of 50 - 400 µm. Weld inspection and fine casting testing requires at least 50 µm resolution (see ISO 17636-2, Tables B.13, B.14). This can also be achieved by magnifying technique with mini- or micro-focus tubes.

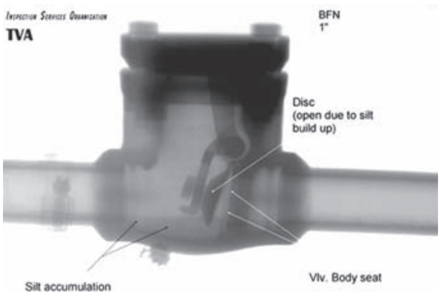

Fig. 3. CR image of a valve with slit deposit, influencing the functionality [9]
Rys. 3. Cyfrowy radiogram zaworu zanieczyszczonego mułem, wpływającym na funkcjonalność części [9]

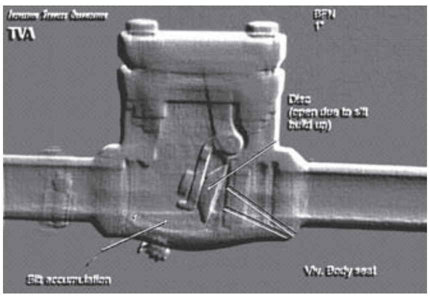

Fig. 4. CR image of a valve with slit deposit, enhanced with a digital gradient filter
Rys. 4. Cyfrowy radiogram zaworu zanieczyszczonego mułem, poprawiony z wykorzystaniem cyfrowego filtru gradientowego

DDAs are suitable for in-house and in-field applications. In-field applications have to be carried out often under harsh environmental conditions, which implies the risk of hardware damage and may exclude the application of DDAs. CR is the recommended technology here.

During the last 15 years a new generation of photon counting and energy discriminating detectors (PCD) has been developed. Most of them are on basis of Si or GaAs [15, 16]. Recently this technology was made available for applications at higher energy (tested up to 300 keV) [2, 17, 18]. The new photon counting detector permits the selection of energy thresholds to obtain an optimum energy range and reduction of the influence of scattered radiation. Since the new detector acquires digital images without offset intensity, long exposure times at low counting rates can be used to extend the range of penetrated thickness permitting a restricted controlled area. A specially designed and developed photon counting CdTe-CMOS detector by XCounter was tested in the TomoWELD project [2, 18]. The detector has a sensitive area of 100 x 50mm and a pixel size of 100 µm.

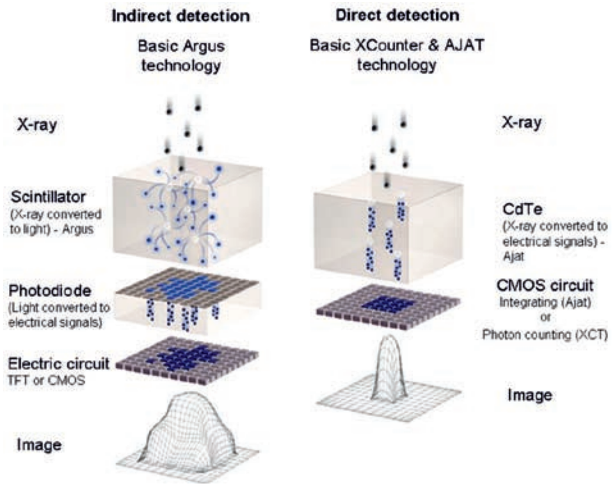

Fig. 5. Comparison between indirect (left) and direct (right) detection of X-rays [2]
Rys. 5. Porównanie pośredniej (z lewej) i bezpośredniej (z prawej) metody detekcji promieni X [2]

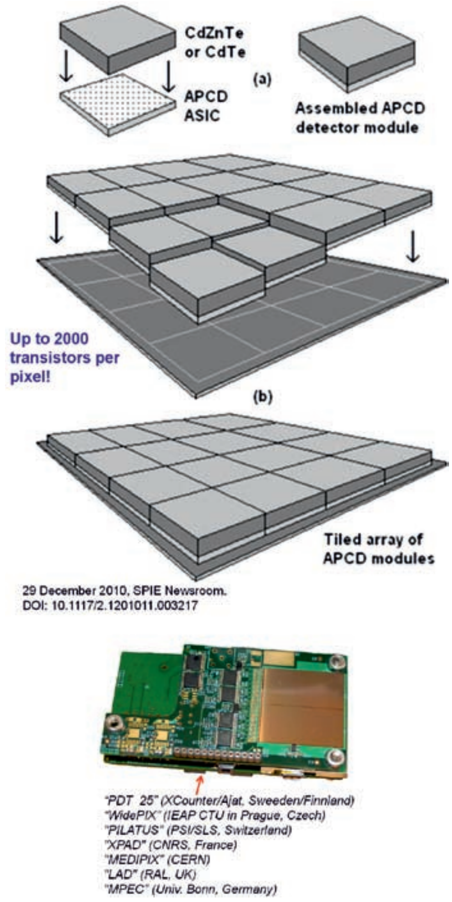

Fig. 6. General sketch of a photon counting energy discriminating detector (up) and photograph of the prototype PDT 25 (down) [18]
Rys. 6. Ogólny schemat detektora zliczającego fotony z dyskryminacją energii (z lewej) i fotografia prototypu PDT 25 (z prawej) [18]

The basic spatial resolution of the detector was determined, with a duplex wire IQI (ISO 19232-5), as equal to the pixel size

(100 µm). Up to 100 mm of steel were radiographed at 270kV, with the low count rate of about two 2 counts per second per detector element. Testing class B of ISO 17636-2 could be achieved after sufficient image integration [2, 18]. It is a direct converting detector, which enables the simultaneous detection of different parts of the X-ray spectrum depending on the control of energy thresholds. Figure 6 shows the tile structure of the detector and a photograph of a former prototype. Each detector element consists of up to two thousand transistors, which enable the energy discrimination and photon counting in each detector element.

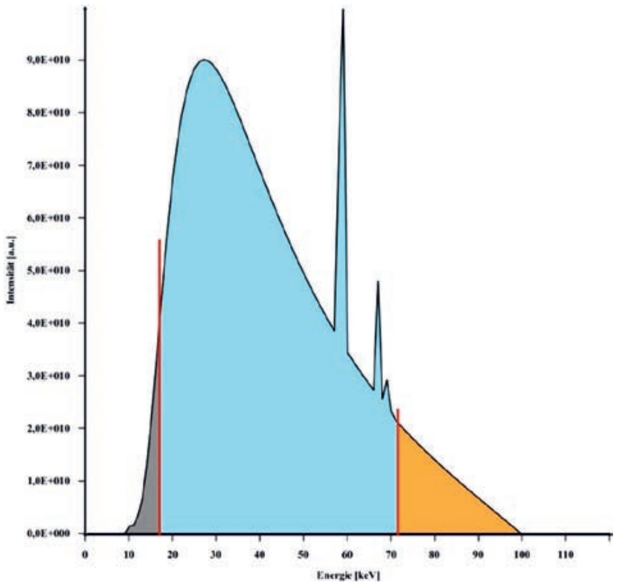

Fig. 7. Selective detection of a bremsspectrum (example) by thresholding inside of the detector [2]
Rys. 7. Selektywne wykrycie promieniowania hamowania (przykład) poprzez progowanie wewnątrz detektora [2]

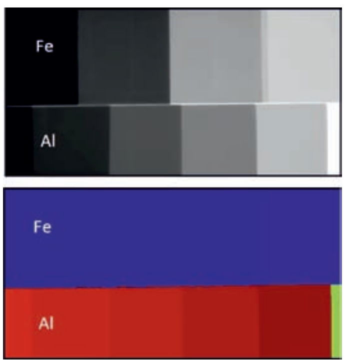

Fig. 8. Radiographic image (left) taken at 160kV and dual energy image (right) of Fe (blue) and Al (red) step wedges (green = free beam/air) [2]
Rys. 8. Radiogram (z lewej) wykonany przy 160 kV i obraz dwuenergetyczny (z prawej) klinów schodkowych wykonanych z Fe (niebieski) i Al (czerwony) (barwa zielona = powietrze) [2]

Photon counting and energy discriminating detectors can be used to acquire dual energy radiographs for discrimination of the different materials [2, 19, 20]. Material's discrimination using X-rays is based on the difference in energy dependency of the mass attenuation coefficient of the investigated materials [21]. When two different energies are used, this technique is called dual-energy imaging. The energy discriminating capability of the PCD enables the separate acquisition of radiographs at the low energy (LE) and high energy (HE) part of the X-Ray spectrum by internal and selective energy thresholding (see Figure 7). Fig. 8 shows a typical example for the thickness visualization and material separation measured with 2 step wedges from steel and aluminum (red).

2.3 High Contrast Sensitivity Technique with DDAs

The image quality depends on the basic spatial resolution, the attenuation coefficient and the signal to noise ratio (SNR) in digital radiology [22]. DDAs need to be calibrated before usage to equalize the different characteristics of the detector elements. This avoids image distortions by fixed pattern noise due to differences in the detector elements and the electronics. Consequently, the image noise depends dominantly on the photon statistic. This can be exploited for radiography with high SNR and improved contrast sensitivity. DDA systems achieve currently a significantly higher SNR, CNR and better contrast sensitivity than imaging plates and films, if they are properly calibrated.

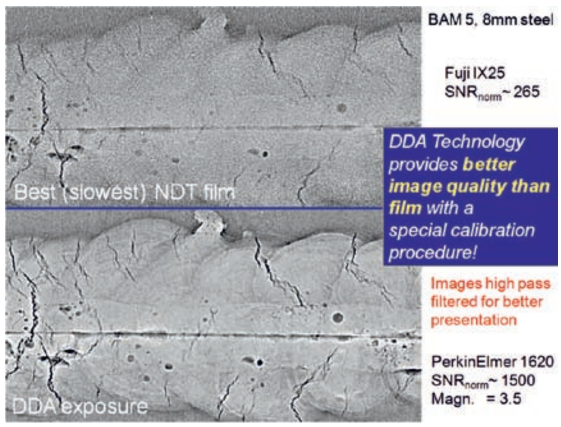

Fig. 9. Enhanced detail visibility of flaws by increased SNR of a DDA image in comparison to a digitized film image of weld sample BAM 5 after numeric high pass filtering [1]
Rys. 9. Poprawiona widoczność detali wad na próbce spawu BAM 5 poprzez zwiększenie SNR obrazu otrzymanego z użyciem detektora cyfrowego, w porównaniu do obrazu otrzymanego ze zdigitalizowanego zdjęcia rentegowskiego przetworzonego za pomocą cyfrowego filtru górnoprzepustowego [1]

Figure 9 shows the effect of SNR increase (equivalent to CNR increase) on the visibility of fine flaw indications [22, 23] in comparison to film radiography. The digitized fine grained film provides a SNR of 265 in the base material region. The DDA image was measured with a SNR of about 1500 and magnification of 3.5. It shows significantly finer flaw indications.

3. X-ray back scatter technique

The X-ray backscatter radiography is based on inelastically scattered X-ray photons, known as Compton Scattering [24]. Objects, which are transparent to X-rays, emit scattered radiation in forward and backward direction. This occurs preferentially in organic and low-numbered materials based on their ranking in the periodic table of the elements. All elements with high atomic numbers (e.g. heavy metals) mainly absorb X-ray photons; so they emit scattered radiation to the outside with a much lesser intensity. Back scattered radiation can be used for imaging of inner structures of volumetric objects. This permits to visualize organic materials behind thin metals as e.g. contraband or explosives in cars and containers. The technology is well established for security applications. It has also high potential for safety applications due to the advantage of single sided access. Figure 10 shows a typical example of the back scatter inspection of an airplane by AS&E, which could not be taken with double sided access by source and detector [25]. The flying spot technique is described in [26].

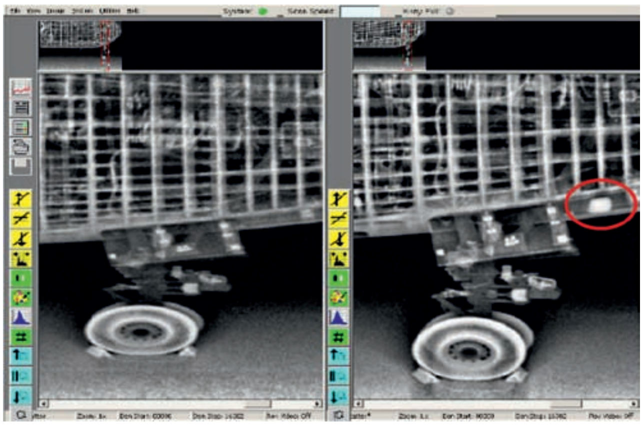

Fig. 10. Back scatter Image of an airplane structure taken with flying spot technology of AS&E [25]
Rys. 10. Obraz elementu struktury samolotu otrzymany techniką rozpraszania wstecznego przy wykorzystaniu technologii flying spot AS&E [25]

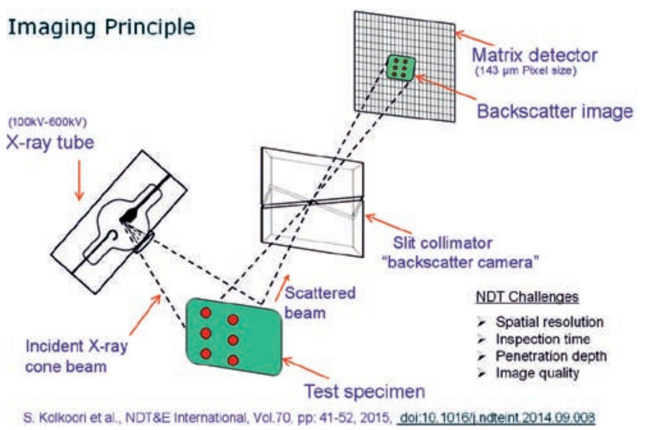

Fig. 11. Scheme of the X-ray back scatter technique using uncollimated incident X-rays and a twisted slit camera with a DDA for imaging of the scattered radiation of the test object [32]
Rys. 11. Schemat techniki rozpraszania wstecznego przy użyciu nieskolimowanych, padających promieni x, kolimatora ze skręconą szczeliną i detektora cyfrowego do obrazowania promieniowania rozproszonego przez obiekt testowy [32]

The general approach for imaging X-ray backscattered radiation from an object is using the 'pinhole camera' principle. A Compton scatter method using an X-ray fan-beam and a pinhole camera for non-destructive testing (NDT) of materials was presented by Strecker [27]. The main drawbacks of this technique are low-efficiency of the pinhole camera and the large measurement time. ComScan (Compton backscatter scanner) a former commercially available backscatter imaging system for NDT applications was described in [28, 29]. Recently, commercial applications of back scatter imaging for NDT in aerospace industry were published by [30, 31].

Alternatively to the flying spot technology of AS&E [25] a diaphragm based camera was developed and explored for applications in NDT [32 - 34]. Figure 11 shows the setup of the scatter camera of BAM with a diaphragm based on a ruled surface slit. Figure 12 shows a comparison of the back scatter image (90° between camera and exposure direction) and a transmission image of carbon reinforced composite plates with internal stiffening structures and water inclusion. The water and the internal structures are clearly visible [35]. Recently multi slit camera optics were developed and explored with aperture focusing techniques to enhance the sensitivity.

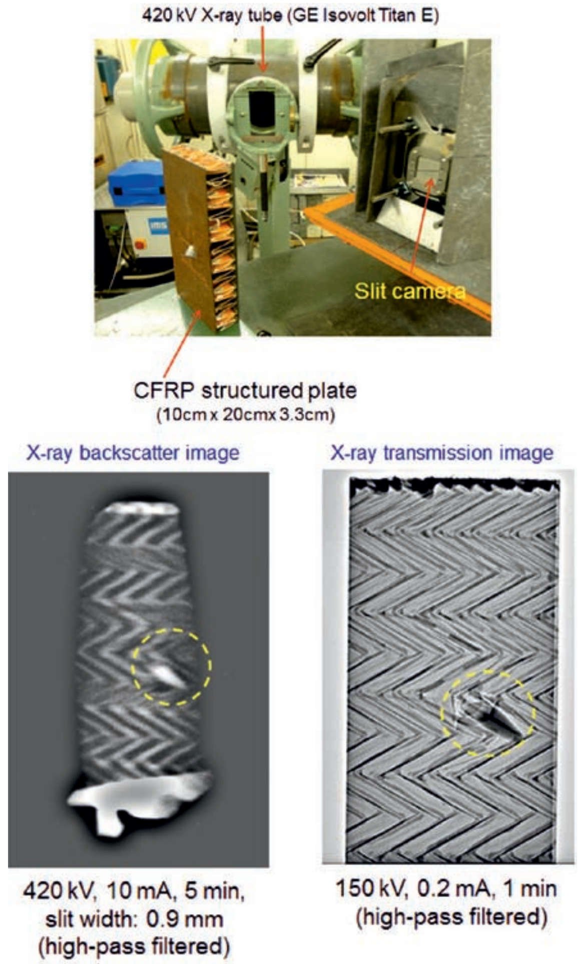

Fig. 12. Set up of a back scatter measurements of a CFRP structure (up) and back scatter image (left) in comparison to transmission radiograph (right) [35]
Rys. 12. Układ do pomiarów struktury CFRP z wykorzystaniem techniki rozpraszania wstecznego (z lewej) i obraz otrzymany tą techniką (w środku) w porównaniu do obrazu otrzymanego w technice transmisyjnej (z prawej) [35]

First results were published in [36]. The camera diaphragm contains a set of equidistant parallel twisted slits, which generate an overlaid image of the scattered radiation projections per slit emitted by the test object (here the letter "A"). Fig. 13 and Fig. 14 shows the CAD design of the multi slit diaphragm and the simulated image with aRTist and McRay [36, 37]. A deconvolution based aperture focusing technique was developed obtaining the undistorted scatter image of the test object with enhanced sensitivity (Fig. 13-14).

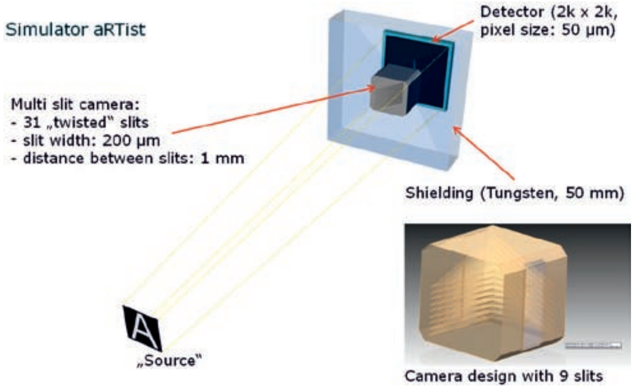

Fig. 13. CAD design of a multi slit camera with parallel twisted slits [36]
Rys. 13. Projekt CAD wieloszczelinowej kamery z równoległymi skręconymi szczelinami [36]

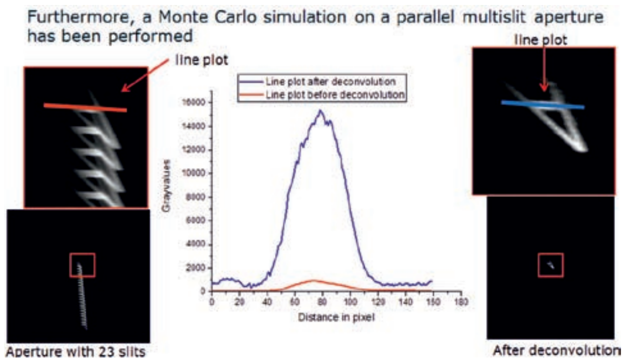

Fig. 14. Simulated camera image (left), profile along the red line (center) and scatter image of the letter "A" after aperture focusing [37, 38]
Rys. 14. Zasymulowany obraz z kamery (z lewej), profil wzdłuż czerwonej linii (w środku) oraz rozproszony obraz litery „A" po wykorzystaniu techniki aperture focusing (SAFT) [37, 38]

4. Simulation

The importance of modelling in NDT was recognized in the last 20 years in the NDT community. Especially the software package CIVA [38] is widely used for modelling different NDT techniques.

In order to adequately simulate the radiographic process several elements need to be considered in a modeling tool. This includes the object's geometry, orientation and position relative to source and detector, material properties, source characteristics and detector parameters. BAM developed the modelling package aRTist (Analytical RT Inspection Simulation Tool [39]) for film based and digital radiography. It permits modelling of Computed Tomography (CT) and laminographic scenarios. There exist also other available modelling software tools for RT as e.g. CIVA, XRSIM and Scorpius XLab. Several variance reduction methods are implemented in aRTist to keep simulation times short [42]. Triangulated surfaces can be processed directly by the code, allowing the use of existing CAD models for complicated objects. aRTist is applied for training in radiography (digital and film), optimization of NDT scenarios, virtual POD trials and recently for development of X-ray optics for back scatter techniques [36, 37]. Fig. 15 shows two modeling examples for design of the new TomoWELD scanner [18].

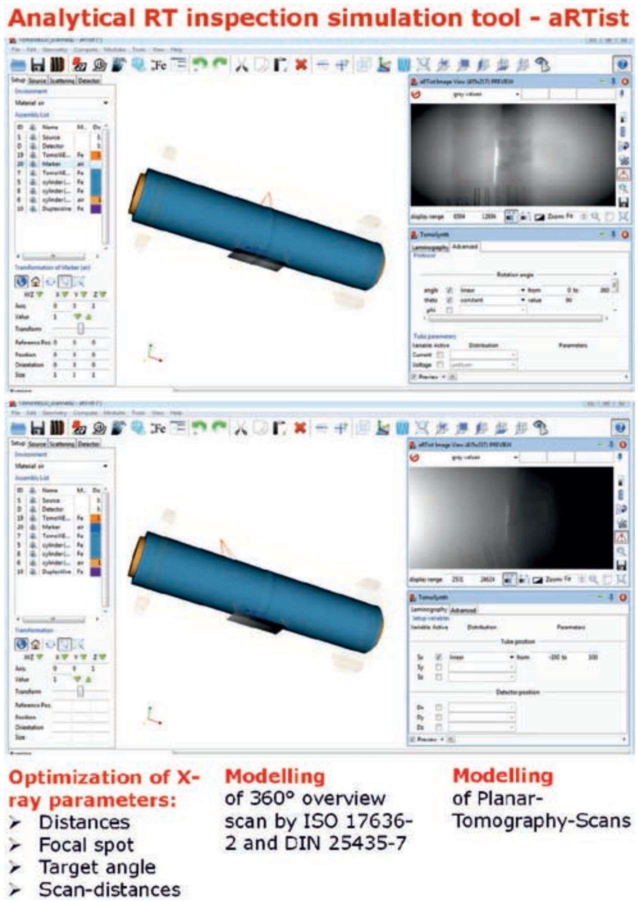

Fig. 15. aRTist scenarios designed for automated weld inspection with 360° circumferential scan (top) and Planar Tomographic scan (bottom) with modelled projections [18]
Rys. 15. Stworzone w programie aRTist schematy automatycznej kontroli spoin za pomocą 360° skanowania po obwodzie (góra) i tomograficznych skanów powierzchni (dół) z zamodelowanymi projekcjami [18]

5. Summary

Computed Radiography with phosphor imaging plates has gained more and more importance for mobile inspection and film replacement. Weld inspection, corrosion and functionality tests are the major applications. Related standard practices are available at ISO, CEN, ASTM and ASME. New calibration methods enable the High Contrast Sensitivity Technique (HCS RT) for radiographic inspection. The contrast sensitivity can be enhanced in comparison to film. New efficient Digital Detector Arrays (DDA) are available for stationary and mobile testing. They are also applied for automated defect recognition (ADR), CT, Back Scatter and Dual Energy applications. New CdTe-based photon counting (PC) and energy discriminating detectors for X-Ray applications up to 300 kV permit the inspection of an increased thickness range of steel, light alloys and polymers in comparison to integrating DDAs. PC detectors can be applied for inspections with low photon flow, since no dark signals need to be considered. The detectors can be used to shape X-ray spectra for reduction of scattered radiation. Dual energy radiographs can be taken to acquire attenuation images with material discrimination. Back scatter techniques are increasingly applied for security and NDT. Additionally to the flying spot technique new diaphragm based optics were designed for application at higher X-ray potentials (up to MeV range). Diaphragms with twisted slits were successfully tested for CFRP applications in aerospace industry. Numeric radiographic modeling is applied for experiment planning, film replacement optimization, POD-calculations and training.

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