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Progress in Digital Industrial Radiology Part II: Computed tomography (CT)

Postępy w cyfrowej radiografii przemysłowej Część II: Tomografia komputerowa

ABSTRACT

Part 1: Film Replacement and Backscatter Imaging. The related paper was published in Vol 1-2/2016 of this journal.
Part 2: Computed tomography (CT). Applications cover the range from nano-meter to meter scale. New specialized high energy CT devices have been laid out for inspection of large building structures or complete cars before and after crash tests. The scope of typical CT applications changes from flaw detection to dimensional measurement in industry substituting coordinate measurement machines. First applications of at line or in line inspection in production lines of car industry are discussed. CT is applied for a variety of applications, where selected areas as e.g. plant and food research in outlined. Mobile computed tomography is applied for in-service radiographic crack detection and sizing of welded pipes in nuclear power plants and for NDT of large CFRP structures of airplanes.
Part 3: Micro Radiography and Micro CT. To be published in this journal.

Keywords: *digital radiography, computed tomography, laminography, CFRP, aerospace, automotive*

STRESZCZENIE

Podobnie jak w przypadku zakończonego sukcesem wdrożenia fotografii cyfrowej, bardzo istotne zmiany można zaobserwować także w cyfrowej radiologii przemysłowej. Niniejsza praca jest podzielona na 3 części:
Część 1: Następca błony radiograficznej i obrazowanie za pomocą rozproszenia wstecznego – publikacja ukazała się w wydaniu Nr1-2/2016 tego czasopisma.
Część 2: Tomografia komputerowa (CT). Zastosowania tomografii obejmują obiekty o wielkości od nanometrów do metrów. Nowe dedykowane urządzenia wysokoenergetycznej tomografii komputerowej skonstruowano w celu inspekcji dużych konstrukcji budowlanych czy też całych samochodów przed i po testach zderzeniowych. Cel typowego zastosowania tomografii komputerowej uległ zmianie z detekcji wad na wymiarowanie wyrobów przemysłowych, co spowodowało zastąpienie współrzędnościowych maszyn pomiarowych. W pierwszej kolejności omówiono zastosowanie tomografii komputerowej na liniach produkcyjnych w przemyśle samochodowym. Tomografia komputerowa ma wiele zastosowań, w tym np. badanie roślin i żywności. Przenośne tomografy komputerowe wykorzystywane są do wykrywania defektów i wymiarowania spawanych rur w elektrowniach jądrowych, a także do inspekcji dużych elementów konstrukcji lotniczych wykonanych z kompozytów węglowych.
Część 3: Mikroradiografia i mikrotomografia komputerowa.

Słowa kluczowe: *radiografia cyfrowa, tomografia komputerowa, laminografia, kompozyty węglowe, przemysł lotniczy, przemysł motoryzacyjny*

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1. Introduction

Computed Tomography (CT) for 3D inspection is applied more and more for industrial applications following its establishment in medicine. In the 1990s, Computed Tomography devices were commonly used for investigations of materials in laboratories of universities and in industrial research. CT was introduced during the last 15 years in industrial quality assurance based on the increasing computer power and the availability of highly sensitive digital detector arrays (DDA). The application areas of CT are diverse and extensive, since any material or component can be examined with CT. The major application areas of CT in science and industry are nondestructive testing, 3D materials characterization and dimensional measurements (metrology). At the 6th Conference on Industrial Computed Tomography (ICT) in 2016, it was concluded [1]: "CT is a non-touching, non-destructive method which reveals the complete 3D geometry of a specimen including inner surfaces. For research, CT is an excellent tool to support the development of new materials, new processes and new parts, but it is also used for quality control and failure analysis".

Radiography and CT cover a wide application range, despite upcoming alternative NDT methods as phased array ultrasonics with synthetic aperture focusing for 3D

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visualization [2] and complex electromagnetic methods, as e.g. THz-based inspections [3]. Radiography and CT are used in a range from a few keV up to about 15 MeV for industrial use and cover applications in the nano-meter to meter range. Selected radiographic application areas will be discussed in this paper. μ- and nano-CT will be covered in a separated paper in this journal.

2. Computed Tomography

2.1 Stationary Industrial Computed Tomography

Computed Tomography (CT) is an X-ray based method for the complete visualization of inner structures and surfaces or interfaces, respectively. The object under inspection is typically rotated during a scan, and several hundred radiographic projections are acquired with a digital detector array. Numeric procedures as e.g. the filtered back-projection, are used to reconstruct the three dimensional (3D) volume images. The ability of CT for measurement of dimensions is well known since its first application in the 70ties. The Nobel Prize was awarded to Cormack and Hounsfield in 1979 for "Computer Assisted Tomography". The first devices were described in scientific literature in 1972. The major application area for CT was and continues to be medicine. Soon after successful medical application, the first CT investigations were performed for material's science and flaw detection.

In the 1990s, the use of CT devices was common for material investigations in institutes and universities as well as in industrial research. With increasing computer power, CT was introduced 15 years ago in industrial quality assurance. Since then the accuracy of CT could be significantly improved, simultaneously the modern CT scanners can be produced with relatively affordable costs. This makes the CT technology interesting as touchless measurement tool for inner and outer dimensions.

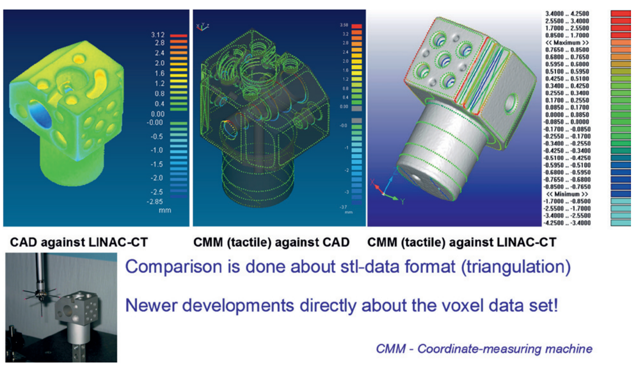

Fig. 1. Result of the comparison of the accuracy of high energy CT with a CMM measurement. The accuracies are encoded by color.

Rys. 1. Porównanie dokładności w przypadku wysokoenergetycznej tomografii komputerowej i współrzędnościowych maszyn pomiarowych. Zakres tolerancji wymiaru odpowiada skali barw

2.2 Dimensional Measurement

The ability of CT for measurement of dimensions is well known since its first application in the 70ties. This makes the CT technology interesting as NDT and touchless measurement tool for dimensions, and especially, for inner dimensions which cannot be accessed by mechanical or optical

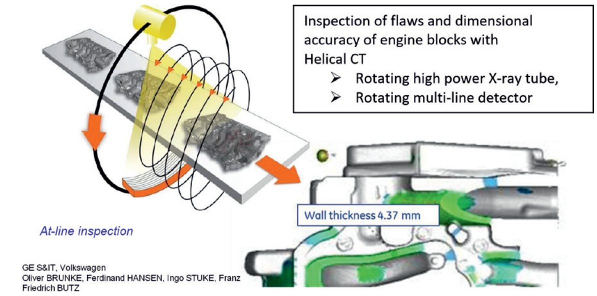

Fig. 2. At-line inspection of engine blocks in the manufacturing process with helical CT for defect detection and dimensional measurement.

Rys. 2. Inspekcja bloków silników podczas procesu produkcyjnego za pomocą spiralnej tomografii komputerowej w celu wykrywania defektów i wymiarowania.

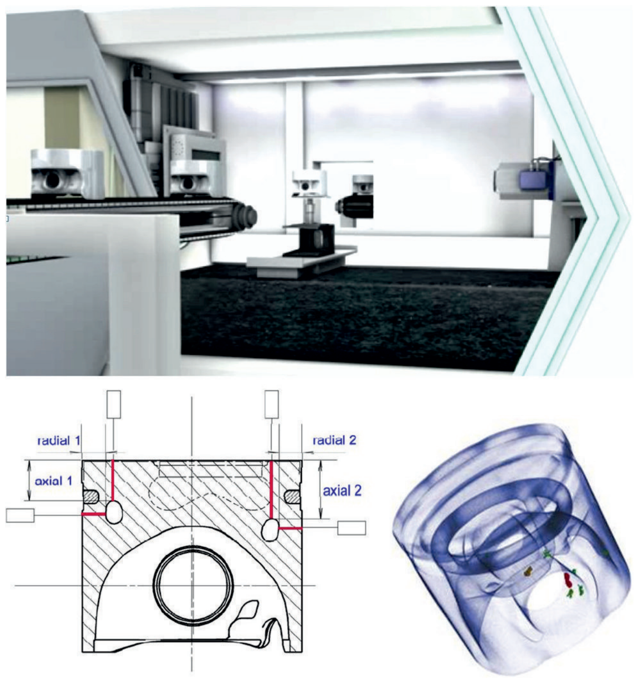

Fig. 3. Inline monitoring of piston production with X-ray CT. Top: the interior of the CT-system with pistons delivered through the front door, placed on a turn table between the X-ray tube (right hand side) and a digital detector array (left hand side). The exact design of the piston (lower left) is given to a fully automatic software algorithm to detect voids, cracks or deviations from the specified geometry (noncritical in green and shrinkage in red in the 3D visualization; lower right)

Rys. 3. Bieżące monitorowanie procesu produkcji tłoka z zastosowaniem tomografii komputerowej. Górna część: zdjęcie wnętrza systemu tomografii komputerowej z tłokami dostarczonymi przez drzwi frontowe, umieszczonymi na stole obrotowym pomiędzy lampą rentgenowską (po prawej stronie) i detektorem cyfrowym (po lewej stronie). Dokładny projekt tłoka (w lewej dolnej części rysunku) przekazywany jest do w pełni automatycznego algorytmu wykrywania pustek i pęknięć oraz odchyleń od zadanej geometrii (w prawym dolnym rogu: na wizualizacji przestrzennej zaznaczono zielonym kolorem odstępstwa niekrytyczne, a czerwonym skurcz.

tools. Prerequisite for the CT application is the accurate validation of the measurement procedure in comparison to coordinate measurement machines (CMM) and the present standards for determination of accuracy parameters with measurement systems. A new generation of multi sensor CMMs combines the CT operation with optical sensors and tactile probing [4]. However, an important aspect of all coordinate measurements is the traceability of the geometry information obtained. To achieve traceability, several standards have been developed in recent years [5-8]. Reference standard gauges with high information content are e.g. a sphere calotte plate made of Zerodur and a sphere calotte cube made of titanium, which provides 2D or 3D information for CT system testing and correction, respectively. The following parameters have to be determined: Sphere distance error (SD), probing error size (PS) and probing error form (PF). This has been performed by parallel measurements of calibration objects and real test objects with high energy CT, micro CT and CMMs. Measurement differences are visualized by color coding (Fig. 1).

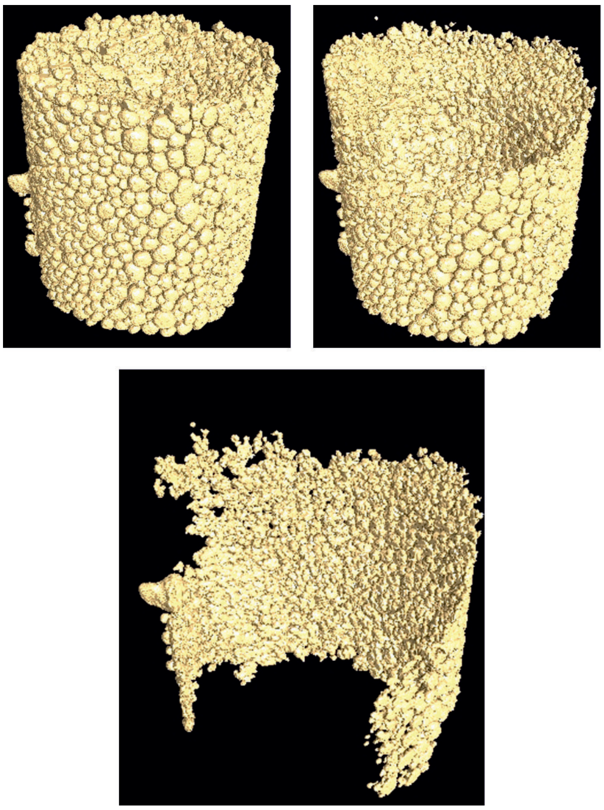

Fig. 4. Temporal change of a milk foam for coffee cream. The decay can be assessed and described from 3D image data acquired after 2, 4 and 6 minutes (from left, right, down) [13]

Rys. 4. Zmiany w czasie zachodzące w piance mlecznej do kawy. Rozpad może zostać oceniony i opisany na podstawie danych z trójwymiarowych obrazów uzyskanych po 2, 4 i 6 minutach (od góry i dół od lewej do prawej) [13].

For example, Volkswagen uses a fast CT scanner for at-line inspection in its production process [9]. Engine blocks are inspected in production as a random selection in the production process. CT is used to test for flaws and control of correct dimensions (Fig. 2). First reports were given on in-line inspection [9].

Another example of in-line Computed Tomography that was realized by the Fraunhofer EZRT is the inspection of motor pistons [10, 11] (Fig. 3). This system for production monitoring is capable of measuring 100% of the parts keeping up with the production rate. Recognizing aberrations early in the production process helps to minimize the rejection rate. Blowholes and pores are not only recognized but also located and geometrically analyzed. Up to now, manufactured parts are often rejected due to lack of information. They can be processed further, if the irregularities are located in a noncritical area or if the location is machined afterwards. Additionally, the metadata obtained are referred back into the production process. By intelligent data feedback, production parameters like pressure or temperature can be adjusted in a way that less critical flaws are produced.

A further relatively new field, where industrial CT is applied, is the analysis and monitoring of organic structures. For instance the temporal change of milk foam for coffee cream can be visualized by fast CT (Fig. 4). The seed or food producing industry set new challenges to 3D imaging, as a support for the development of improved plant varieties and pharmaceuticals or for monitoring of the production of high quality foods.

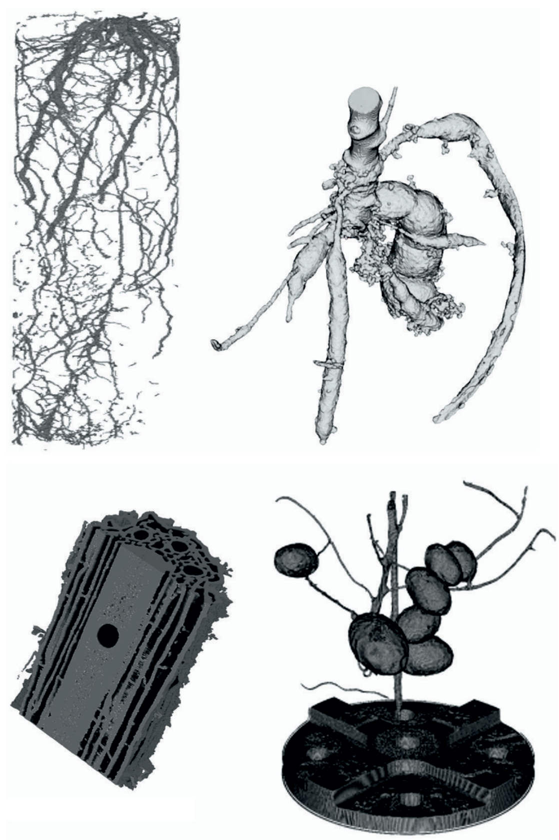

Fig. 5. 3D visualizations of (from left to right) root architecture beneath the soil, reservoirs, capillary tube inside the stem or trunk, fruits and organs. In all cases the soil which covers the complex structures is virtually removed.

Rys. 5. Trójwymiarowe wizualizacje podziemnego systemu korzeniowego, zbiorników, naczyń kapilarnych wewnątrz łodygi lub pnia, owoców i organów. We wszystkich przypadkach gleba, która okrywała złożone struktury została wirtualnie usunięta.

In agricultural engineering, many interesting parts of the plant are hidden to visual inspection beneath the soil wherein the plant is growing (Fig. 5). Thus the task for X-ray CT is to visualize these parts not only with high spatial and temporal resolution of the data set, but also with a high sensitivity for very similar contrasts between different organic materials, which typically contain a high fraction of water.

Another upcoming application for 3D X-ray imaging technology is related to cultural heritage protection. More and more singular, precious, irreplaceable and culturally significant objects are digitized. The benefits are obvious and manifold: more than 90% of all historically relevant objects are hidden in storage facilities today and not accessible to the broad public. In addition, objects made of wood, leather, cloth, ivory or various other organic materials– in opposite to metallic tools, weapons and instruments – are subject to decay and disintegration. Thus preservation, monitoring of the status, virtual access and detailed inspection of for example musical instruments, sacral equipment, furniture and clothing is becoming extremely important to preserve the world's cultural heritage of all nations, religions and continents.

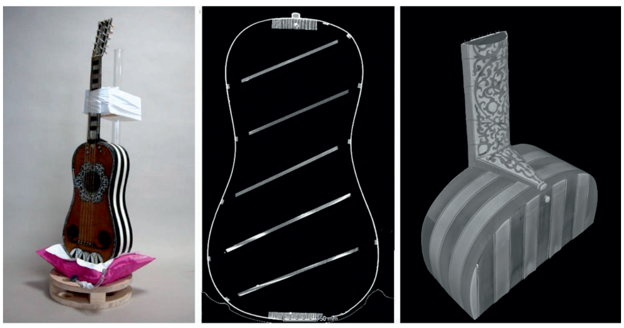

Fig. 6. Investigation of a precious guitar built in the first half of the 17th century in Italy [14]: Photography of the specifically designed support construction of the instrument (left), horizontal slice through the stabilizing structures inside the resonance body of the instrument (center), a surface rendered 3D display of the delicate ornaments embedded into the corpus and the neck (right).
Rys. 6. Badanie cennej gitary zbudowanej w pierwszej połowie 17 wieku we Włoszech [14]: Fotografia specjalnie zaprojektowanej konstrukcji wsporczej instrumentu (z lewej), poziomy przekrój wzdłuż stabilizującej struktury pudła rezonansowego instrumentu (środek), obraz trójwymiarowa wizualizacja powierzchni renderowanej z delikatnymi ornamentami zdobiącymi korpus i gryf (po prawej).

Presently, CT-systems face three major challenges with such culturally relevant objects: 1st many pieces like cupboards, pianos or statues are larger than the field of measurement provided by today's 40 cm by 40 cm standard flat panel detectors. 2nd historical objects often contain various materials, in particular mostly organic substances like wood, cloth, leather, or ivory, bones etc., in direct neighborhood with steel, copper or even gold, which have to be assessed with sufficient contrast in the reconstructed CT volume data sets. 3rd the investigation or digitization of a historical object may require a spatial resolution better than that needed for conventional non-destructive testing in industry, e.g. if the interior structure of wooden parts shall be examined. Thus CT systems, which can adequately be applied for cultural heritage, should provide the combined capability of high-resolution imaging of large objects with respective techniques for extension of the field of measurement and multi-energy analysis for a wide range of material contrast. Fig. 6 shows an example of a CT investigation of a precious guitar, built in the first half of the 17th century in Italia [14, 15].

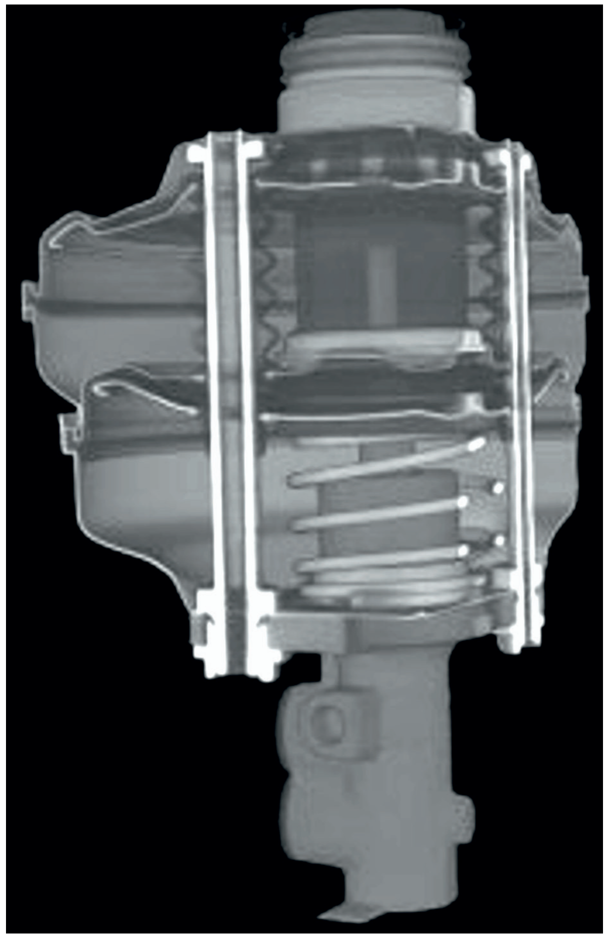

Fig. 7. High Energy (6MV) Axial CT image of a booster [7].
Rys. 7. Obraz z wysokoenergetycznej CT wzmacniacza [7].

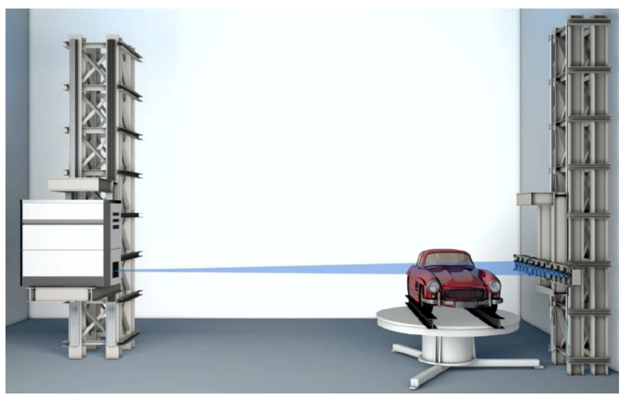

Fig. 8. High Energy CT at Fraunhofer EZRT: Schematic presentation of the set-up of the high-energy facility.
Rys. 8. System wysokoenergetycznej tomografii komputerowej w Fraunhofer EZRT: schematyczny widok konfiguracji systemu.

High energy CT is basically applied for investigations of large objects as e.g. rocket motors, artillery ammunition, radioactive waste barrels, large castings and steel-reinforced concrete blocks. Several units are installed for investigation of weapons worldwide, with restricted information about these systems. The first high energy unit in Germany was installed at BAM in 1992 [16] for inspection of barrels with radioactive waste. The CT scanner consists today of a linear accelerator (LINAC) with a maximum energy of 10.5 MeV, a manipulation system (translation and rotation) for objects of up to one metric ton and different detection systems for 2D and 3D tomography. Other labs exist worldwide, which are offering services for DR and CT. A typical application is the visualization of internal structures as shown in Fig. 7 [17].

In 2013 the Fraunhofer Center for X-ray Development (EZRT - Entwicklungszentrum Röntgentechnik) opened a new facility for industrial X-ray research. This center was equipped with the second high energy CT-laboratory in Germany in 2014. This lab is equipped with a 9 MV Linac and a 4 m line detector. Objects need to be manipulated on a turn table for CT scan. This lab offered first time high resolution 3D inspections of whole cars. Especially the crash tests of cars require time consuming mechanical analysis of the damages. Using a CT of a crashed car provides fast and highly resolved data on the structural deformations (Fig. 8, 9).

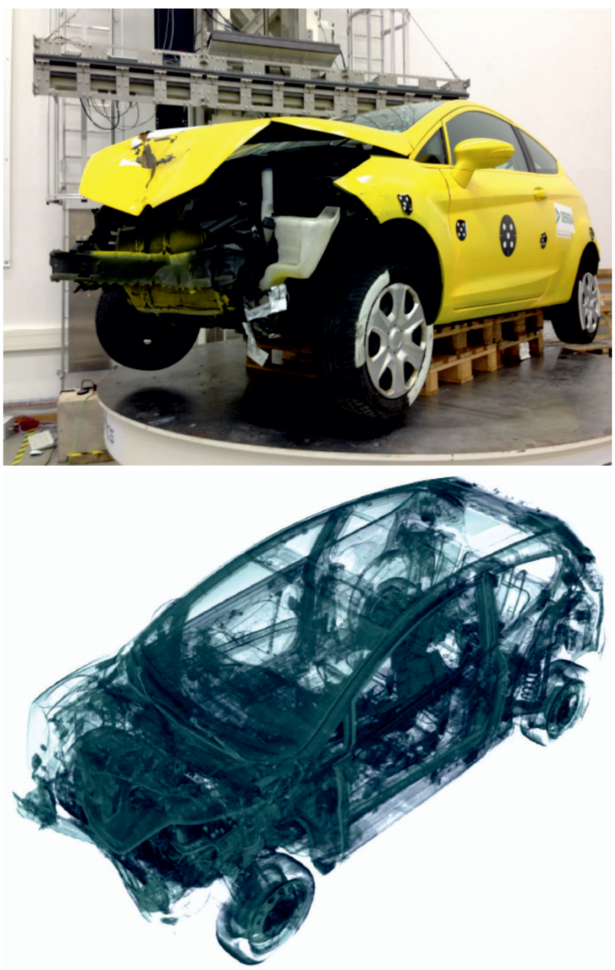

Fig. 9. High Energy CT at Fraunhofer EZRT: Up: photography of a test car after crash test. Down: 3D visualization of the volume data set resulting from a CT measurement with the 9-MV-LINAC as X-ray source.

Rys. 9. System wysokoenergetycznej CT w Fraunhofer EZRT: (góra) fotografia samochodu po teście zderzeniowym, (dół) trójwymiarowa wizualizacja danych otrzymanych z CT z zastosowaniem 9-MV-LINAC jako źródła promieniowania.

A second high energy CT device was installed at BAM in 2013 (Fig. 9) consisting of a 7.5 MV source and a 2 m line detector and a DDA witch can be used at different tile positions to obtain large area projections. The source, object and detectors can be manipulated with 13 numerically controlled axis and a resolution better than 50 µm. All manipulation systems are mounted on granite blocks. Fig. 10 shows the unit with a mounted concrete block of 1.5 x 1.5 by 0.3 m³ for visualization and measuring of impact initiated crack fields. Fig. 10b represents the reconstructed crack field, centrally oriented from impact position. The used 40 x 40 cm² Perkin Elmer detector was computer controlled positioned at different tile positions in a detection field of 3 x 5 positions, covering an area of about 1.4 m². A special filtered and weighted shift average reconstruction was developed to implement the reconstruction of tiled laminographic scans [18]. The goal of the project is the investigation of the material response under pulse impact loading of airplanes to buildings. The CT is used to quantify the material damages as input and verification of finite element simulations to predict the behavior of the reinforced concrete after an impact.

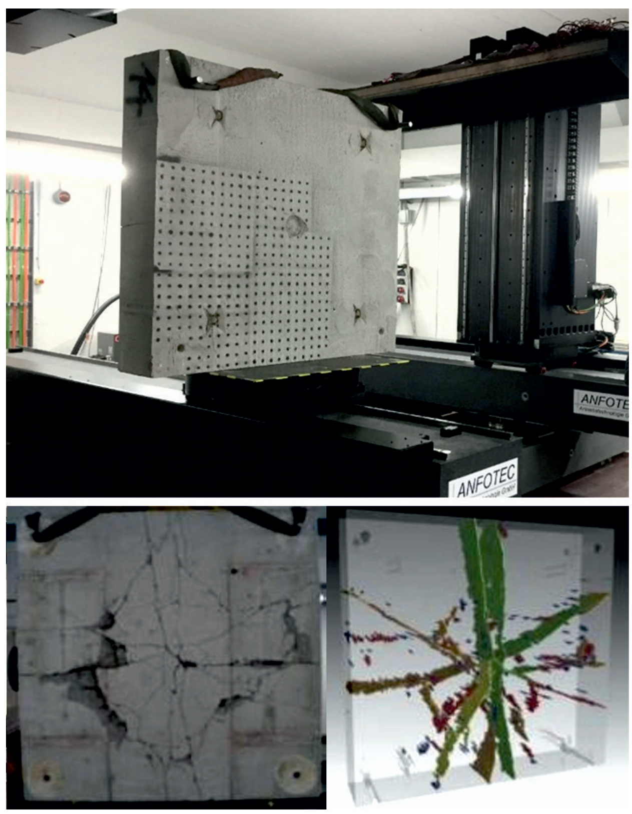

Fig. 10. Pictures of high-energy planar CT (7.5 MV) system (up), impact damaged slab (left), 3D CT image of slab illustrating the crack volume (right).

Rys. 10. Zdjęcie wysokoenergetycznego (7,5 MV) systemu CT (góra), płyta uszkodzona w wyniku uderzenia (dół-lewa), trójwymiarowa wizualizacja z CT płyty pokazująca pęknięcia (dół-prawa).

3. Reconstruction and Visualization Software for CT and Laminography.

Different software tools are used for reconstruction, visualization and data analysis. For the standard axial CT geometry, usually the classical Feldkamp reconstruction (filtered back-projection) is used. For special geometries, projections can be acquired under limited data, limited angle and limited view conditions. Different groups developed complex reconstruction methods considering a reduced set of projections to save measurement time. Missing measurement angles are compensated considering a priori knowledge, Bayesian approaches and total variation for the solution of the inverse problem [19 - 21].

Special software tools were also developed in BAM for the algebraic reconstruction technique. The multiplicative SART method is suitable for the limited data CT if the number of projections need to be reduced due to low pulse rates or slow acquisition times. The next to base plane method [18] permits the reconstruction from limited number of projections and considering dead angles with no negative density in the resulting voxel data set.

4. Mobile Industrial Computed Tomography

For industrial objects, as e.g. bridges, pipelines and aircrafts, which cannot be brought to the laboratory, mobile CT scanners were developed. They are typically based on the planar tomographic design. The first applications were qualified by third party organizations for sizing of planar defects in nuclear power industry and aircraft industry.

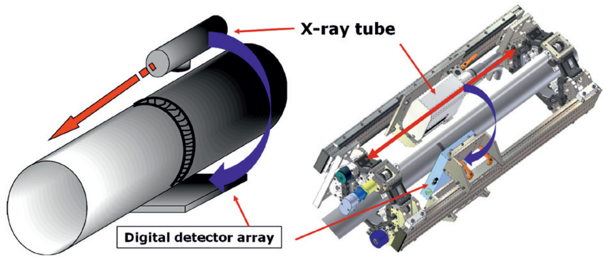

Fig. 11. Tomoweld manipulator for 360° circumferential scan and laminographic inspection; scheme and photograph.
Rys. 11. Manipulator Tomoweld do obwodowego skanowania w zakresie 360 °i laminografii; schemat i zdjęcie.

The mechanized mobile tomographic system "TomoCAR" (Tomographic Computer Aided Radiometry) was developed first for inspection of circumferential welded seams of pipes [22]. It consists of the manipulator based position control of an X-ray tube in front of the region to inspect and a Digital Detector Array (DDA) behind it. Several hundred radiometric projections in small angular steps are acquired. The tomographic reconstruction allows the three dimensional (3D) representation of the material structure and included flaws. This is equivalent to a metallographic cross sectioning. It allows the reliable detection of planar defects with openings larger than 25 µm by subpixel resolution due to the achieved high signal-to-noise ratio of the used CdTe DDA.

The European project TomoWELD [23] was established to modernize the TomoCAR concept for effective inspection. This includes high contrast sensitivity measurements with a photon counting and energy discriminating CdTe detector [24, 28], and an optimized 3D reconstruction algorithm using GPUs. Fig. 11 shows a sketch and a picture of the TomoWELD system. A computer controlled manipulator permits two measurement modes. In overview mode the source and detector can be moved 360° around the pipe axis, which provides a digital radiograph according to ISO 17636-2 [25].

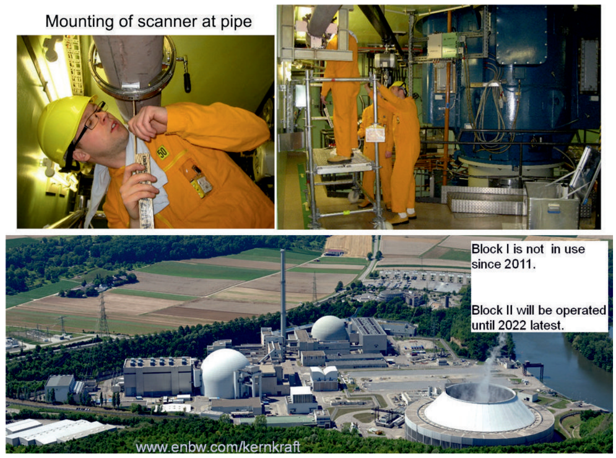

Fig. 12. View of the nuclear power station "Neckarwestheim" (bottom) and of mounting the TomoWELD scanner in Block I (top).
Rys. 12. Widok elektrowni jądrowej "Neckarwestheim" (na dole) i montażu skanera TomoWELD w Bloku I (u góry).

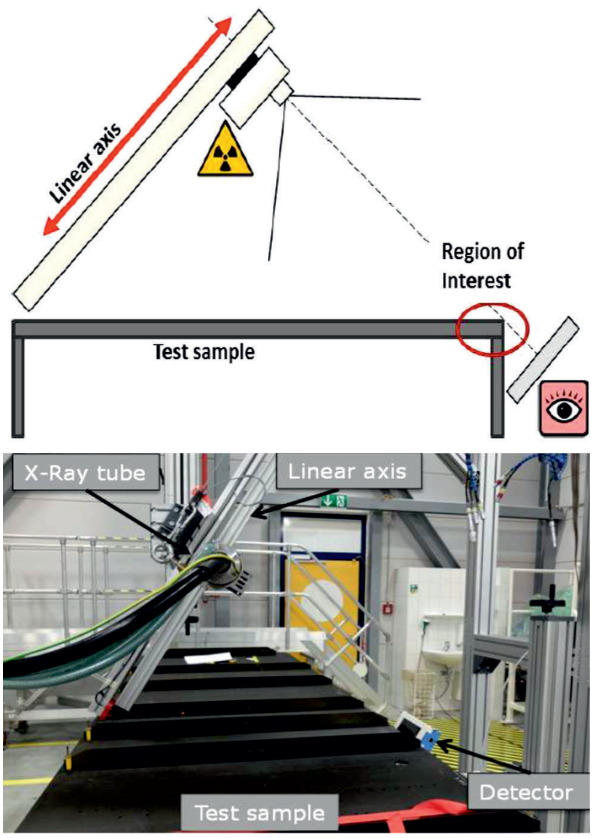

Fig. 13. Up: Schematic sketch of inspection setup. Down: Inspection setup in production environment. Only the X-Ray source is moving during image acquisition.
Rys. 13. Góra: Schematyczny szkic systemu kontroli. Dół: Aplikacja systemu kontroli w warunkach produkcyjnych. Źródło promieniowania rentgenowskiego jest w ruchu podczas akwizycji obrazu.

The planar tomographic mode is used to obtain cross sectional information of the weld seam by 3D reconstruction.

Therefore, the X-ray tube is moved with constant speed parallel to the detector plane. In general, the movement is parallel to the pipe axis as well. For special investigations, the tube scan axis can be tilted with respect to the pipe axis by a fixed angle (15°). This allows the simultaneous detection of transversal and longitudinal cracks [23, 26]. The X-ray tube is manufactured in a flat design and achieves 240kV at 0.6mm spot size [27]. A new flat X-ray tube prototype was manufactured, which was tested at 270kV [27]. The completed TomoWELD scanner was tested successfully in Block I of the Nuclear Power Plant "Neckarwestheim" (see Figure 12).

The TomoCAR design was modified for in situ inspection of large aircraft components under production conditions [22]. A gantry gate based planar tomograph was constructed and tested for inspection of the integrity of large CFRP components. The TomoCAR design was modified and equipped with a specially developed X-ray tube and a larger DDA. CFRP panels (Carbon Fibre Reinforced Polymers) of aircrafts of up to 3 x 9 m size were inspected [22]. The same concept was applied for analysis of indications found by UT investigations of 18 m long airplane structures (Fig. 13) [28].

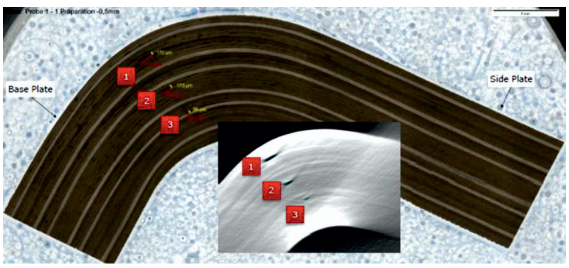

Fig. 14. Comparison of X-Ray Planar-CT (inside) and micrograph (outside large image).
Rys. 14. Porównanie wyników z planarnej tomografii komputerowej (na dole) i mikrografii (u góry, duży obraz).

An 18 m long U-shaped CFRP airplane structure was tested with laminography (Fig. 13). The standard NDT-inspection is based on an UT scan in order to detect defects larger than 6 by 6 mm². The ultrasonic (UT) inspection is not accurate enough to distinguish between large area material separations and clustered porosity. The UT inspection fails mostly at sharp material radii due to missing back wall echoes. X-ray based planar tomography was explored to obtain cross section images with higher resolution for better evaluation of flaw types and measurement of flaw dimensions. A specially designed gantry was used to acquire projections in tangential direction to the radius. In order to inspect the complete test object over the length, a gantry gate based planar tomograph was developed and tested (Fig. 13). The linear manipulator for the X-ray tube was positioned about 45° over the long area of the U shaped test object and parallel to the detector.

A Technical Qualification was performed at Airbus to demonstrate compliance of the applied process to the related standard process specification [28]. Here, the results of the laminographic scans were compared with photographs of cross sections of specially treated reference samples to validate the accuracy of the method. Fig. 14 shows the comparison of a cross section with the corresponding laminographic slice presentation.

The imported dataset was analyzed with a VG Studio defect algorithm that yielded the requested defect parameters length (C), width (D) and depth. These are determined by the length and the width of a "Bounding Box" that surrounds a defect whereas the depth is defined as the minimal distance from the defect to the outer surface of the reconstructed volume. The size of defect is derived from length and width and is used for a first defect classification as shown in Fig. 15.

A similar concept was used for the inspection of glass fiber structures of wind mill wings. Glass fibers show a better contrast to the polymer matrix than carbon fibers. Undulations and unsuitable fiber alignments were better visualized.

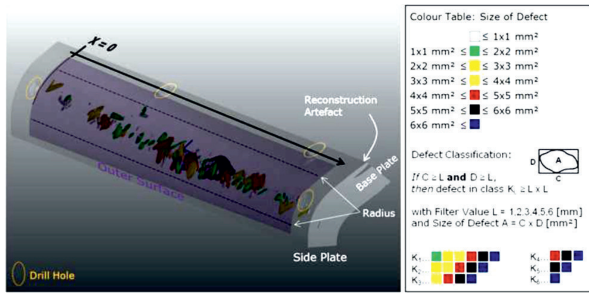

Fig. 15. 3D visualization and classification by size of defect and definition of the filter value.
Rys. 15. Trójwymiarowa wizualizacja i wyniki klasyfikacji wad pod względem ich wielkości określenie parametrów filtru.

5. Summary

Computed Tomography systems were significantly improved during the last years and are now commercially available for NDT. Applications cover the range from nano-meter to meter scale. During the last 15 years the method was enhanced from a specialized laboratory testing technique to routine industrial quality assurance systems. The application of CT as dimensional measurement devices may replace coordinate measurement machines in future. CT can measure inner and outer surfaces accurately. First applications are known, where CT is used for at-line and later in-line inspection in automobile industry for combined flaw detection and dimensional measurement. The CT is universally applicable for all kinds of investigations, including food industry and art work investigations. High energy CT devices are available for inspection of large and heavy samples. This reaches from inspection of crashed cars to impact investigations of concrete building structures. Mobile laminography is applied for non destructive cross sectioning of welded pipes and CFRP structures of airplanes and provides the dimensions and distribution of the indications as precondition for fracture mechanical evaluation.

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