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RECENT TRENDS IN DIGITAL INDUSTRIAL RADIOLOGY

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0. Abstract

New digital detectors were developed for medical applications, which have the potential to substitute the X-ray film and revolutionise the radiological technique. Flat panels and imaging plates allow a fast detection of radiographs in a shorter time and with higher dynamic than film applications. The properties of these detectors can be controlled by electronics and exposure conditions. New names appear in literature like "direct radiography" and "film replacement techniques". The basic advantage of new digital techniques is the possibility to use numeric procedures for image interpretation. Intelligent procedures, which include a special inspection geometry and multi angle inspection are applied for depth measurement and 3-dimensional inspection. Industrial radiology can be optimised for crack detection as well as for analysis of flaw depth and shape measurement. Parallel with the development of flat panel detectors, an extraordinary increase of Computed Tomography (CT) applications can be observed. Nowadays, also mobile CT-applications are available for sizing of flaws in components of industrial plants and in pipelines. Parallel to the development of 2-dimensional detectors, improved line cameras open new ways for mobile applications in radiology. High resolution detector lines and time delayed integrating (TDI) lines speed up the data acquisition and enable an image quality, that is suitable for weld inspection and casting production surveillance. High quality radiographs can be obtained even from media filled pipelines. The analysis of scattered radiation and energy disperse techniques provide additional information about the chemical composition and structure. Dual energy applications lead to contrast enhancement for multi-component systems as well as the inspection of filled pipelines and other containers. X-ray topography of scattered radiation allows imaging of micro- and nano-structures complementary to absorption radiography. Synchrotron radiation yields fast and accurate information about materials properties.

1. Introduction

Since more than 100 years industrial radiology is based on X-ray film. Special film systems have been developed for NDT-applications, which have better image quality than medical film systems. High spatial resolution is obtained by combination of these films with lead screens instead of fluorescence screens. Medical film systems have been developed under other requirements. It is always necessary to find a compromise between minimum patient dose and suitable image quality.

New digital detectors have been developed for medical applications, which have the potential to substitute the X-ray film and revolutionise the radiological technique. These detectors allow new computer based applications, which permit new intelligent computer based methods and also could substitute film applications. These technological and algorithmic developments are highly beneficial for new NDT-procedures too.

Basically, the following systems are of interest: The first development is the equipment for film digitisation, which can be performed with high accuracy and speed nowadays [1]. A spatial resolution of better than 10 µm and optical density ranges of up to 5 allow digital archiving and sophisticated image processing techniques for film interpretation. This paves the way from simple film viewing to quantitative analysis.

[1] This paper is based on the contributions, which are published in the proceedings of the Naarri-conference 2001, India and the 8th ECNDT 2002, Spain. It contains some modifications, corrections and the present state of the art.

Direct digitising systems accelerate the application of intelligent procedures to facilitate and enhance image interpretation. Since almost 10 years imaging plate systems are available which can be used as filmless radiography technique, also known as computed radiography (CR). Imaging plates can be exposed and scanned by a laser scanner to obtain a digital radiograph. They can be erased by an optical process and be reused up to 1000 times. Different systems are available with different unsharpness and sensitivity. It is an urgent task to develop guidelines and standards which define the good workmanship criteria for the new digital detectors to avoid a loss of information and reduced probability of flaw detection by taking over the medical systems without adaptation to NDT requirements. First standard proposals are under discussion.

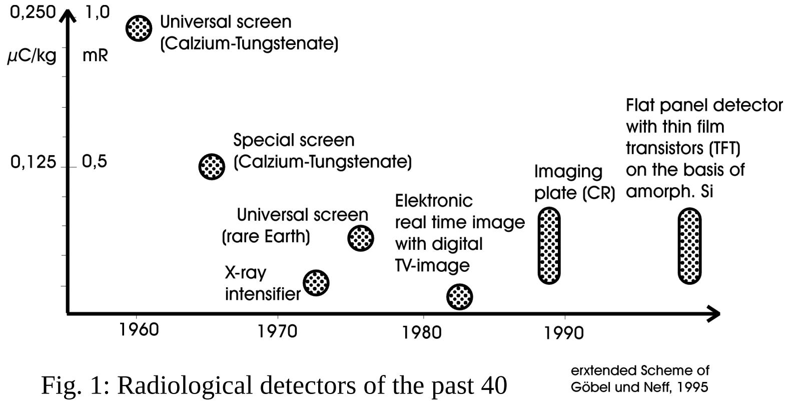


Fig. 1: Radiological detectors of the past 40 years

The new flat panel detectors may become an alternative technology for both storage phosphor based computed radiography and image intensifier based real time radiography. They are mostly based on amorphous silicon detector arrays with thin film transistors for read out control and photo diodes as light detectors, which are covered with a fluorescence screen for light conversation. Recently developed detector systems use a direct converting process. Amorphous selenium or CdTe-systems permit the separation of charges, generated by high energy radiation, and read this charges by micoelectrode systems. Direct converting systems are characterised by a higher inherent spatial resolution than the systems which use fluorescence screens. Flat panel systems entered the NDT-market in an relatively short time. They substitute radioscopy systems for digital radiography applications and open new possibilities for the application of computed tomography (CT).

Parallel to the development of flat panel detectors an extraordinary increase of CT-applications can be observed. This may be due to the significant lower expense for CT-devices caused by cheaper computer hard- and software.

Parallel to the development of 2-dimensional detectors, improved line cameras open new ways for mobile applications in radiology. High resolution detector lines and time delayed integrating (TDI) lines speed up the data acquisition and lead to an image quality, that is sufficient for weld inspection and casting production surveillance. Mobile CT-applications allow additionally the determination of the flaw depths and shape, which was not accessible by radiography before.

Dual energy applications lead to contrast enhancement for multi-component systems as well as the inspection of filled pipelines and other containers.

2. Overview about the development of the last years

The detector development of the past 40 years is shown in Fig. 1. Promising new developments are technologies like computed radiography (CR) with imaging plates and flat panel detectors, which raised an upheaval in industrial radiology. The progress is accelerated by the possibilities of the fast developing computer technology. The opportunity to combine digital radiographs with modern and affordable computer technology, corresponding to fig. 2, paves the way for new stationary and mobile intelligent methods. Furthermore, this new digital industrial radiology (DIR) also opens new application fields which have been inaccessible with classical radiography.

Since 1980 the radioscopy with the system X-ray tube, manipulator and X-ray intensifier is increasingly covering all on-site (not mobile) problems for polymer and light alloy testing. This system has the potential of real time testing corresponding to the TV-standard. The dynamic testing yields a higher probability of detection of all kinds of flaws including cracks. Modern automated flaw detection software makes this method increasingly attractive for automated serial inspection in production lines. Automated car wheel inspection is a typical example here.

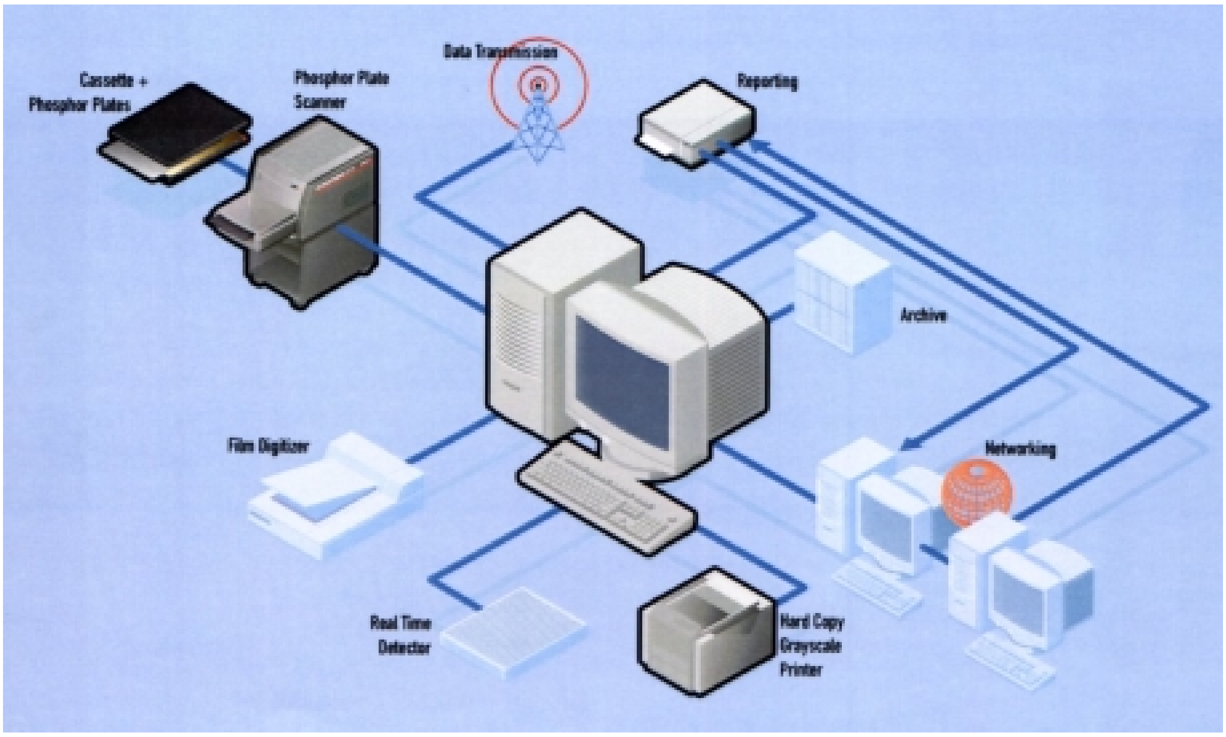


Fig. 2: Overview about the methods of digital industrial radiology

The development of X-ray detectors for medical and NDT (non-destructive testing) applications is shown in fig. 1. Especially the development of new detectors and intelligent algorithms opens new possibilities for the industrial radiology. Fig. 2 provides an overview about the new developments. Film digitisation enables the transition from classical film radiography to the digital world. The essential tool is the computer which provides visualisation, image processing and “intelligent” interpretation of radiographs. It also allows image transfer to remote interpretation facilities or information sharing by networks, archiving, documentation and film printing. New detectors like phosphor imaging plates (Computed Radiography) and flat panels as well as classical real time systems (e.g. Intensifier systems, X-ray TV) provide instantly digital radiographs accessible to computer processing which yields full efficiency of the new “digital industrial radiology” (DIR).

Before new methods and detectors will be described, the advantages of the classical film radiography should be summarised. One of the major advantages of X-ray film radiography is its practicability. Important X-ray film properties are:

- They are dust- and water proof packed.
- They consist of flexible and breakproof material.
- The storage period is > 50 years (expected shelf life > 500 years).
- The readability is independent of technological development (e.g. independent of „Data-format“).

Filmless Radiography

3.1 Computed Radiography with Phosphor Imaging Plates

Phosphor imaging plates (IP) are a medium for filmless radiography. The technique is also called Computed Radiography (CR). IP-s are routinely used in medicine and biomedical autoradiography since more than 15 years. Recently, several systems are offered for NDT-practice. Since most of these systems are modified medical developments, its application cannot substitute film radiography in the full range yet. Nevertheless, additional applications to film radiography are now possible with those systems, due to the higher sensitivity (shorter exposure time) and the digital processing as well as analysis of the digital radiographs. Standards are under development which define the limits for CR-applications in dependence on the required instrumental properties [3].

Imaging plates (IP) are exposed nearly in the same way as radiographic films. They are read by a LASER scanner producing a digital image without any developing process (see fig. 3). After erasing the remaining latent image with a light source (e.g. halogen, incandescent) the same IP can be recycled up to more than 1000 times. An IP consists of a flexible polymer support which is coated with the sensitive layer. On top it is covered with a thin transparent protective layer. The sensitive layer of the most common systems consists of a mixture of BaFBr doped with Eu^{2+}. X-ray or gamma ray quanta result in an avalanche of charge carriers i.e. electrons and holes in the crystal lattice (see also [4]). These charge carriers may be trapped at impurity sites i.e. electrons at a halogen vacancy (F centre) or holes at an interstitial Br_2^+ molecule (H-center). Red laser light (600-700nm) excites electrons trapped in a Br^- vacancy (F_{Br^-}- centre) to a higher state from which they may tunnel and recombine with a nearby trapped hole. Transfer of the recombination energy excites a nearby located Eu^{2+} ion. Upon return to its ground state this Eu^{2+} ion emits a blue photon (390nm). This process is described as PSL or photo stimulated luminescence. Essential is the occurrence of defect aggregates consisting of a hole trap, an electron trap and a luminescing point defect such as a Eu^{2+} ion substituted at a Ba^{2+} lattice site. Aggregating defects are located within a range of typically 10 lattice cells.

The advantages of the IP-Technology are:

- High linearity.
- High dynamic range > 10^5 .
- High sensitivity.
- 1000 cycles reusable.
- No darkroom process.
- Image processing is possible.

Disadvantages are:

- Limited spatial resolution.
- High sensitivity in the low energy range,
- sensitive to scattered radiation.

The available systems of phosphor imaging plates and corresponding laser-scanners cover radiation dose differences of > 10^5. This is equivalent to more grey levels than the human eye can distinguish. Fig. 4 demonstrates this advantage of the CR-technology. Both images are produced from the same exposure data. They are presented with different contrast and brightness adjustment only. No other

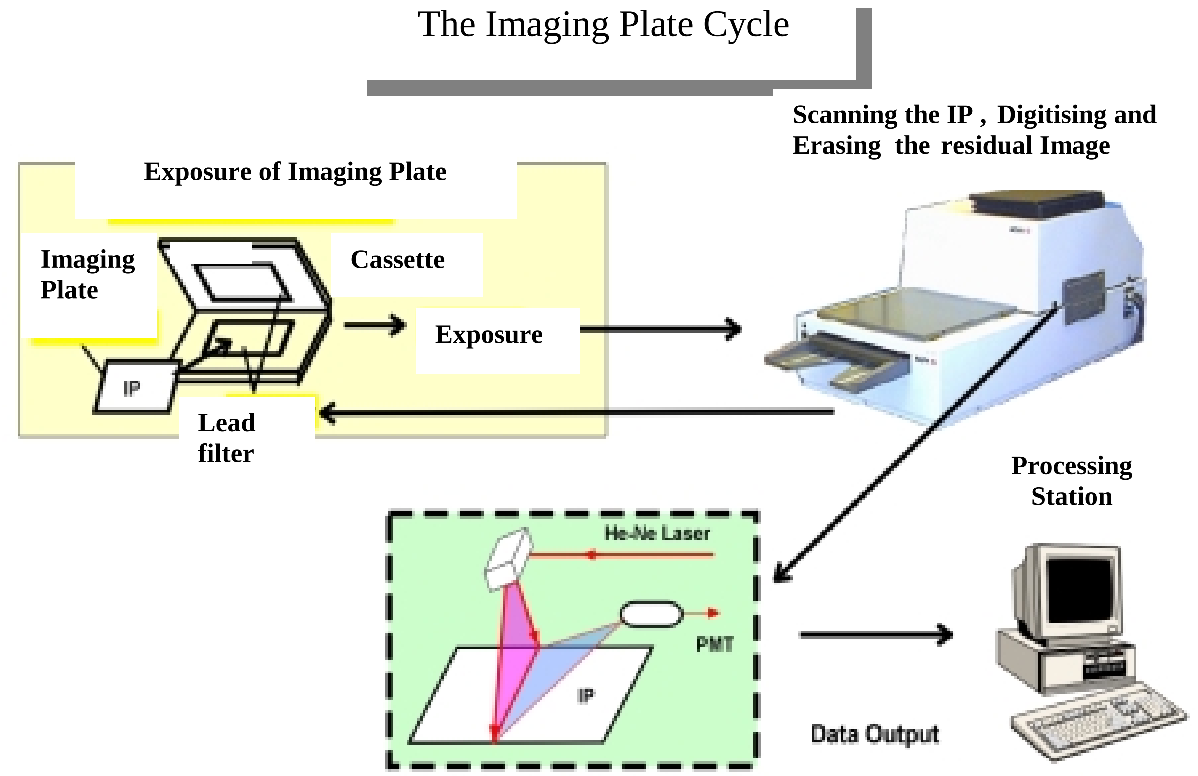


Fig. 3: Principle of the imaging plate cycle. Imaging plates can be exposed, read out and erased several times.

image processing feature was applied. The left image (a) is optimised for the visualisation of the radiographic "light" materials. Plastics and the conductor lines of the circuit board are visible. The right image (b) is optimised for the contrast of the radiographic "dense" materials. Heating wires and the motor of the hair dryer are visible as well as the conductors in and below the integrated circuits of the board. This feature reduces the number of exposures for objects with high wall thickness difference. It also compensates for wrong calculated exposure times. The number of so called "test exposures" is reduced and can be omitted usually.

All these new possibilities bear the risk of misuse of the CR-technology. To limit this risk and to avoid a serious drop in the probability of flaw detection special guidelines are necessary. New standards have been developed in several countries. Pioneer work was performed in the USA [2] and Europe [3]. The most detailed and restrictive standard is the CEN draft part 2 [3] in Europe. It defines a set of minimum requirements for the application of CR, to make the technique comparable with the film radiography, carried out corresponding to EN444 and/or ISO 5579. The basic idea of the new standard is the application of two image quality indicators (IQI). This is the wire or step hole indicator for the wall thickness contrast (e.g. EN462 -1...4) and the Duplex wire IQI (ASTM- E2002, EN 462-5) for the measurement of the spatial resolution. The standardisation for the qualification of the systems is under common development together with ASTM and CEN. The CEN draft part 1 reflects the current level of discussion. The systems shall be characterised by signal to noise ratio (SNR) determinations as a measure of contrast resolution and measurements of the best spatial resolution via modulation transfer function (MTF) or special IQI's. These standards have the goal to make CR comparable with film radiography. Nevertheless there exist also other application fields which can be covered by CR under consideration of the specific advantages of the technology. CR-testing of thick components extends the application field of film radiography considerably. CR can be applied with 5-10% of the exposure time in dependence on the required contrast and spatial resolution. For example, the application of a system "film Ir-192" which requires 2 hours of exposure time is in most cases not acceptable. In contrast, thick IP's can be exposed in about 10 minutes only, which is an acceptable time.

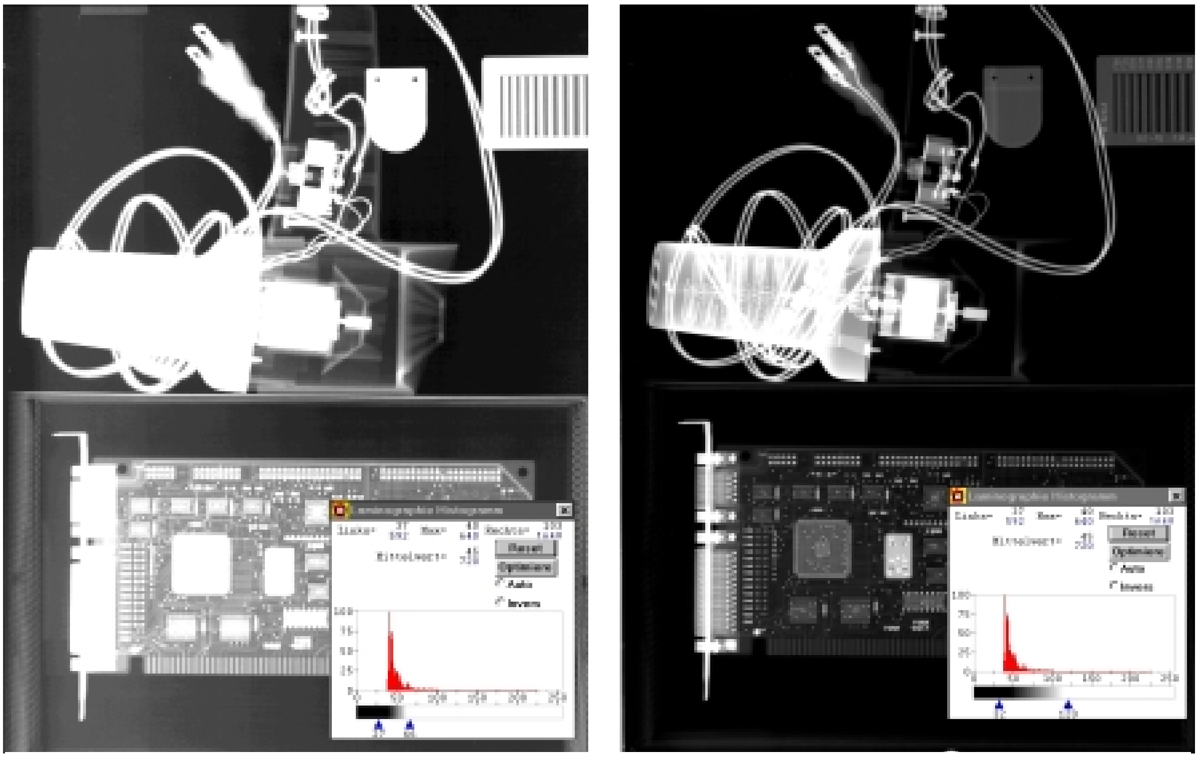


Fig. 4: Radiograph of a hairdryer, circuit board and some image quality indicators by CR (Lumisys).
Left (a): The Histogram shows the contrast and brightness adjustment, which is optimised for the plastics.
Right (b): The histogram shows a different contrast and brightness adjustment, which is optimised for the metals.

A typical application for the CR-technology is the radiographic corrosion inspection. Fig. 5 presents a typical example. The pipeline is thermally insulated. The insulation is covered with an aluminium envelop. The radiographic inspection can be performed without removing the insulation. This is a considerable advantage relative to the other known methods. Radiographic pipe inspection for corrosion and wall thickness measurement is especially in the chemical industry a major NDT-technique for predictive maintenance.

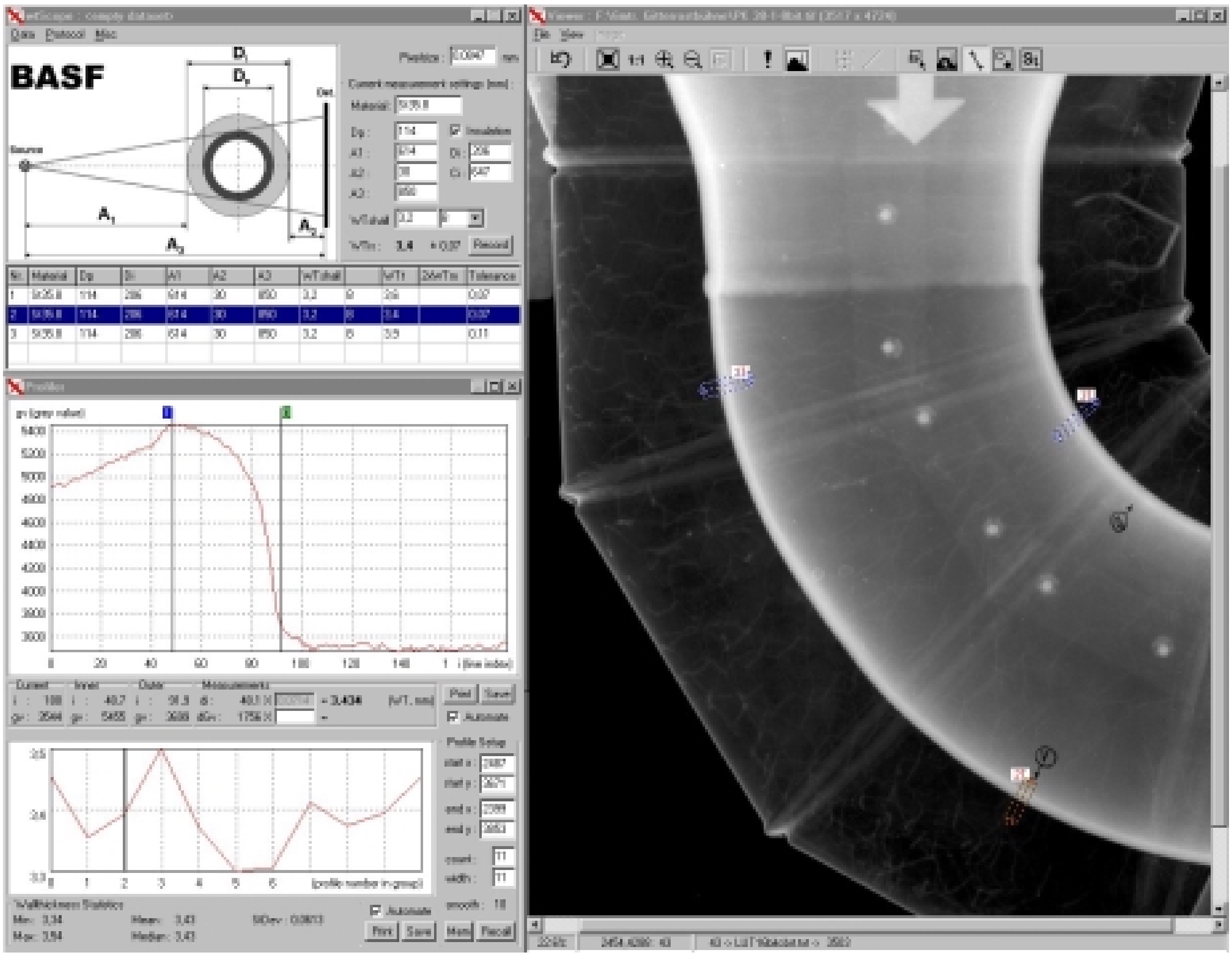


Fig. 5: Computer based inspection of an insulated pipe by projection radiography. The wall thickness can be measured and no corrosion is visible (interactive evaluation program developed by a common research project between BAM and BASF).

There exist different systems for CR. Similar to film radiography, the appropriate system has to be chosen according to a specific application. Sometimes manufacturers leave the impression to offer an universal system for all applications. This is not acceptable. Fig. 6 presents a comparison of computed radiographs of a duplex wire IQI as model for fine structures like for instance fine cracks.

Different IP's were tested. All of them were exposed at 220 kV and read out with an AGFA-scanner with 900 dpi (System AGFA DPS, 28 µm pixel size; laser spot about 40 µm). The FUJIFILM-IP (ST-V_N) was optimised for a scanner with 100 µm pixel size (AC3). The Agfa NDT (MD10 modified) was developed for a 50 µm scanner and the prototype "AGFA blue" for high resolution applications. The last one resolves all line pairs and has a spatial resolution better than 100 µm (MTF-measurements: 80 µm). It is the slowest detector. It is about 100 times slower than the fast FUJIFILM-IP related to the same SNR but only 10 times slower related to the normalised SNR_{UA}, which is normalised to a unit area (UA) of 88.6 x 88.6 µm^2. The normalised SNR_{UA} of all other (white) IP's is similar (measurement range: 3 - 300 mAs). It was measured for 220 kV, 936 mm SDD, 8mm Cu filter:

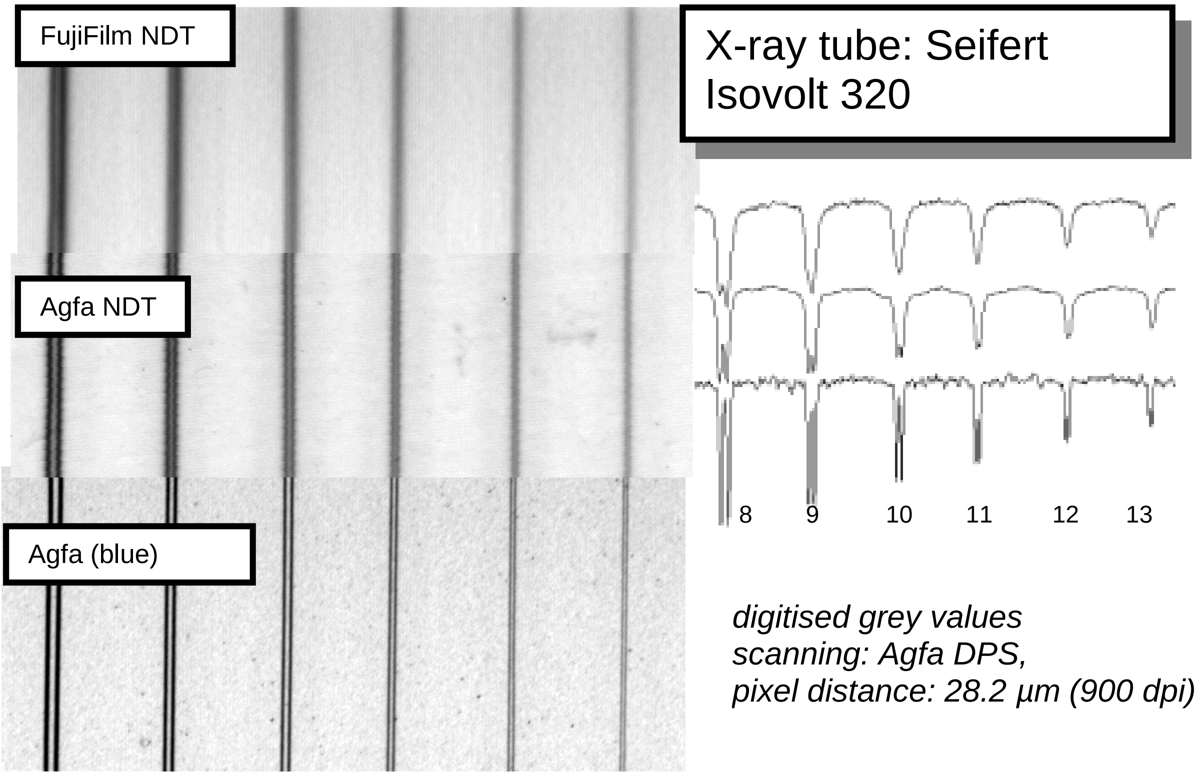
$$SNR_{UA} \approx 30 \cdot \lg(\text{Exposure}) \qquad (1)$$

Exposure: - tube current · exposure time - unit is: milli Ampere · seconds (mAs)
Unit area: - 88.6 x 88.6 µm^2 square or circular area with a diameter of 100µm

The FUJIFILM-IP resolution was determined to 230 µm and for the AGFA-NDT a spatial resolution of 170 µm was obtained. The SNR (not normalised) corresponds to :

$$SNR \approx (\text{spatial resolution}/88.6\ \mu m) \cdot SNR_{UA} \qquad (2)$$

The normalized SNR_{UA} was limited to about 90 as a consequence of the fixed pattern noise of the phosphor layer. Longer exposure time would not contribute to a better SNR_{UA}. All SNR-measurements were made with the ACR2000 (Lumisys). The contribution of instrumental noise could not be considered yet.



8	9	10	11	12	13	double wire
0.32	0.25	0.20	0.16	0.13	0.10	mm resolution

Fig. 6: Computed radiographs and profiles taken with different types of imaging plates and a high resolution scanner (DPS of AGFA) of a duplex IQI corresponding to ASTM E2002 and EN 462-5. The spatial resolution values, read of the IQI-radiographs, varies from FujiFilm-NDT with 250 µm over Agfa NDT with 160 µm to Agfa blue with better than 100 µm.

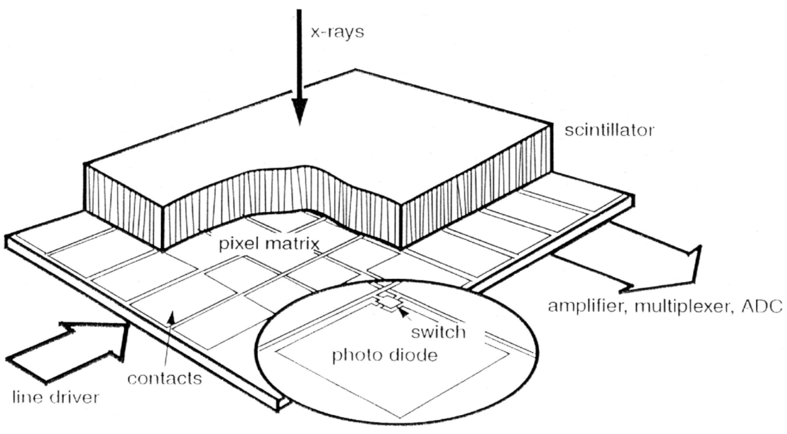


Fig.7: Scheme of a flat panel detector: The scintillator converts X- or gamma rays into light, which is detected by the photo diodes. They are read out by thin film transistors (TFT) on the basis of amorphous silicon, which is resistant against radiation.

The tests above show that the discussed advantage of shorter exposure time for phosphor imaging plates in comparison to film radiography (with lead screens) applies for inspection of objects with higher wall thickness. This is the energy range of X-rays above 300 kV and Ir-192. CR with high resolution plates may need the same exposure time like NDT-film applications, but provides the advantage of immediately digitised data. These plates may be used for low energy applications and weld inspection.

3.2 Direct Radiography with Flat Panel Detectors

Two types of flat panel detectors are now on the market: The first design (see fig. 7) is based on a photo diode matrix connected to thin film transistors (TFT) [10]. These components are manufactured of amorphous silicon and they are 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. This scintillator could be a polycrystalline system that provides some additional unsharpness by light scattering or an directed crystalline system which acts like a face plate (fibers in light direction) with lower unsharpness due to reduced light scattering (fig. 8). The next generation of flat panels is based on a photo conductor like amorphous selenium [11] or CdTe on a multi-micro electrode plate, which is read out by TFT's again (fig. 9b). This generation provides the highest sharpness and has the potential for high resolution systems which could compete with NDT-film. Direct converting photo diodes also provide high sharpness. These systems are not applicable for NDT yet, because the quantum yield of the silicon diodes is low at high energies (fig. 9a). Currently all available systems on the market reach a resolution of 120 - 140 µm. Weld inspection and fine casting testing requires at least 50 µm resolution. This could be obtained by magnifying technique with mini- or micro-focus tubes. Systems with 50 µm detector resolution are under development for medical applications like mammography.

Flat panels are suitable for in-house and in-field applications. Nevertheless, in-field applications are limited by the rough environmental conditions in some areas. However, digital data may be obtained either by film digitization or directly by the application of computed radiography (CR) using phosphor imaging plates (IP). The IP-reader is always separated from the inspection site. CR is based on flexible IP's which can be exposed and erased up to 1000 times (10000 in medicine). The exposed IP is read

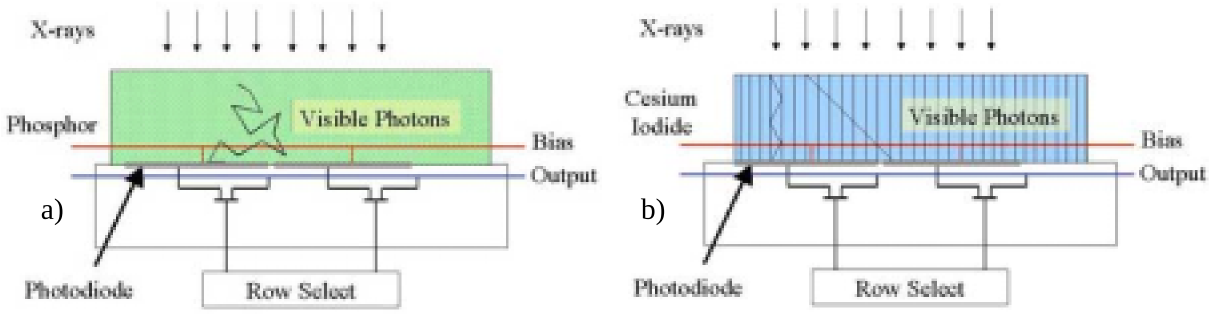


Fig. 8: Principle of amorphous silicon flat panels with fluorescence screens.

a) Additional unsharpness is generated in the phosphor layer due to light scattering.
b) Needle crystals of CsI on the surface of the photodiodes improve the spatial resolution, because the crystals conduct the light to the photo diodas light conductors.

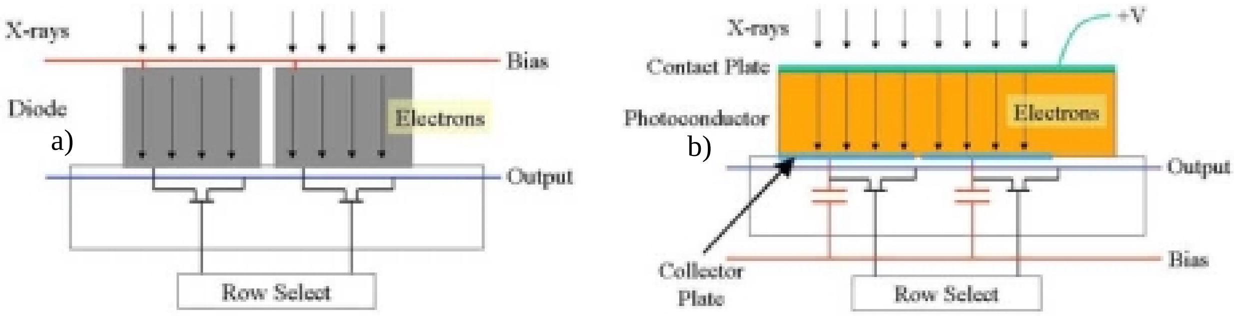


Fig. 9: Principle of direct converting flat panels with amorphous silicon thin film transistor arrays for read out. There is no light scattering process involved. The spatial resolution is determined by the pixel size of the detector array.

a) Photo diodes convert directly the X-ray photons to electrons. This technique is suitable for low energy applications.
b) A semiconductor (e.g. amorphous selenium or CdTe) is located on micro-electrodes in a strong electrical field. Radiation generates charges, which can be stored in micro-capacitors.

out by a laser scanner and needs no chemical processing. IP's are available for spatial resolutions of about 50µm up to 300µm. The latter ones are very fast and can be exposed more than 10 times faster than film. Using adequate IP's and scanners, the image quality is sufficiently for weld inspection up to corrosion detection (see also [14]).

3.3 Line Detectors

The classical concept of NDT with line detectors is based on a fixed radiation source, moving objects and a fixed line camera. This is the typical concept for baggage, car and truck control. Line detectors are available with a resolution of 0.25 - 50 mm. The most common principle is the combination of scintillator and photodiodes. The scintillator is selected in accordance to the energy range.

Recently also high resolution lines were introduced for weld inspection [6]. Fig. 10 shows a mechanised X-ray inspection system which is based on an X-ray tube, a manipulation system and a line camera (see below). The camera is based on an integrated circuit consisting of 2048 photodiodes and a CCD-read out logic. Each photodiode has an area of $25x2500\mu m^2$. An GdOS-scinillator screen is coupled via a phase plate to the diodes. A glass taper was used to enlarge the diode width from 25 µm to 50 µm and enable the scan of a 100 mm track.

Fig.10: View of the line scanner. X-ray tube and camera are mounted on a manipulator for mechanized inspection.

New applications take advantage of the TDI technology (time delayed integration) to speed up the scan of the welds [8]. Several hundred lines are used in parallel. In the system the signal is transferred from line to line synchronously with the movement of the object or the scanning system. The information is integrated on chip and the speed enhancement corresponds to the number of lines about. Scanning times of minutes for girth welds are needed instead of hours for double wall inspections.

3. Intelligent Methods as Result of New Detector Technology

4.1 Computed Tomography

The typical example for an intelligent method is the computed tomography (CT). Only the numeric back-projection of the measured projectional data yields the cross-sectional image information. This method requires inevitably a computer. In principal CT is the most effective available method for 3D-analysis of any object as long as there are differences in the density and/or atomic number of the components to inspect. NDT applications need different energies and dimensions for the objects to inspect. This is the reason that medical CT-scanners are only exceptionally applicable for NDT-problems. The spectrum of available NDT-CT devices reaches from microfocus units with few kV tube voltage for microscopy up to large units with linear accelerators of several MeV-s. There exist also very specialized equipment which uses neutrons or synchrotron radiation. X-ray tube based CT-microscopy can visualize fine pores and pore channels [12]. Fig. 11 shows an example of a micro CT of a porous Ti_2O sample.

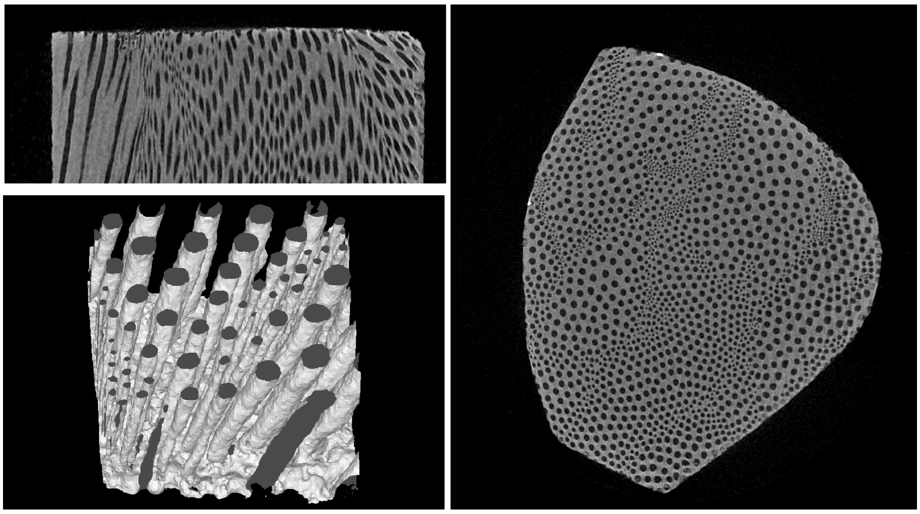


Fig. 11: Micro CT of a TiO_2 sample. The pixel size is $2{*}2{*}2\ \mu m^3$. The picture shows a vertical and horizontal slice of the sample and a 3D visualization of some pore channels.

CT is fully developed for laboratory applications but not yet satisfactorily for field applications. The reasons for restrictions in mobile usage are the need of full access from all directions to the object and the requirement of several hundred projections, taken at different angles through the object. Access and measurement time are restricted in most cases.

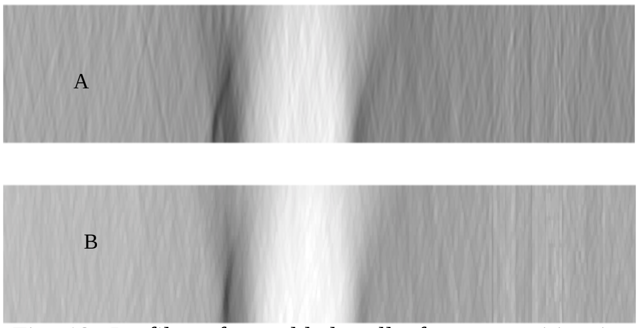


Fig. 12: Profiles of a welded wall of an austenitic pipe after stress crack corrosion. The crack (black) is located near the weld (light area). A and B are reconstructed profiles at different positions.

A solution is provided by a mechanized X-ray inspection system, which is based on the combination of an X-ray line camera and X-ray tube, mounted on a manipulation system. It was constructed for the purpose of a tomographic analysis of welded pipelines. Fig. 10 shows the prototype for inspection of pipe segments. The X-ray tube can be rotated synchronously with the line camera for acquisition of digital radiographs of girth welds. An additional manipulator axis for shifting the X-ray tube parallel to the pipe axis permits to perform the inspection under different angles. Specialized numeric routines were developed to reconstruct the 3D-image of the weld [5,7]. This method is very sensitive to cracks and lack of fusion. The depths and shape of these defects can be reconstructed and measured. Fig. 12 shows the image of a reconstructed crack in an austenitic girth weld.

The special advantage of the line camera technique is the good collimation of radiation. This reduces the scattered radiation and yields a corresponding contrast enhancement. The system was successfully applied for inspection of water filled pipelines.

4.2 X-Ray Topography

X-ray topography uses the scattered radiation only as shown in fig. 13 with the typical measurement geometry. The primary radiation is absorbed by a beam stopper. The detector receives the scattered radiation in an defined angle depending on the sample position. Scanning the sample results in a 2D-image (topogram). In addition to the radiography with primary rays, topography provides information about textures, crystal structures, fiber debonding, fiber orientations, porosity and more [9].

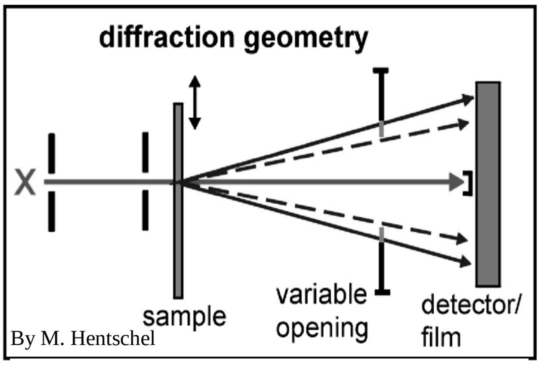


Fig. 13: Principle of X-ray topography

Classical X-ray inspection can visualize fine cracks down to about 10 µm. Micro cracks cannot be detected by this method. Fig. 14 shows a scheme of the measurement arrangement for micro crack analysis [13]. X-ray refraction topography provides nondestructive spatially resolved full volume characterization of composites, ceramics and other heterogeneous materials. The measured refraction value C corresponds to the interface density and permits to estimate microstructural parameters and their correlation to mechanical properties. X-ray refraction visualizes the selective contrast of different crack orientations and quantifies the internal surface density (fig. 15).

As more and more the synchrotron radiation is available, it is also included in the process of materials characterization. In this context new methods were developed, such as: X-ray microscopy, micro-CT, K-edge radiography, phase contrast radiography and others.

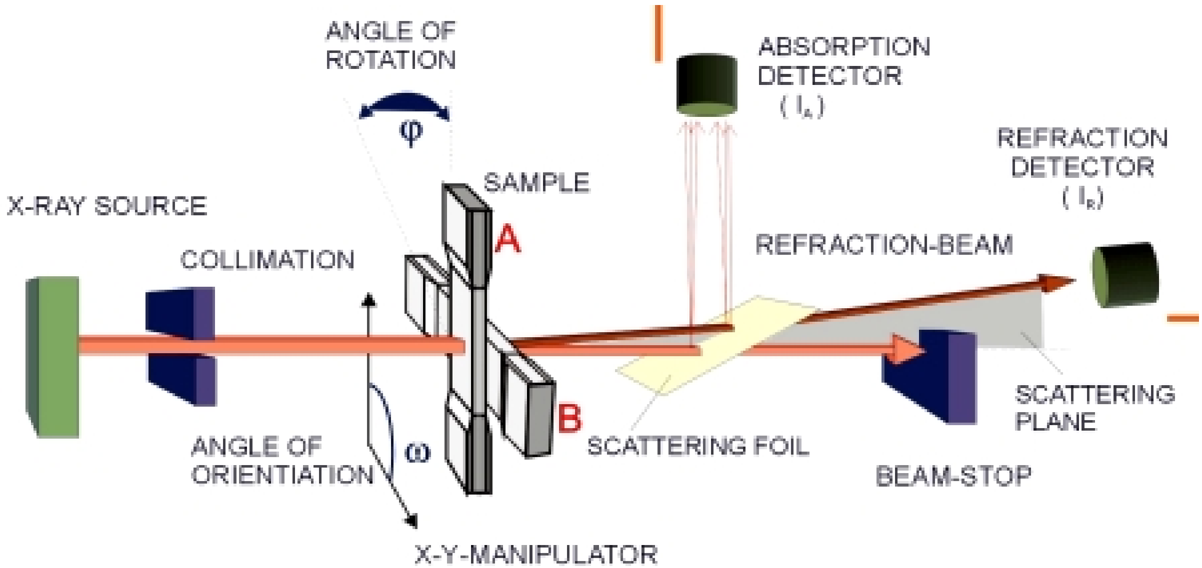


Fig. 14: Detailed arrangement for measurement of topography of scattered radiation and primary radiation.

4.3 Dual Energy Radiography for Baggage Control

Public safety is another application field of digital industrial radiology. In addition to the classical radiological inspection, it becomes increasingly important to obtain information about spatial structure and chemical composition of the objects.

Commercially, the dual energy technique is well introduced in modern baggage inspection equipment. It provides an additional information about atomic numbers of the inspected material. Fig. 16 shows a dual X-ray tube set and a typical dual energy radiograph of a bag. This technique provides the operator with color coded images where the color indicates the chemical composition of the inspected specimen. This could provide hints for the presence of illegal drugs or explosives. Advanced versions of inspection units include additionally a spectrometer to measure the spectrum of the scattered radiation. This method is very sensitive and allows to detect and specify various chemical compounds in the object. These techniques are also suitable for the inspection of soldered pipes and mixed polymers with high contrast.

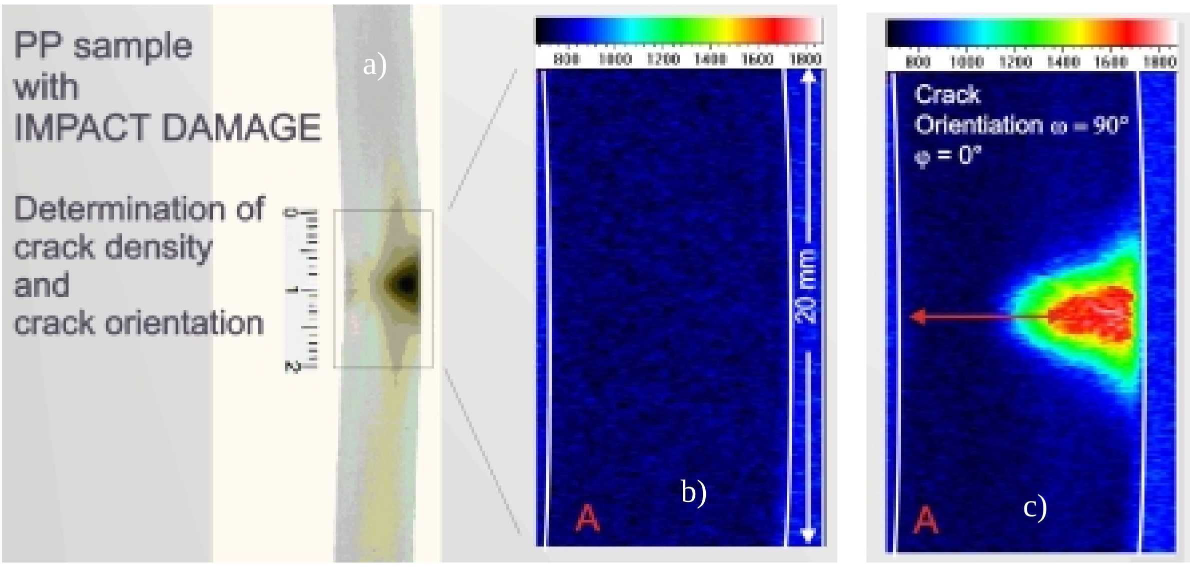


Fig: 15: Impact damage of a polypropylene sample. a) Photograph of the impact damage in transmission b) X-ray radiography does not show the micro cracks of the impact damages. c) X-ray refraction topography shows the micro cracks and quantifies the internal surface density.

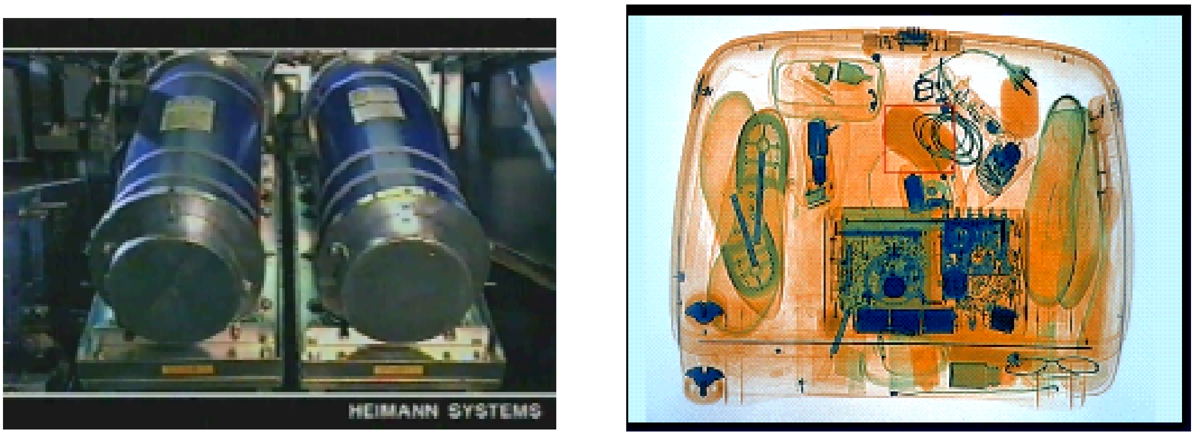


Fig. 16: Dual X-ray tube assembly for dual energy inspection of baggage and typical image of a bag. The atomic number of the components in the object are represented by the color usually.

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