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Nuclear Instruments and Methods in Physics Research A 591 (2008) 14–18

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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X-ray based methods for non-destructive testing and material characterization

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Available online 20 March 2008

Abstract

The increasing complexity and miniaturization in the field of new materials as well as in micro-production requires in the same way improvements and technical advances in the field of micro-NDT to provide better quality data and more detailed knowledge about the internal structures of micro-components.

Therefore, non-destructive methods like radioscopy, ultrasound, optical or thermal imaging increasingly gain in importance with respect to ongoing product and material development in the different phases like material characterization, production control or module reliability testing. Because of the manifold different application fields, i.e., certain physical NDT methods applied to material inspection, characterization or reliability testing, this contribution will focus on the radioscopic-based methods related to their most important applications.

Today, in modern industrial quality control, X-ray transmission is used in two different ways:

- Two-dimensional radioscopic transmission imaging (projection technique), usually applied to inline inspection tasks in application fields like lightweight material production, electronic component soldering or food production.
- Computed tomography (CT) for generation of three-dimensional data, representing spatial information and density distribution of objects. CT application fields are on the one hand the understanding of production process failure or component and module inspection (completeness) and on the other hand the dimensional measuring of hidden geometrical outlines (metrology).

This paper demonstrates the methods including technical set-ups (X-ray source and detector), imaging and reconstruction results and the methods for high speed and high-resolution volume data generation and evaluation.
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PACS: 07.79.7c; 68.37.yz; 81.70.Tx; 87.57.Q−; 87.59.−e; 87.59.B−; 87.59.bd; 87.59.bf

Keywords: X-ray; Radioscopy; Micro-computed tomography; Image processing

1. Introduction

Radioscopic inspection has become one of the most powerful tools in the field of non-destructive testing for industrial material inspection since the discovery of X-rays by Wilhelm Conrad Röntgen in the year 1895 (Nobel Prize 1901). Already at this time, W.C. Röntgen had to face the same problems, which are still today regarded as major challenges with respect to advanced research and development for non-destructive testing:

- The high dynamic range of measured intensities caused by the exponential attenuation law for radiation in matter.
- The superposition of object structures along the radiation beam direction, caused by projective geometrical imaging (projection technique).
- Long exposure times, essential for a sufficient signal-to-noise ratio (SNR).
- Loss in contrast by diffuse background, generated by scattered radiation, which occurs during Compton

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0168-9002/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2008.03.016

interaction of photons with electrons of the outer atomic shell.
- The strong attenuation by metals compared to weak absorption of human skin, organs and tissue.

2. X-ray beams—a short introduction

2.1. X-ray generation

X-rays are generated during acceleration of electrons, e.g., in synchrotrons (synchrotron radiation) or by deceleration of electrons in solid-state materials (Bremsstrahlung).

Synchrotron radiation provides a highly brilliant beam (up to some 10^{18} photons/mrad s) especially capable for diffraction or for experiments which need coherent light (phase contrast method) but is unfortunately only available at some few research facilities in Europe.[1]

On the other hand, X-ray tubes, which essentially create Bremsstrahlung, provide a considerably lower photon flux (some 10^{12} photons/mrad s), however are transportable and thus available in every laboratory. As this paper primarily will discuss industrial applications, hence the beam generation is focused on X-ray tubes.

Depending on the focal spot size, macro-focus tubes (usually sealed tubes with spot sizes above 100 μm) or micro-focus tubes (open tubes with spot sizes down to 1 μm) are commercially available. The principle of beam generation is shown in Fig. 1 (by courtesy of Viscom AG).

Fig. 1 demonstrates the generation of Bremsstrahlung with a reflection target, i.e., X-ray photons are emitted from a massive target anode usually used in a 90° angle to the direction of the impacting electron beam. As can be seen from the figure, due to the target angle the size of the optical X-ray focus is different from the electron focus and also the characteristics of the Bremsstrahl spectrum changes with the length of the absorption path due to varying target absorption of the generated X-rays (Heel effect).

An alternative geometry is the transmission target solution, which means that electrons are impacting on a thin metal sheet target and the generated X-rays are emitted in the same direction as the electron beam. This solution offers of course a more homogeneous photon intensity characteristics and enables the realization of smaller focal spot sizes, however creates lower photon intensities compared to the reflection target due to a worse heat dissipation.

2.2. X-ray detection

Besides the conventional film radiography, digital imaging became more and more relevant in industrial radioscopy within the last 20 years. Today, most industrial digital detectors are still based on indirect conversion technology via scintillation effect (cf. Fig. 2), which means integrating the detected photon intensity over all energies and converting this intensity into a local signal of visible light, which in turn is detected by silicon semiconductor detectors.

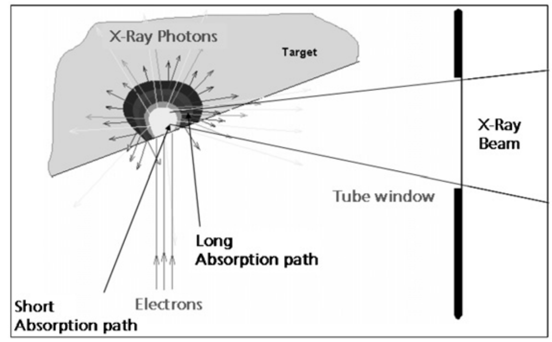

Fig. 1. Generation of Bremsstrahlung by impact of electrons on a reflection target (courtesy of Viscom AG).

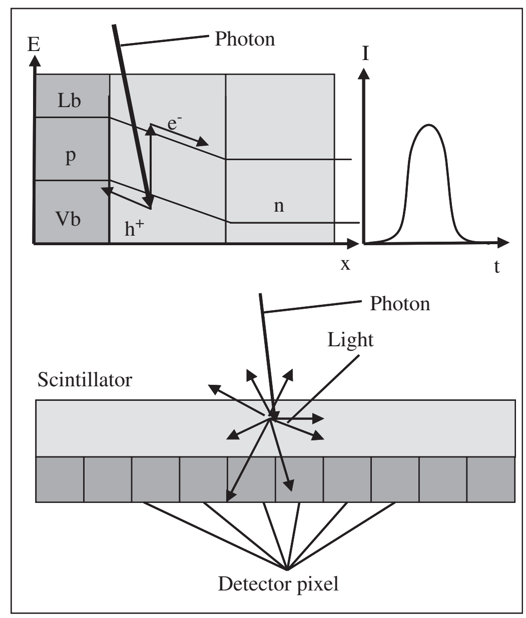

Fig. 2. Principle of direct (top) and indirect (bottom) detection of X-ray photons.

Standard cameras are image intensifiers, a-Si flat panels or CMOS detectors, coated with scintillators (GdOx, CsI and others). Depending on the sensor pixel size, the coating thickness has to be adapted to achieve the best detective quantum efficiency (DQE) on the one hand [1] and to gain the optimal spatial resolution of the sensor on the other hand.

Another way for X-ray photon detection is the direct conversion of the photons by semiconductors, which means, the impacting photons directly are converted into electron/hole pairs. Because of the progress of these alternative direct converting sensors within the last 10 years, this technology may be expected to substitute or at least to partially replace the indirect converting technology

[1] http://www-als.lbl.gov/als/synchrotron_sources.html.

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