Energy-selective neutron radiography

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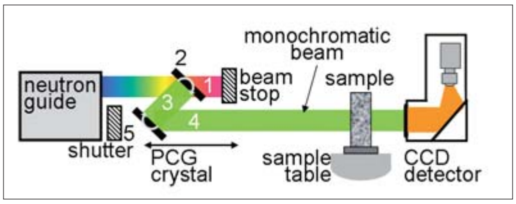

Fig. 1: Schematic sketch of CONRAD including the double monochromator device: (1) upper guide and neutron beam (2) first PG(002) monochromator, (3) diffracted monochromatic neutron beam, (4) second PG(002) monochromator, (5) lower guide and shutter of lower part of the neutron beam

Neutron imaging and especially neutron tomography gained a lot of importance in neutron instrumentation for scientific and industrial applications within the last decade. Monochromatic neutrons, however, have not been in the focus of mainstream developments due to the high intensity losses and correspondingly longer measuring times. In spite of that the neutron radiography and tomography with a monochromatic beam shows promising results in comparison to the standard technique where a white beam is used.

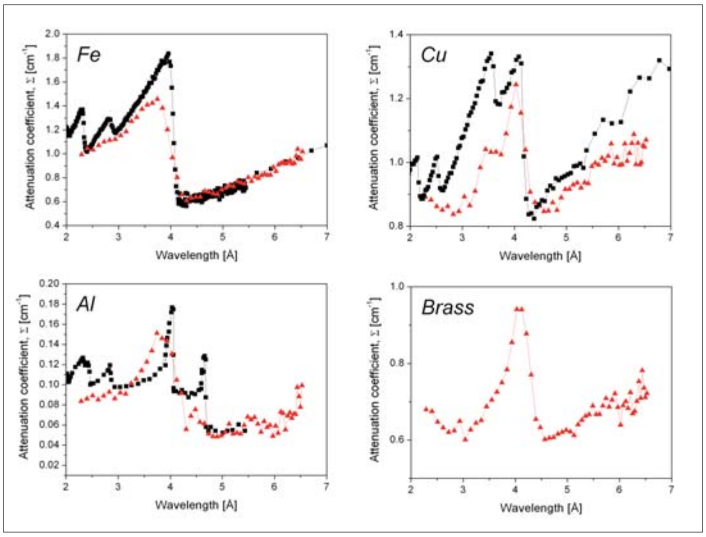

Fig. 2(a) – (d): Tabulated (dark) and radiographically (light) measured attenuation coefficients of Al, Fe, Brass and Copper. The measured values are smeared due to the rather large mosaic spread of the C- crystals.

In the case of polychromatic neutron tomography severe problems for quantification of components of a sample in neutron imaging arise from scattering effects and beam hardening – an effect caused by the fact that the attenuation coefficients are different for different energies present in the beam. The use of monochromatic radiation avoids beam hardening, and the use of wavelengths beyond the Bragg edges of a material avoids Bragg scattering if $\lambda > 2d_{max}$, where d_{max} is the biggest crystal lattice spacing of the sample material (see Table 1). For crystalline solids, these effects and strong incoherent scattering from hydrogenous materials give rise to unwanted background scattering. Monochromatic cold neutrons allow for a much better quantification and are much more sensitive to inhomogeneities in samples. Therefore, a double monochromator option was designed and set up at the neutron radiography instrument CONRAD at HMI [1].

The first measurement position of CONRAD immediately behind the neutron guide was used to install a double monochromator device as shown in Fig.1. Both crystals of the device can be rotated to chosen Bragg angles; the second one can additionally be positioned along the original beam direction in order to reflect the monochromatic beam coming from the first crystal into the initial beam path of the CONRAD instrument. This construction enables one to choose a monochromatic beam with a defined wavelength band ($0.1 < \Delta\lambda/\lambda < 0.01$) between 2.0 Å and 6.5 Å. This wavelength range (depending on the Bragg angle) includes the Bragg edges of many important engineering materials like e.g. Al, Brass (CuZn), Cu and Fe.

Material (hkl)	Al (111)	C (001)	Cu (111)	Fe (110)	β-CuZn (110)
Cut-off, d_{max} [Å]	4.68	6.71	4.17	4.08	4.20

Table 1: Bragg cut-offs of important engineering materials

Quantitative measurements were performed on test samples of Al, Fe, Brass and Copper and the data compared with tabulated values. Figs.2a–2d show the results (for brass tabulated values could not be found). The worse resolution is due to the broad mosaic spread of the graphite crystals, however, a smaller mosaic spread would decrease the reflected intensity and increase the exposure time for radiography and tomography.

The advantage of such a continuously adjustable wavelength is apparent. Different parts of an object under investigation having very similar attenuation coefficients can be made transparent at a certain wavelength (cp. the attenuation of copper at $\lambda = 3.4$ Å and $\lambda = 4.2$ Å, and for steel at $\lambda = 4.2$ Å and $\lambda = 4.6$ Å) or enhanced using another wavelength, where the particular attenuation differs much more, see Fig. 3. Moreover, the method gives the possibility to distinguish between alloys like Cu and ZnCu (Brass). Additionally, the attenuation of PE is nearly constant within narrow wavelength band. So it is possible to eliminate scattering from H-containing parts in a radiography (and tomography) using proper wavelength for other materials that show high contrast in the pictures, see Fig. 3 (right).

Material stress and strain regions in samples usually require point-like scans of neutron diffraction to determine the proper region of interest (ROI). Using the tuneable option of CONRAD these ROI can now investigated in a much more efficient manner. Based on the Bragg edges (of different crystals) the attenuation spectra of these regions show enhanced contrast behaviour in the neighbourhood of proper wavelengths but not only in one point but all over the sample simultaneously. Recording radiographs at different (equidistant) wavelengths, one gets of each point of the sample the full information of attenuation. As a Bragg edge originates in the diffraction from a specific crystal lattice spacing of a material, lattice changes due to material stress can be imaged with this

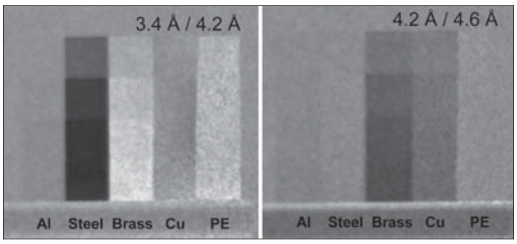

Fig. 3: Quotient images at wavelengths where the attenuation coefficients for Cu (left) and Fe (right) stay without change.

new method by mapping the shape, position and amplitude of a Bragg edge. In order to test this method a deformed steel plate of 5 mm thickness has been measured radiographically from 2.2 Å until 6.4 Å. in steps of 0.1 Å. The attenuation

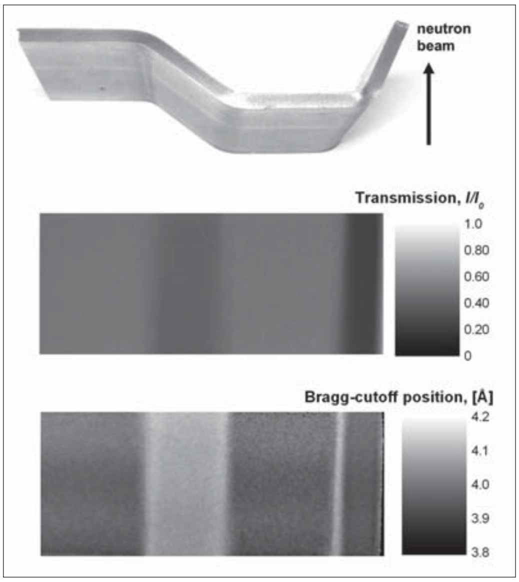

Fig. 4: Steel plate (50×10 mm^2) of 5 mm thickness was deformed – photo on the top. The radiography image is shown in the middle. 2D mapped position of the Bragg edge for each pixel in the deformed plate is shown in the bottom image. The obtained map can be related to the residual stress distribution in the plate.

spectrum (see Fig. 1b) for each point of the sample was derived and the resulted curve was fitted by a Gauss function. From the fit parameters the position of the Bragg edge was determined and a grey value was related to the obtained value. The results of the data evaluation are shown in Fig. 4. These promising results can be improved by decreasing the mosaic spread of the C–crystals and increase of energy resolution and hence the resolution of the Bragg edge scans. This would enable a fast spatial resolved stress mapping of big sample areas eventually to determine specific areas for more accurate diffraction investigations in dedicated stress and strain diffractometer.

[1] W. Treimer et al., Appl. Phys. Lett. **89**, 203504 (2006).

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