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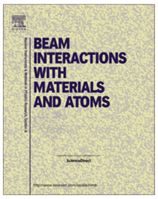

The influence of boron micro-inhomogeneities on neutron transmission

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ABSTRACT

Boron alloyed steels and boron-polyethylene have been investigated by applying neutron transmission analysis. A high degree of boron homogeneity has been confirmed in these materials. However, the neutron transmission through thick and strong absorbing steel sheets is slightly enhanced due to boron micro-inhomogeneities. Although such micro-structure remains invisible in neutron images they reveal themselves by the enhanced neutron transmission, especially in the low transmission probability rates of 10^{-2} and below. The transmission data have been analyzed by applying different models of micro-inhomogeneities in MCNPX, (in the range of 20 μm) all of them yielding an elevated transmission compared to the homogeneous case. It will be shown that, including the micro-structure in the analysis, provides a more suitable modeling of neutron transmission through strong absorbing materials.

1. Introduction

Boron, and especially the B-10 isotope, is a strong neutron absorber used for neutron screens, advanced neutron converters detectors [1], and in nuclear engineering as reactor shielding, fuel storage and transportation baskets. Some related cross sections are listed in Table 1, [12]. The realization of uniform boron distribution is an important property for these applications in order to homogenize and minimize the neutron transmission. The scope of this project is a comprehensive analysis of neutron transmission data for quality assurance, thereby considering energy distribution, detector response, beam hardening, background, and finally, as a new tool in the analysis, absorber inhomogeneities. The macroscopic absorber homogeneity can be directly verified by high-resolved neutron imaging [2–7], however, micro-structures reveal themselves only in strong absorbing materials, i.e., transmission probabilities of 10^{-2} and below, which requires an efficient background shielding [6,7]. The main objective of this work is to investigate the effect of micro-inhomogeneities on neutron transmission, in order to obtain additional information about the absorber distribution beyond the detector resolution.

2. Enhanced neutron transmission

The transmission of monochromatic, collimated neutrons through a thin and perfectly homogeneous material is described by an exponential law:

$$T = \exp\left(-d\frac{\lambda}{\lambda_{\mathrm{th}}}\sum_i(\sigma_{\mathrm{th}}N)_i\right) \qquad (1)$$

d = thickness, λ = neutron wavelength, λ_{th} = thermal wavelength (=0.18 nm), σ_{th} = total microscopic thermal cross section, N = nuclear density, i = isotope index. However, secondary effects like beam hardening, scattering and absorber fluctuations always enhance the neutron transmission [8,9]. Another source of enhanced transmission is the background of scattered neutrons bypassing the sample. This background effect has to be eliminated experimentally by appropriate sample and detector shielding. The most interesting effect is the absorber fluctuation because even micro-heterogeneities below the imaging resolution can reveal themselves by a slightly elevated neutron transmission. This effect can be explained by the exponential nature of the transmission law where particle density fluctuations (δN) to smaller densities have a greater effect than compared to higher densities. Assuming a Gaussian absorber fluctuation the transmission enhancement reads [8]:

$$T(\delta N) \approx T(0) \times \exp\left[\left(d\sum_i \sigma_i \delta N_i\right)^2/2\right] \qquad (2)$$

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However, Eq. (2) provides only a qualitative understanding, for a comprehensive modeling of the stochastic transmission processes MCNPX simulations are used.

3. Transmission measurements

Experimentally, the transmission is derived from the count numbers, pixel-wise or preferably averaged over larger areas to reduce the statistical uncertainty:

$$T = \frac{N_s - N_b}{N_o - N_b} \qquad (3)$$

N_s and N_o are the count numbers behind the sample and in the open beam respectively, and N_b represents the background [7,10]. Ideally, the background is determined by replacing the sample by an 'infinite' strong absorber with same dimensions (in practice 5 cm thick borolene is sufficient). A set of boron alloyed steel sheets has been provided by Böhler Bleche GmbH, Austria [11] with identical thickness ($d = 0.137$ cm, 1.88 wt% boron content) and smooth surface. The distribution of boron in steel alloys (Ferro-borides) on the surface can be visualized with SEM, thereby revealing a random distribution with typical grain sizes between 15 and 25 microns (Fig. 1). This micro-structure has been confirmed at the ultra-small angle scattering (USANS) instrument of the Atominstitut yielding an average grain radius of $R \approx 10$ µm. Such small absorber fluctuations are not visible in neutron images [7], but macroscopic boron inhomogeneities have been observed in boral (boron aluminum).

According to Eq. (2) the transmission enhancement increases (compared to homogeneous model) with increasing thickness of the absorber material. The steel sheets are combined to thicker stacks (Fig. 3). The transmission of the homogeneous model simulated is shown in Fig. 3. The homogeneous model includes wavelength spectra of the neutron beam, the geometry of the set-up, and multiple-scattering effects inside the sample. To improve the statistical accuracy the count numbers in the detector pixels are averaged over a field of 1 × 1 cm^2 and 2 × 2 cm^2 (Fig. 2). For the elimination of scattered neutrons circumventing the sample all crucial parts (sample, detector, beam line) have been shielded with a strong absorbing polyethylene-based material (borolene) with 20 wt% boron content (Fig. 3, right) realizing in this way background scattering correction.

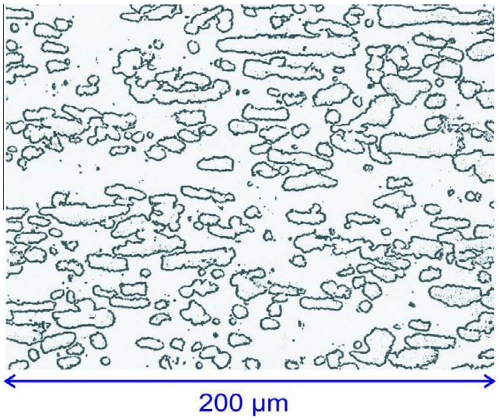

Fig. 1. SEM image showing the surface distribution of ferro-borides in the steel matrix (magnification 400×).

Table 1
Neutron cross sections for boron and borolene.

Boron material	Total microscopic cross section σ	Total macroscopic cross section Σ	Density ρB10
Steel		1.16 cm^{-1}	
Elemental boron	772 barn		
B-10 isotope	3838 barn		
Natural boron alloyed steel 1.88 wt% boron 0.35 wt% B-10		7.3 cm^{-1}	0.00377 g/cm^3
Borolene 10.3 wt% boron		15 cm^{-1}	0.023 g/cm^3

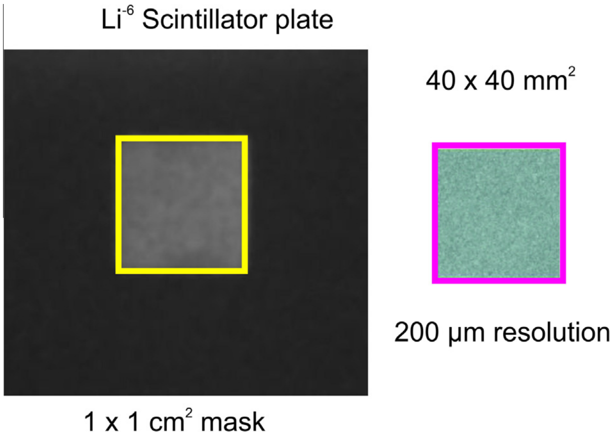

Fig. 2. Transmission image of a 0.137 cm thick boron alloyed steel plate taken with a 100 µm thick scintillator layer. Contrast is enhanced only for presentation.

The transmission measurements were performed using a scintillator detector with 16 bit full dynamic range and a 100 µm thick layer. Within the scintillator's resolution no statistically significant regions of reduced boron were found, a selected sample image is shown in Fig. 2. The read out noise depends on the readout speed of the CCD chip, where the best signal-to-noise ratio is obtained at lowest speed and an overall signal-to-noise ratio of 60 has been obtained [6,7]; the lowest detectable transmission level at our beam line when approaching the noise limit level is: $T_{min} \geqslant 5.0 \cdot 10^{-5} \pm 2.0 \cdot 10^{-5}$ (see Fig. 3 at maximum thickness $d = 2.3$ cm). The resolution is mainly limited by the statistical fluctuation due to the low count numbers and the unavoidable flux of neutrons circumventing the steel plate samples.

Fig. 3 demonstrates that both, the exponential and the homogeneous model are not valid anymore in the low transmission regime.

4. Monte Carlo simulations of boron inhomogeneities

Every neutron track through the sample experiences a slightly different amount of boron, and Monte Carlo simulations (MCNPX) are able to estimate an averaged transmission of a large number of stochastic paths, thereby considering the Maxwellian energy spectrum at our beamline, multiple scattering, absorption probabilities of the ^{6}Li scintillator [6], and as a new feature in our analysis different models for the absorber structure. In the absence of macroscopic inhomogeneities the models focus on the micro-structure as indicated by SEM and USANS measurements. Fig. 4 shows four artificial lattice models containing alloys of boron plus steel (dark regions) concentrated in the center of the steel cells. The light gray part of the cells contains only steel without boron. As reference serves the homogeneous model, where boron is uniformly distributed in the whole volume. The total amount of boron (weight fraction 1.88(3) wt%), provided by the manufacturer and confirmed with TOF transmission measurements [2], has been preserved in all simulations.