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Evaluation of the sensitivity for the track-etch neutron radiography method

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Abstract

The sensitivity of the track-etch neutron radiography method, to discern thickness of materials, has been investigated. The radiographs have been obtained in a facility installed at the IEA-R1 nuclear research reactor by using the solid-state nuclear track detector Makrofol-DE. In order to minimize image distortions caused by the neutron beam angular divergence, the samples have been positioned as close as possible to the detectors. For this irradiation geometry, neutrons scattered by sample can contribute to the image formation and consequently to the method's sensitivity.

1. Introduction

The neutron radiography is a versatile non-destructive testing technique largely employed for materials inspection (Berger, 1965; Bayon, 1998). The sample under inspection is irradiated in a uniform neutron beam and a converter screen transforms the transmitted neutron intensity into ionizing radiation which is able to sensitize a film.

In the track-etch neutron radiography method, the film is a solid-state nuclear track detector (SSNTD), usually combined with a boron-based converter screen. In this case the ionizing radiation will induce damages into the SSNTD. After chemical etching (development), these damages are enlarged and are called tracks, and they will form a two-dimensional image, which is visible to the naked eye (Lferde et al., 1984). When compared with the X-ray emulsion films, the main disadvantage of the SSNTD is the low optical contrast achieved in the radiographic image, leading to a low capability to discern thickness of materials (Assunção et al., 1992; Pereira, 2000; Matsumoto et al., 1986). However, the high spatial resolution achieved in the image as well as the insensitivity of the SSNTD to register visible light, β- and γ-radiations are their main characteristics, making the track-etch method desirable for some applications, such as to inspect high radioactive materials.

In order to minimize image distortions caused by the neutron beam angular divergence, usually the samples are radiographed as close as possible to the detectors. However, the smaller the sample to detector distance, the greater the scattered neutron contribution by sample to the image formation and hence the smaller the method's sensitivity. The objective of the present work was to evaluate the sensitivity of the track-etch neutron radiography method for the irradiation geometry in which the samples are radiographed as close as possible to the detectors.

2. Theory

Theoretically the neutron transmission by matter obeys the following exponential law (Curtiss, 1959):

$$\phi(x) = \phi_0 \exp(-\Sigma x), \tag{1}$$

where ϕ_0 and $\phi(x)$ are the incident and transmitted neutron fluxes through the sample having thickness x and total macroscopic cross section Σ.

This law is valid if the transmission measurement is performed at the good geometry condition in which neutrons scattered by sample are not detected (Curtiss, 1959). Since

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Table 1
Characteristics of the neutron beam at the sample irradiation position

Neutron flux	3×10^6 n/s cm^2
Collimation ratio	70
Neutron/gamma ratio	$> 10^5$ n/cm^2 mR
Diameter	20 cm
Mean energy	7 meV
(Au)–Cd ratio	150

for the present radiographs, the samples were positioned as close as possible to the detectors, scattered neutrons will contribute to the image formation. Such contribution will increase the transmitted neutron flux, by a factor ϕ_s and expression (1) becomes (Kobayashi, 1998)

$$\phi(x) = \phi_0 \exp(-\Sigma x) + \phi_s. \quad (2)$$

In order to take into account the effective response of samples, in terms of neutron transmission, this flux increase has been interpreted as an apparent decreasing of their total macroscopic cross sections, and expression (2) has been approximated to (Pereira, 2000; Assunção et al., 1992)

$$\phi(x) = \phi_0 \exp(-\Sigma_{\text{eff}} x), \quad (3)$$

where Σ_{eff} is the effective total macroscopic cross section and $\Sigma_{\text{eff}} \leqslant \Sigma$.

The optical density is defined by $D_{\text{op}} = \log(I_0/I)$, where I_0 and I are the intensities of the incident and transmitted light through the detector, respectively. For the present converter screen/detector set, $D_{\text{op}} = G \log(E)$. Here, G is the mean contrast obtained from the characteristic curve that relates optical density as a function of the neutron exposure $E = \phi t$ (t is the irradiation time) (Pereira, 2000; Hardt and Roettger, 1981). Hence the optical density as a function of the material thickness is given by the following linear function:

$$D_{\text{op}} = D_0 - (0.43 G \Sigma_{\text{eff}})\, x, \quad (4)$$

where D_0 is the optical density for the direct neutron beam.

The minimal discernible thickness $-\Delta x$, can be evaluated from expression (4) (Hardt and Roettger, 1981)

$$\Delta x = \Delta D_{\text{op}}/(0.43 G \Sigma_{\text{eff}}), \quad (5)$$

where ΔD_{op} is the minimal discernible optical density.

3. Experimental

The neutron radiography facility employed in this work, installed at the radial beam line 08 of the 2MW IEA-R1 Nuclear Research Reactor, has a thermal neutron flux of about 10^{13} n/s cm^2 near the reactor core. Table 1 shows the main characteristics of the neutron beam at the sample irradiation position (Pugliesi et al., 1999).

The SSNTD used was the Makrofol-DE which is a poly-carbonate 500-μm-thick, manufactured by Bayer AG.

Table 2
Experimental conditions to obtain the best contrast and spatial resolution in the radiography image

Exposure interval (n/cm^2)	Etching time (min)	Mean contrast
$1.8 \times 10^9 < E < 2 \times 10^{10}$	6	$G = (1.10 \pm 0.01)$

The damages into the detectors were induced by the products of the nuclear reaction $B^{10}(n, \alpha)Li^7$ (α-energy = 1.47 MeV; Li-energy = 0.84 MeV). After irradiation, the damages have been etched (developed) in a KOH (15%), ethanol (40%) aqueous solution at a constant temperature of 70°C (Lferde et al., 1984; Durrani and Bull, 1987).

The minimal discernible thickness has been determined for the materials iron, lead, copper and plexiglas. The samples are step wedges with thicknesses varying from 0.2 to 1.2 cm, which were fixed on the outside face of an aluminum cassette, inside which the converter screen and the detector are kept in a tight contact during irradiation. For such irradiation geometry, the sample to detector distance was about 0.1 cm.

The radiographs were obtained in the same neutron exposure interval and etching time in which the mean contrast G was determined. Such conditions which have been previously determined, together with the mean contrast value, are summarized in Table 2 (Pereira, 2000).

The data employed to determine the minimal discernible thickness of materials were the optical density readings (including the detector background), as a function of the step wedge thickness. Such readings have been performed in a Jarrel-Ash optical microphotometer, having a light beam width of 3 μm, length of 700 μm, and a minimal discernible optical density capability of $\Delta D_{\text{op}} = 0.02$.

4. Data analysis

The Fig. 1 shows the optical density behavior as a function of the step wedge thickness for the materials iron, lead, copper and plexiglas. Each data point has been obtained by averaging 10 individual optical density readings and the error bars correspond to the standard deviation.

The minimal discernible thicknesses, shown in Table 3, have been calculated by means of expression (5) with $\Delta D_{\text{op}} = 0.02$, and using the values of the parameters $0.43 G \Sigma_{\text{eff}}$ for each material, obtained from the fitting of expression (4) to the data points of Fig. 1. The uncertainties in these values have been determined by the usual quadratic propagation rule applied to expression (5).

In order to quantify the influence of the neutrons scattered by sample on sensitivity, the ratio between the minimal discernible thickness values for the good geometry condition (in which neutrons scattered by the sample do not contribute

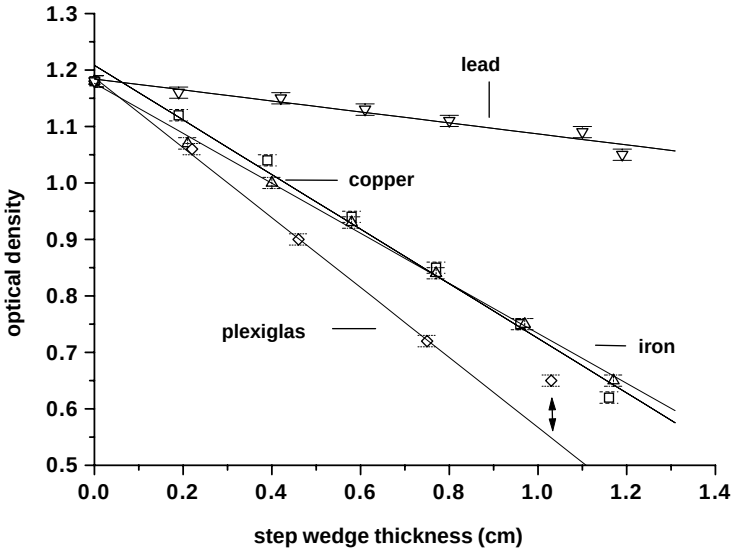

Fig. 1. Optical density behavior as a function of the step wedge thickness, and the fitted linear function, for lead, Iron, copper and plexiglas.

Table 3
Minimal discernible thickness values obtained at the sample to detector distance of 0.1 cm and for the good geometry condition

Material	0.1 cm	Good geometry (theoretical)
Iron	0.045 ± 0.001	0.040 ± 0.002
Lead	0.20 ± 0.02	0.18 ± 0.03
Copper	0.042 ± 0.002	0.042 ± 0.002
Plexiglas	0.032 ± 0.001	0.013 ± 0.001

to image formation) and for the present one were determined. The values for the good geometry, shown in Table 3, have been determined by means expression (5) with $\Delta D_{op} = 0.02$, by using the mean contrast value shown in Table 2, and the total macroscopic cross sections Σ, which were theoretically evaluated for the present neutron spectrum (Menezes, 1994). The ratio for plexiglas was about 2.5 and for the other materials, it was 1.1 (iron), 1.1 (lead) and 1.0 (copper). Although the studied materials possess non-negligible scattering cross sections, such influence was markedly high for plexiglas. This is because it is a hydrogen-rich material and hence the neutrons are essentially attenuated by scattering (Curtiss, 1959).

In addition, the sample to detector distance for which the good geometry condition is reached was also evaluated. For such evaluation the selected sample was plexiglas which has been positioned at two distinct distances from the detector. The obtained results for the sensitivity at 10 and 20 cm, together with the previous one at 0.1 cm, are presented in Fig. 2. As can be observed the sensitivity reaches a maximum value of about 0.016 cm, near a distance of 10 cm.

By comparing this maximal value with the one theoretically evaluated, shown in Table 3, the former is slightly greater. This difference can be attributed to the imprecision in the theoretical calculation of the total macroscopic cross section Σ, since the atomic density of the elements for the present plexiglas as well as its purity, are not precisely known.

5. Conclusions

By comparing the presently obtained result for the mean contrast with those for the X-ray emulsion films (Menezes et al., 1996), the former is about three times smaller and this justifies the capability of the SSNTD to discern lesser material thicknesses in the radiography image.

Although the minimal discernible thicknesses have been determined here by using a microphotometer, the same discerning capability will be achieved by the unaided eye since, for both, the minimal discernible optical density is about 0.02 (Pereira, 2000).

The interpretation of the transmitted neutron flux increase, as an apparent decreasing of the total macroscopic cross section, is a strictly experimental artifice which has been used to evaluate the obtained results since, for the purpose of the present work, the important factor is to know the effective response of sample in terms of neutron transmission.

As observed in Fig. 1, for thickness of plexiglas greater than ~ 0.7 cm, the linear behavior between optical density and sample thickness, as given by expression (4), begins to disappear (as indicated by the arrow). This is a consequence of the multiple scattering contribution to the transmitted flux (Curtiss, 1959; Pereira, 2000) and for such cases the present methodology must be improved.

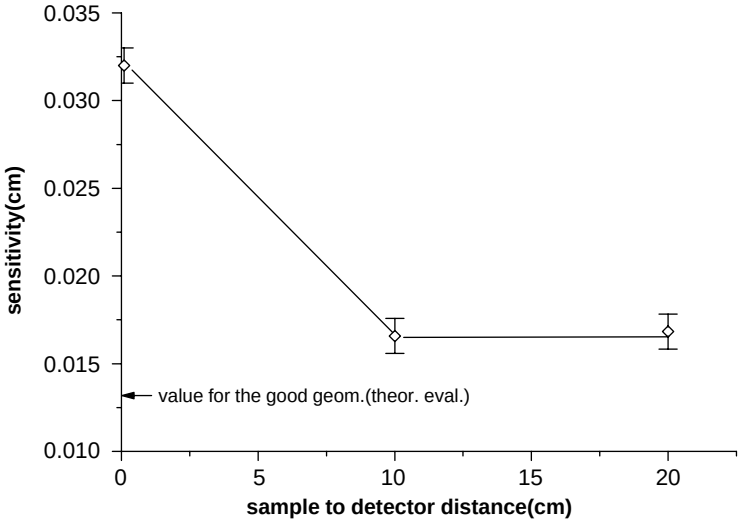

Fig. 2. Sensitivity behavior as a function of the sample to detector distance for plexiglas.

In order to minimize the neutron scattering contribution in the image and hence optimize the method's sensitivity, hydrogen-rich samples must be radiographed at the distances $\geqslant 10$ cm from the detector. However, for the present radiography facility, the distortions in the image caused by the neutron beam angular divergence will restrict the resolution in the image to values of about 1.5mm which, for many practical purposes, are usually not acceptable.

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