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Comparative Study on Phase Imaging of X-Ray and Neutron Sources

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Abstract: ***After the discovery of X-ray in 1895 the vast majority of radiographs have been taken and interpreted on the basis of absorption contrast of the object. In recent years the possibility of utilizing phase-contrast effect has received considerable attention. This new technique is capable of providing improved information from weakly absorbing samples, together with improved edge enhancement. The method requires use of coherent X-rays to allow wave interferences to occur and manifest itself as contrast formation in the intensity distribution recorded at the detector plane. This paper presents study of phase contrast imaging technique using X-rays & neutron sources.***

Keywords: Phase contrast imaging, Neutron source, edge enhancement, Neutron imaging

1. Introduction

In recent years, phase contrast imaging with X-ray and neutrons has been the subject of a significant research effort in the improvements in image contrast compared to conventional radiography [1- 4]. The contrast produced relies not only on differences in absorption but also on differences in real part of the refractive index. The refractive index is given by $n = 1 - \delta - i\beta$, the real part (δ) of the refractive index is responsible for refraction and results in a phase shift, while the magnitude of imaginary part (β) determines absorption. The radiography with thermal neutrons is a powerful non-destructive method for the investigation of materials and various industrial samples. We have done phase-contrast imaging with X-ray source, but X-ray phase imaging have got limitation for imaging of high Z materials like Pb, Ti, ZrO_2 etc, as the X-ray absorption is very high for such materials. Unlike X-rays, neutrons interact with various materials with very specific cross-sections largely independent of atomic number (Z) of the material and neutrons can pass through many high Z materials. Hence for objects of high Z materials but with poor neutron absorption phase imaging is the technique one should use. With neutron phase imaging it is possible to image minute quantities of such materials in the specimen of high Z with poor neutron absorption. However like X-ray phase imaging neutron phase imaging also requires source size to be small. For technical consideration such technique have been implemented by restricting neutron beam be 400µm. Unlike X-rays the real term of refractive index which is responsible for phase depends on elemental composition. Theoretical simulations have done for materials like Pb with air bubble, ZrH_2 in zircollay. This paper deals with application of this technique for material science applications using X-ray & neutrons.

X-Ray Phase Imaging at Elettra

Experiments have carried out at SYRMEP bending magnet beam- line Elettra, Italy. A CCD detector and fiber-optic combination having effective pixel pitch of 4.5 µm was used, for collecting high resolution images. Fig.1 shows the X-ray phase contrast image of carbon-felt taken at E = 10 keV, exposure time = 2 sec and object - detector distance (Z2) = 50cm. Fig. 2 (a) shows the phase contrast image of pyrocarbon (PyC) coated alumina micro-spheres with a diameter of 500 µm, which was taken at E = 16 keV, t =1.6 sec and Z_2 = 50 cm. The coated sample was prepared in a high temperature graphite vessel. These kinds of materials are important for nuclear science applications. The average PyC coating thickness has determined to be 60 µm on alumina micro- spheres. This technique is found to be very useful in visualizing and determining coating thickness of PyC, uniformity of the coating and optimization of coating parameters.

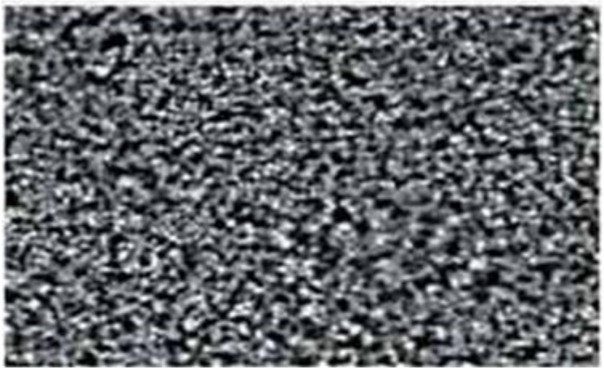


Figure 1: X- ray phase - contrast image of carbon-felt

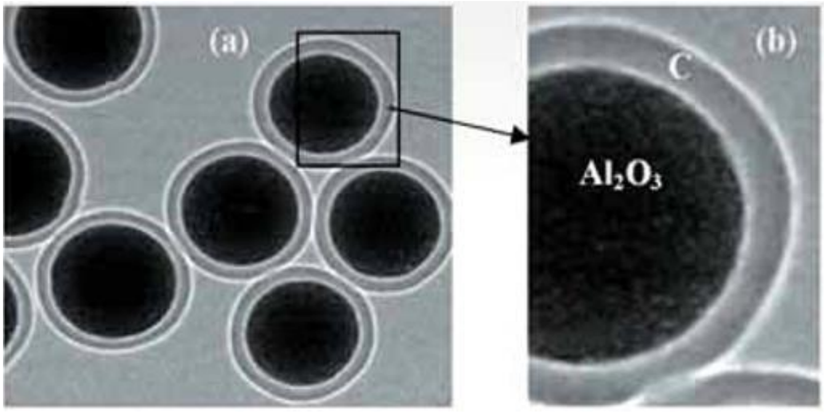


Figure 2: (a) X-ray phase-contrast image of PyC coated alumina micro- spheres. (b) Magnified phase contrast image of the black-rectangle portion revealing the coatings.

Theoretical Simulation of Phase-Contrast with Thermal Neutrons

We have used Fresnel-Kirchhoff integral formula [5] of parallel wave for simulation, to calculate the wave function and the intensity of the image at the detector plane:

$$f(x;zod) = \left(\frac{i}{\lambda\, zod}\right)^{\frac{1}{2}} \exp(-ikzod) \int q(X) \times exp\left(\frac{-ik(x-X)^2}{2zod}\right) dX$$

$$k = \frac{2\pi}{\lambda} \;; \qquad I(x;zod) = |f(x;zod)|^2 \qquad (1)$$

Where *x* is the position coordinate within the image plane, z_{od} is the object to image distance, I(x; zod) is the intensity of the object and q(X) is the transmission function of the object. The phase shift ϕ of a neutron with a wavelength λ on its way through the object, with regard to propagation in free space, is given by

$$\phi = -\frac{2\pi}{\lambda}\int \delta\, ds = -\frac{\lambda}{2\pi}\int a_{coh}\,\rho\, ds, \quad \delta = \frac{\lambda^2}{2\pi}\, a_{coh}\,\rho \qquad (2)$$

Where a_{coh} is the bound coherent scattering length and ρ is the average number of atoms per unit volume.

For X-rays, the phase difference is given by

$$\phi = -\frac{2\pi}{\lambda}\int \delta\, ds = -\frac{\lambda}{2\pi}\int r_e\,\rho\, f_r\, ds \quad and \;\; \delta = \frac{\lambda^2}{2\pi}\int r_e\,\rho\, f_r \qquad (3)$$

For calculation of contrast (C) we have used formula [5,6], C = (Imax – Imin) / (Imax + Imin), where Imax (maximum value of intensity) and Imin (minimum value of intensity) are values obtained from the 1-D plot of radial distance and transmitted intensity of the object. Table1 shows the cases where the use of X-rays is impractical, because of their high attenuation. Table 2 shows the differences in δ values of Pb, ZrO_2 and ZrH_2 for X-rays and thermal neutrons and contrast values for neutrons. Eqs. (2) and (3) show that the phase difference is proportional to wavelength for both X-rays and neutrons.

Table 1: A comparison of the linear attenuation coefficient in Pb, ZrO_2 & ZrH_2 for X-rays and neutrons

Object name	Neutron and X-ray energy	Neutron and X-ray wavelength (Å)	Neutron linear attenuation coefficient (cm-1)	X-ray linear attenuation coefficient (cm-1)
Pb	25 meV	1.81	0.38	58.933
ZrO_2	58.5 keV	0.212	0.21	16.658
ZrH_2			2.39	21.713

Table 2: Real part delta (δ) differences in lead, ZrO_2 and ZrH_2 for X-rays and neutrons

Object name	ρ(·10^{28}) (μ^{-3})	Neutron & X-ray λ(Å)	X-ray δ(rad) (×10^{-7})	Neutron δ(rad)
Pb	3.3031	1.81	5.4306	1.6177×10^{-6}
ZrO_2	8.2211	0.212	9.328	8.0336×10^{-6}
ZrH_2	10.884		9.2794	1.802×10^{-7}

For neutrons there is more scope to increase sensitivity by using longer wavelengths without a significant increase in attenuation. However, for X-rays, attenuation prevents the use of longer wavelengths (>2 Å) and limits sensitivity. Eq. (1) has solved using FFT technique, to simulate the ideal phase-contrast imaging conditions. The objects were assumed to be circular ZrH_2 (r = 40 mm) in cylindrical ZrO_2, (r = 80mm), circular lead (radius r = 100 mm) with air bubble (r = 20 mm and the thermal neutrons was assumed to be monochromatic radiation with a wavelength of 1.81Å (E = 25meV). Figs. 3 and 4 show the result of the simulation, object to detector distance of 11 and 25 cm respectively. The presence of primary maxima along with secondary maxima is a characteristic feature of phase contrast imaging. This result corresponds to idealistic case where source has perfect coherence and detector has infinite resolution. Figure 3 (a) shows the X-ray phase contrast image of spherical ZrH_2 bubble in cylindrical ZrO_2 pipe. Fig.3 (b) shows the intensity profile of Fig. 3 (a). Figure 3 (c) shows the phase contrast image of same sample with thermal neutrons & Fig. 3 (d) shows the intensity profile of Fig. 3 (c). The ZrH_2 bubble is not visible in Fig. 3 (a) as the X-ray absorption is very high for them. However, with neutrons in Fig. 3 (c) it is clearly visible even they have low neutron absorption.

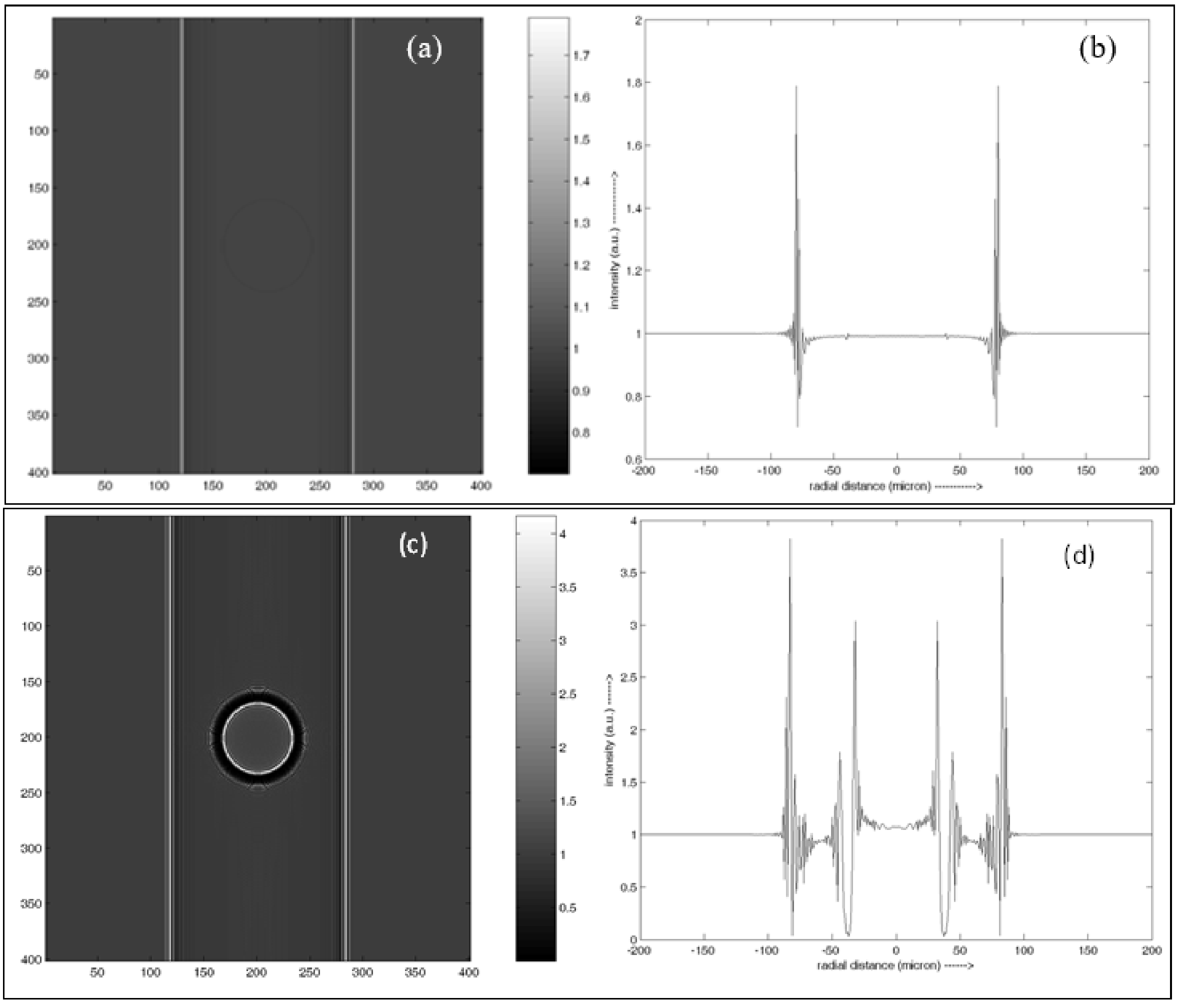
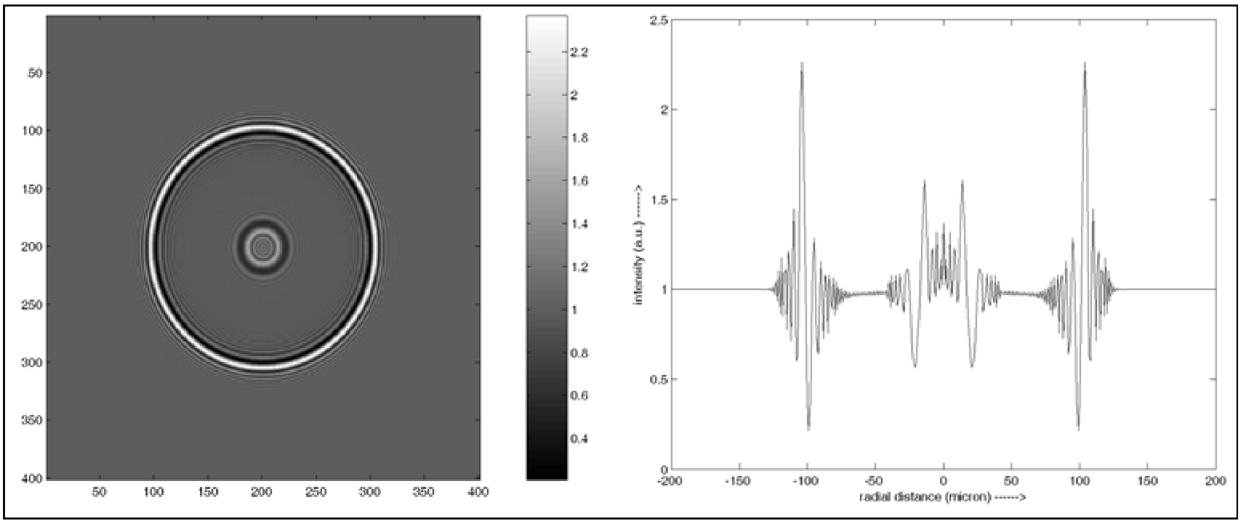


Figure 4:
(a) Phase-contrast image of spherical Pb sheet (r = 100 μm) with air bubble (r = 20μm) using thermal neutron, E = 25meV & (b) intensity profile of (a)

Figure 4 (a) shows the phase contrast image of spherical lead sheet with air bubble at object to detector distance = 25cm using thermal neutrons. Fig. 4 (b) shows the intensity profile of Fig.4 (a). With neutrons air bubble is clearly visible even though it has low neutron absorption. It shows the importance of phase-contrast imaging with neutrons for these types of materials.



(a) **(b)**

Figure 3: (a) Phase-contrast image spherical ZrH_2 bubble (r = 40μm) in cylindrical ZrO_2 pipe (r = 80μm) with X-ray energy at E = 58.5 keV, (b) intensity profile of (a), (c) phase-contrast image of same sample with neutrons at E = 25meV & (d) intensity profile of (c).

2. Conclusions

X- ray phase - contrast images of carbon-felt and PyC coated alumina micro- spheres have taken at SYRMEP bending magnet beam - line Elettra, Italy. This technique is found to be very useful in visualizing and determining coating thickness of PyC, uniformity of the coating and optimization of coating parameters. The phase contrast technique is also useful for imaging of defects, cracks and other fine features in low neutron absorptions materials. The theoretical simulation for materials like spherical ZrH_2 bubble in cylindrical ZrO_2 pipe, spherical Pb with air defect objects have been done. The ZrH_2 bubble cylindrical ZrO_2 pipe is not visible with X-ray source as the X-ray absorption is very high for them. However, with neutrons it is clearly visible even they have low neutron absorption. With neutrons air bubble in spherical Pb is also clearly visible even they have low neutron absorption. This shows the importance of phase-contrast imaging with neutrons for such objects. The phase contrast imaging technique is going to be very useful in improving the resolution in the Neutron imaging for the composites, detection of cracks at micron level resolution.

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