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Phase Contrast X-ray Radiography for the TRISO-coated Fuel Particles

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1. Introduction

The TRISO-coated fuel particle for a HTGR(high temperature gas-cooled reactor) with a diameter of about 1 mm is composed of a nuclear fuel kernel and outer coating layers. The coating layers consist of a buffer PyC(pyrolytic carbon) layer, inner PyC(I-PyC) layer, SiC layer, and outer PyC(O-PyC) layer as shown in Fig. 1[1], [2]. X-ray radiography can be one of the nondestructive alternatives to measure the coating thickness without generating a radioactive waste[3]-[6]. Phase contrast X-ray radiography technology is more powerful for acquiring a radiography image with clear boundaries, when compared with the conventional X-ray radiography[7], [8]. The coating thickness for the TRISO-coated fuel particle can be measured accurately by the phase contrast X-ray radiography image.

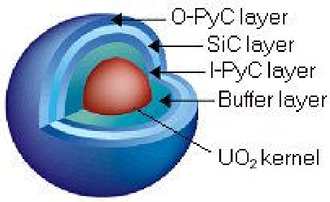

Fig. 1. Structure of a TRISO-coated fuel particle.

2. Phase Contrast X-ray Radiography

X-ray radiography is a powerful tool to inspect internal structures nondestructively. In a conventional X-ray radiography, the image contrast results from variations in the X-ray absorption arising from the density differences, composition and thickness of the objects. In the case that there is a little absorption difference, the image contrast will be poor. But the contrast can be enhanced for the weakly absorbing materials by using phase contrast X-ray radiography(PCXR) technology. PCXR detects the intensity variation due to a variation of a phase of the X-rays in the boundary between two objects.

Variations in thickness and density change the phase of an X-ray beam when passing through an object. In the geometrical optics approximation, the phase difference, Φ, for a ray path through an object relative to a vacuum is given by equation (1)[8].

$$\phi(x,y,z,k) = -k\int_{-\infty}^{z} \delta(x,y,z';k)\,dz' \quad (1)$$

$$= -\frac{2\pi r_e}{k}\int_{-\infty}^{z} \rho(x,y,z';k)\,dz'$$

The optics axis is parallel to z, $k=2\pi/\lambda$, r_e is the classical electron radius, ρ is the electron density of an object. The X-ray refractive index is $n=1-\delta-i\beta$, where δ is typically of the order of $10^{-5} \sim 10^{-7}$, so the refraction angles are usually quite small(a few arc seconds). The intensity of the image is expressed by the Kirchhoff formula (2)[8].

$$I(Mx, My, R_1+R_2, k) = (I_o/M^2)\left[1+\frac{R_2}{kM}\nabla_{xy}^2\phi(x,y,R_1,k)\right] \quad (2)$$

$M=(R_1+R_2)/R_1$ is the magnification of the image, and I_o is the uniform intensity in the object plane. From the equation, the contrast initially increases with R_2 and a phase laplacian. Fig. 2 shows a schematic illustration of the formation phase contrast for the edges of a circular object.

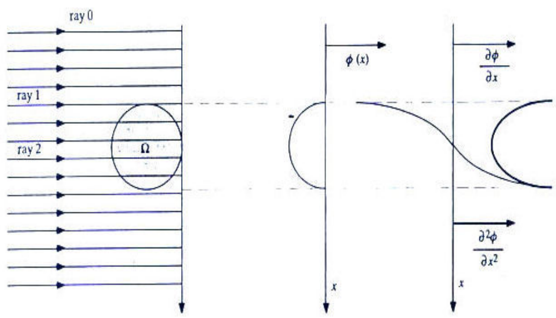

Fig. 2. The formation of phase contrast for a circular cross-section object.

The PCXR requires a highly monochromatic X-ray beam with a high spatial coherence. Synchrotron X-ray beam and sophisticated X-ray optics are needed to apply the PCXR. But, Wilkins suggested that the PCXR image could be acquired by a polychromatic hard X-ray with a small focus size of the X-ray tube generator[8]. We tried to phase contrast images for simulated TRISO-coated fuel particles by using a polychromatic micro-focus X-ray source.

3. Micro-focus X-ray Imaging System

To acquire the PCXR image for the simulated TRISO-coated fuel particles, a micro-focus X-ray imaging system was developed. The focus spot size of the X-ray generator was 1~2 μm. The number of pixels of the used flat panel X-ray detector was 1024x1024. The size of a pixel was 48x48 μm^2. In the experiment, the tube voltage/current was 50 kV/100 μA under the inspection condition. The radiographic image was enhanced by an image processing technique to acquire clear boundary lines between the coating layers.

4. Phase Contrast X-ray Radiography Image

We are developing a TRISO coating process by using a simulated kernel made of ZrO_2 instead of UO_2. The radiographic image of the simulated TRISO-coated fuel particle was acquired by a microfocus X-ray system. Fig. 3 shows an image acquired by a conventional X-ray radiography. Fig. 4 shows an image acquired by a phase contrast X-ray radiography. The distance from the object to the detector was 1400 mm. Phase contrast effect was expressed on the boundaries between the coating layers for the phase contrast image.

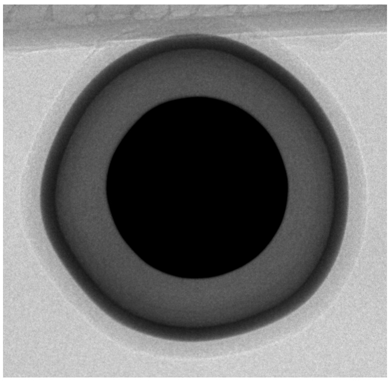

Fig. 3. A conventional X-ray radiographic image for a simulated TRISO-coated fuel particle.

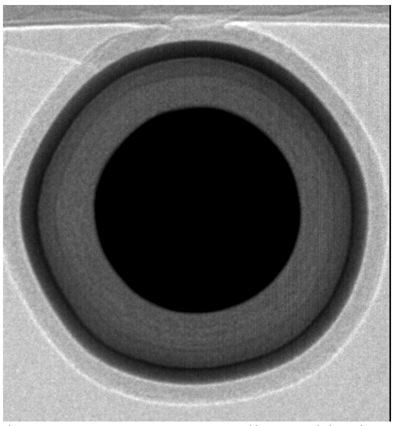

Fig. 4. A phase contrast X-ray radiographic image for a simulated TRISO-coated fuel particle.

5. Conclusion

In this study, phase contrast X-ray radiography technology was developed to nondestructively inspect simulated TRISO-coated fuel particles. The experimental results are as follows.

- The used micro X-ray imaging system consisted of a micro focus X-ray generator with a focus spot of less than 2 μm and a flat panel detector with a high resolution of 48 μm.
- Phase contrast X-ray image was acquired for the simulated TRISO-coated fuel particle with a kernel made of ZrO_2 instead of UO_2.
- The boundaries between the coating layers was clearly expressed on the phase contrast image, when compared with conventional X-ray radiographic image.

The coating thickness of the TRISO-coated fuel particles will be effectively measured by applying the phase contrast X-ray radiography and image processing technology.

Acknowledgement

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