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# Measurement of the Coating Thickness for Simulated TRISO-coated Fuel Particles by Phase Contrast X-ray Radiography

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## 1. Introduction

The TRISO-coated fuel particle for a HTGR(high temperature gas-cooled reactor) 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[1,2]. X-ray radiography is one of the nondestructive alternatives to measure a 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[7-9].

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. The contrast can be enhanced for weakly absorbing materials by using phase contrast X-ray radiography(PCXR) technology. PCXR detects the intensity variation due to the variation of a phase of the X-rays in the boundary between two objects. The intensity, $I(x)$, of an X-ray image with a phase variation, $\phi(x)$, is represented by equation (1) when passing through an object[10].

$$I(x) = 1 + \frac{R\lambda}{2\pi}\phi''(x) \tag{1}$$

$R$ is the distance between an object and a detector screen, and $\lambda$ is the wavelength of the X-ray. From the equation, the contrast initially increases with $R$ and $\lambda$.

Phase contrast X-ray radiography image for the simulated TRISO-coated fuel particle was acquired by adjusting $R$ and $\lambda$ with a micro-focus X-ray imaging system. The coating thickness was measured by using the phase contrast X-ray image for the fuel particle.

## 2. Acquisition of Phase Contrast X-ray Image

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 $\mu m^2$. In the experiment, the distance $R$ was adjusted from 40 cm to 140 cm, the tube voltage was adjusted from 40 kV to 80 kV to control the wavelength of the X-ray. The quality of the X-ray image was evaluated by the suggested phase contrast effect factor(PCEF) defined by equation (2).

$$PCEF = (c_1-c_2+c_3-c_4)/c_4 \tag{2}$$

Where, $c_1$ is the image intensity at a boundary between the SiC and O-PyC layer, $c_2$ is the image intensity at the O-PyC layer, $c_3$ is the image intensity at a boundary between the O-PyC and air layer, and $c_4$ is the image intensity in the air layer. In the experiment, the phase contrast effect increased at a lower tube voltage(longer wavelength) and longer object-to-detector distance. A lot of exposure time as well as a precise mechanism is required in this case. The tube voltage was adjusted to 60 kV, and the object-to detector distance was adjusted to 140 cm by considering the exposure time.

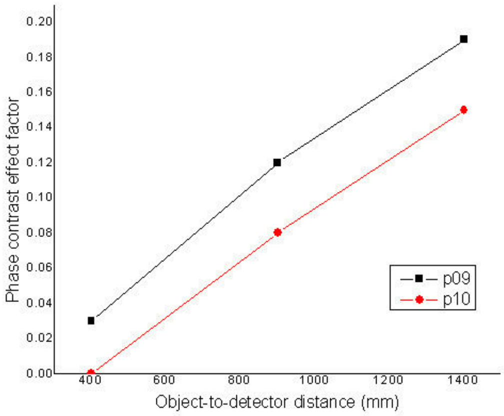


Fig. 1. A phase contrast effect according to object-to-detector distance.

## 3. Measurement of the Coating Thickness

Fig. 2 shows an image acquired by a phase contrast X-ray radiography. The coating thickness was automatically measured by the developed measurement algorithm based on digital image processing techniques which include a brightness and contrast enhancement, random noise reduction, edge detection and recognition. The validity of the nondestructive method was verified by the resultant average difference of 3.2 um and the average difference ratio of 5.7 % when compared with the destructive measurement.

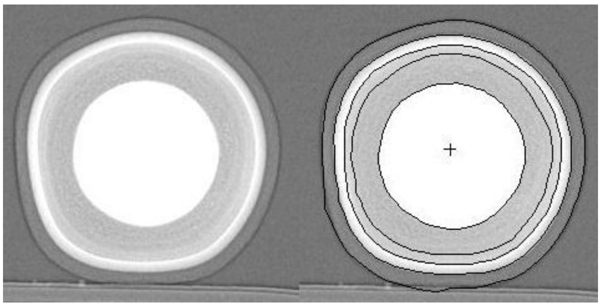

Fig. 2. A phase contrast X-ray image and boundary detection for a simulated TRISO-coated fuel particle.

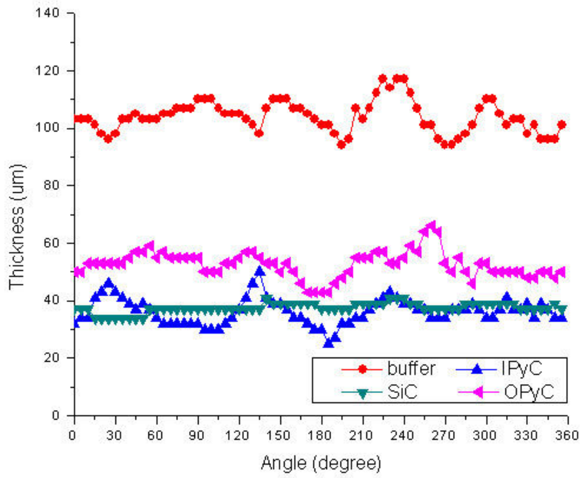


Fig. 3. The measured coating thickness of a simulated TRISO-coated fuel particle.

## 4. Conclusion

In this study, the coating thickness of simulated TRISO-coated fuel particles was measured by phase contrast X-ray radiography. The experimental results are as follows.

- A micro-focus X-ray imaging system with a focus spot of less than 2 μm was used to acquire a phase contrast X-ray image of the simulated TRISO-coated fuel particles with a kernel made of $ZrO_2$ instead of $UO_2$.
- The optimum condition was confirmed by the suggested phase contrast effect factor to acquire a phase contrast image with clear boundaries between the coating layers.
- The coating thickness was measured by the developed measurement algorithm for the phase contrast X-ray image for a fuel particle.
- The validity of the nondestructive method was verified by the resultant average difference of 3.2 um and the average difference ratio of 5.7 % when compared with the destructive measurement.
- In conclusion, the coating thickness of the TRISO-coated fuel particles can be measured nondestructively by the phase contrast X-ray radiography and digital image processing technology.

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