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Simulation of an X-ray Computed Tomography for the Coating Thickness Measurement in the TRISO-coated Fuel Particle

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1. Introduction

TRISO(Tri-Isotropic)-coated fuel particle is widely applied for it's higher stability for high temperature and efficient retention capability for fission products at the HTGR(high temperature gas-cooled reactor), one of the high efficient Generation IV reactors. The typical ball typed TRISO-coated fuel particle with a diameter of about 1 mm is composed of a nuclear fuel particle as a kernel and outer coating layers. The coating layers consist of a buffer PyC(pyrolytic carbon), inner PyC(IPyC), SiC, and outer PyC(OPyC) layer as shown in Figure 1[1~6].

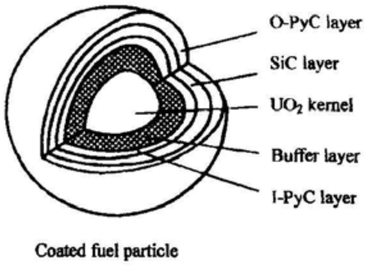


Figure 1. The structure of a TRISO-coated fuel particle

A variety of inspection items are concerned by the specification of TRISO fuel. Most of the items depend on destructive methods, but a few items can be inspected by nondestructive methods. Recently, X-ray radiography or X-ray CT(computed tomography) methods are being applied to nondestructively measure the coating thickness by research organizations in USA, China, Japan, and Germany[2, 7~10].

An X-ray radiography can be one of the nondestructive alternatives. The X-ray radiographic image is acquired by the projected direction of the X-ray. Boundary lines are not clear in the projection images compared with the cross-sectional image with clear boundary lines due to the density difference of each coating layer. Measurement error can be increased for the projection image with blurred boundary lines. To measure the coating thickness with precision, the image with clear boundary lines is required. Not only two-dimensional phase contrast image[11] with intensified boundary lines but also CT(computed tomography) with the reconstructed three-dimensional density distribution[12] can be powerful solutions to acquire image with clear boundary lines. CT is more helpful to acquire the cross-sectional image with clear boundary lines. In this study, FBP(filtered backprojection) algorithm was applied to reconstruct the cross-sectional image using a simulated TRISO-coated fuel particle. The coating thickness was measured on the reconstructed image.

2. CT by FBP(Filtered Backprojection)

FBP is one of the powerful CT algorithms to reconstruct tomographic image by backprojecting the forward projection image as shown in Figure 2. FBP algorithm can be represented by the equation (1)[12]

$$f(x,y) = \int_0^{\pi} d\theta \int_{-\infty}^{\infty} P(\omega,\theta)|\omega|\, e^{j2\pi\omega(x\cos\theta + y\sin\theta)}\, d\omega \quad (1)$$

where, f(x,y) is the reconstructed image, and $P(\omega,\theta)$ is the X-ray projected data for the object. $P(\omega,\theta)|\omega|$ means the high pass filtered projection multiplied by the frequency ω. The filtered projection profile is projected backward(backprojected) to the object image plane to reconstruct the original cross-sectional image.

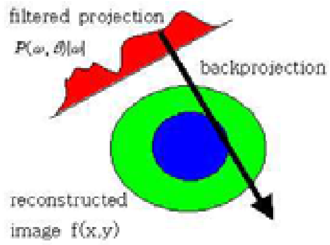


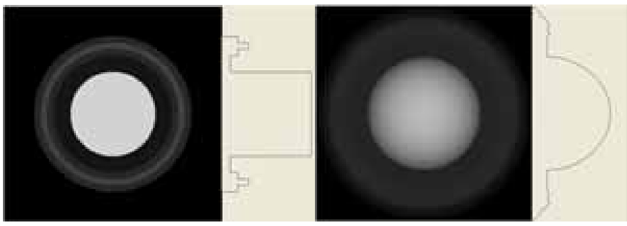
Figure 2. Image reconstruction by filtered backprojection

3. Simulation of the Image Reconstruction for the TRISO-coated Fuel Particle

Table 1 shows the specification of HTR-10 fuel as an example[8] and the simulation parameters for the TRISO-coated fuel particle. Image plane was designed with 512x512 pixels and 256 gray levels(8 bit resolution) per pixel. The cross section of the virtual TRISO fuel generated from the simulation parameters as shown in Figure 3(a). Figure 3(b) shows projection image by the virtual fan beam and the intensity profile on the center line. The projection image was blurred by the accumulated density parameters. The quality of the real X-ray projection image will be much worse than that of the simulated projection image because of large focus size of X-ray generator and the induced noises in detector.

Table 1. Specification and simulation parameters of TRISO

		Spec. of TRISO fuel particle	Simulation parameters
UO_2 kernel	Diameter	500 µm	200 pixels
	Density	10.5 g/cm^3	210 gray level
Thickness of coating layers	Buffer	95 µm	38 pixels
	IPYC	40 µm	16 pixels
	SiC	35 µm	14 pixels
	OPYC	40 µm	16 pixels
Density of coating layers	Buffer	<1.10 g/cm^3	20 gray level
	IPYC	1.9±0.1 g/cm^3	38 gray level
	SiC	>3.18 g/cm^3	64 gray level
	OPYC	1.9±0.1 g/cm^3	38 gray level
Coated fuel particle	Diameter	920 µm	368 pixels
	Sphericity	<1.2	1



(a) (b)

Figure 3. (a)Intensity profile for cross section, (b)Intensity profile for projection image of virtual TRISO fuel particle

The cross-sectional image was reconstructed by the filtered backprojection algorithm as shown in Figure 4. The boundary lines were clearly represented on the reconstructed image.

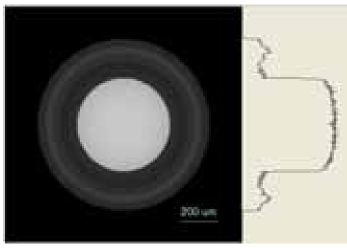


Figure 4. The reconstructed image by filtered backprojection

4. Measurement of the Coating Thickness

The radius r_n of each layer can be calculated by equation (2) using the measured distances, d_1, d_2, , , d_5, on the reconstructed image

$$r_n = kd_n, \quad n=1, 2, 3, 4, 5 \qquad (2)$$

where,

k : calibration coefficient

r_1~r_5 : radius of kernel, buffer PyC, IPyC, SiC, OPyC

d_1~d_5: measured distance for radius of kernel, buffer, IPyC, SiC, OPyC layer.

As the result of simulation, The measurement error for coating layers ranged from -0.8 to +0.9 µm. The error rate ranged from -1.14 to +2.25 %. The measurement error could be reduced by using the X-ray CT technique compared with the X-ray radiography with the error rate of 6 %[13].

5. Conclusion

The cross-sectional image was reconstructed by CT technique to precisely measure the coating thickness of a simulated TRISO-coated fuel particle. The measurement error was less than 1 µm, so the error rate was less than 2.3% on the reconstructed cross-sectional image. It could be possible to precisely measure the coating thickness of TRISO-coated fuel particle by using the X-ray CT technique. It is also expected that the density of each coating layer can be also measured by acquiring the 3D density function.

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