Simulation of the Digital Image Processing Algorithm for the Coating Thickness Automatic Measurement of the TRISO-coated Fuel Particle

Woong-Ki Kim*, Young-Woo Lee*, and Sung-Woong Ra**

Abstract: TRISO (Tri-Isotropic)-coated fuel particle is widely applied due to its higher stability at high temperature and its efficient retention capability for fission products in the HTGR (high temperature gas-cooled reactor), one of the highly efficient Generation IV reactors. The typical ball-type TRISO-coated fuel particle with a diameter of about 1 mm is composed of a nuclear fuel particle as a kernel and of outer coating layers. The coating layers consist of a buffer PyC, inner PyC, SiC, and outer PyC layer. In this study, a digital image processing algorithm is proposed to automatically measure the thickness of the coating layers. An FBP (filtered backprojection) algorithm was applied to reconstruct the CT image using virtual X-ray radiographic images for a simulated TRISO-coated fuel particle. The automatic measurement algorithm was developed to measure the coating thickness for the reconstructed image with noises. The boundary lines were automatically detected, then the coating thickness was circularly by the algorithm. The simulation result showed that the measurement error rate was less than 1.4%.

Keywords: TRISO-coated Fuel Particle, Coating Thickness, X-ray CT, Computed Tomography, Filtered Backprojection, Automatic Measurement

1. Introduction

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

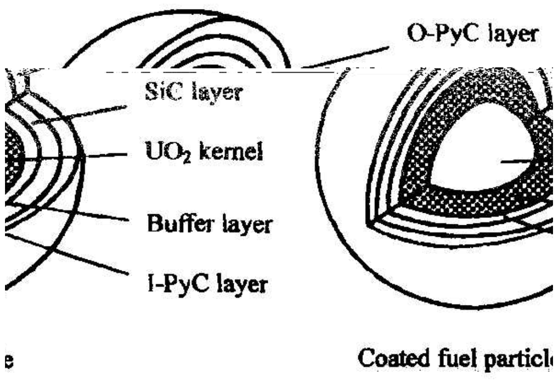

Fig. 1. Structure of a TRISO-coated fuel particle

A variety of inspection items are concerned with the specification of a 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 have been applied to nondestructively measure the coating thickness by research organizations in USA, China, Japan, and Germany [2, 7~10].

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. However, the boundary lines are not clear in the projection images when 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 a projection image with blurred boundary lines.

To automatically measure the coating thickness with precision, an image with clear boundary lines is required. Not only a two-dimensional phase contrast image [11] with intensified boundary lines, but also a CT (computed tomography) with a reconstructed three-dimensional density distribution [12] can be powerful solutions to acquire an image with clear boundary lines. A CT is more helpful to acquire a cross-sectional image with clear boundary lines. In this study, the FBP (filtered backprojection) algorithm was applied to reconstruct the CT image using a simulated TRISO-coated fuel particle. Then, an automatic measurement algorithm was developed to measure the coating thickness for the reconstructed image by FBP.

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2. FBP (Filtered Backprojection) Algorithm

FBP is one of the powerful CT algorithms used to reconstruct a tomographic image by backprojecting the forward projection image, as shown in Fig. 2. The FBP algorithm can be represented by 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 $P(\varpi,\theta)$ is the X-ray projected data for the object. $P(\varpi,\theta)|\varpi|$ means high pass filtered projection multiplied by the frequency. The filtered projection profile is projected backward (backprojected) to the object image plane to reconstruct the original cross-sectional image.

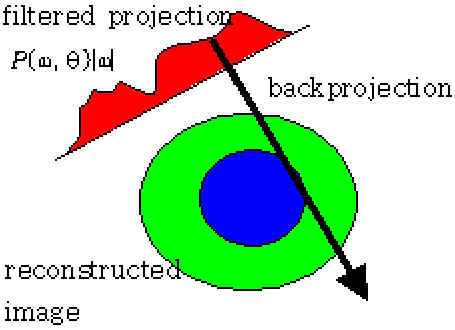

Fig. 2. Image reconstruction by filtered backprojection

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

Table 1 shows the specification of the HTR-10 fuel as an example [8] and the simulation parameters for the TRISO-coated fuel particle. The image plane was designed with 512x512 pixels and 256 gray levels (8-bit resolution) per pixel. The cross-section of the virtual TRISO fuel was generated from the simulation parameters as shown in Fig. 3. Fig. 4 shows the projection image by the virtual fan beam and the intensity profile for 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 the large focus size of the X-ray generator and the induced noises in the detector.

Table 1. Specification and simulation parameters of TRISO

		Specifications	Simulation Parameters
UO_2 kernel	Diameter	500 µm	200 pixels
	Density	10.5 g/cm^3	210 gray level
Coating thickness	Buffer	95 µm	38 pixels
	I-PYC	40 µm	16 pixels
	SiC	35 µm	14 pixels
	O-PYC	40 µm	16 pixels
Coating density	Buffer	≦1.10 g/cm^3	20 gray level
	I-PYC	1.9±0.1 g/cm^3	38 gray level
	SiC	≧3.18 g/cm^3	64 gray level
	O-PYC	1.9±0.1 g/cm^3	38 gray level
Coated fuel particle	Diameter	920 µm	368 pixels
	Sphericity	<1.2	1

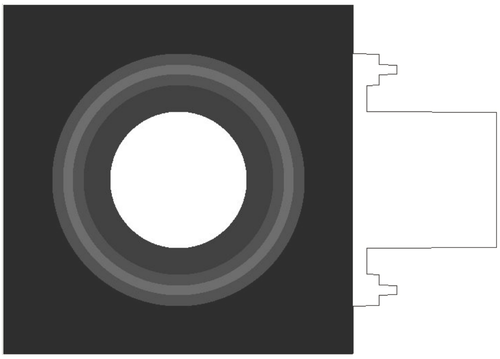

Fig. 3. Cross-sectional image of the virtual TRISO fuel particle

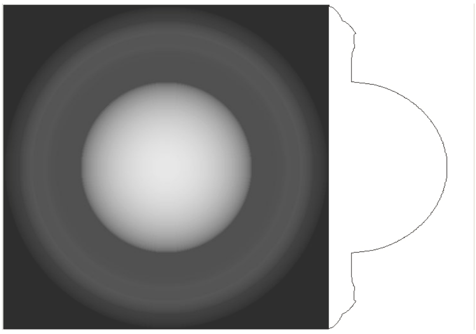

Fig. 4. Projection image of the virtual TRISO fuel particle

The cross-sectional image was reconstructed by the filtered backprojection algorithm, as shown in Fig. 5. The boundary lines were clearly represented for the reconstructed image.

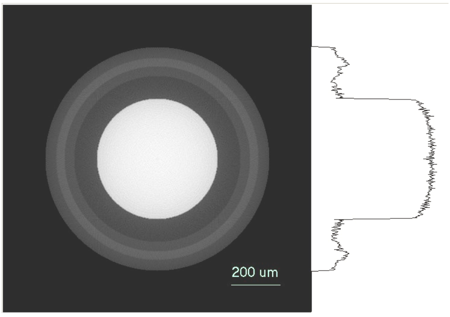

Fig. 5. The reconstructed image by the filtered backprojection

4. Algorithm for Automatic Measurement of the Coating Thickness

The coating thickness is measured for the reconstructed image of the TRISO-coated fuel particle. The thickness can be measured manually or automatically. Generally, the coating thickness measurement depends on a manual method by human recognition due to some vague boundaries. Recently, automatic measurement has been attempted using digital image processing technology [7]. Advanced automatic measurement technology is required to precisely measure the coating thickness for images with vague boundaries acquired by nondestructive X-ray radiography or CT when compared to the ceramographic image [13, 14].

In this study, an automatic measurement algorithm was developed to measure the coating thickness for the reconstructed image by the FBP by using a simulated TRISO-coated fuel particle as shown in Fig. 6.

4.1 Reduction of the Noises in the Reconstructed Image

It is not easy to automatically find the boundary lines due to a great deal of noise involved in the reconstructed image by the CT technique for a simulated TRISO-coated fuel particle as shown in the profile in Fig. 5. Noises must be reduced to detect the correct boundary lines on the image. A general LPF (low-pass filter) removes both noise and boundary information composed of high frequency components, simultaneously. The boundary information must be maintained during the noise reduction process. One alternative is to use a median filter. The gray level of each pixel is replaced by the median of the gray levels in a neighborhood of that pixel. The median filter is effective for spike-like noises and the edge sharpness can be preserved [15]. In this study, a 3x3 median filter was applied to reduce the noise for the reconstructed image. Fig. 7 shows images with reduced noise and profiles. The error can be minimized by using the profile without noise when the boundary lines are extracted automatically.

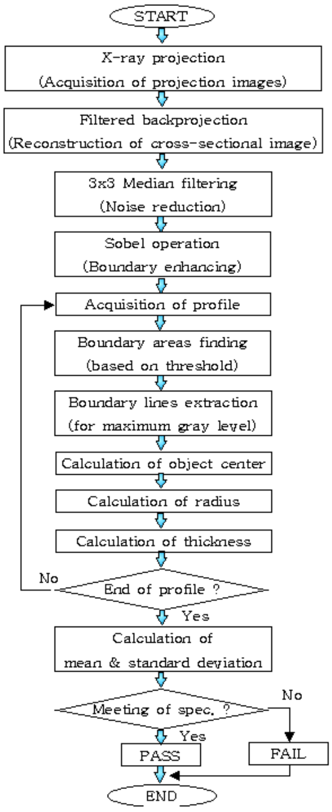

Fig. 6. Automatic measurement algorithm for the coating thickness

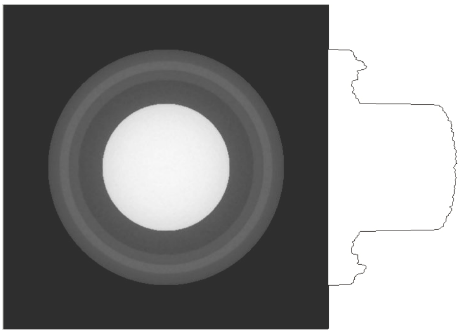

Fig. 7. Noise reduced image using the 3x3 median filter

4.2 Extraction of the Layer Boundary

In this study, a Sobel operator [15], one of the edge detection algorithms in a digital image processing, was applied to extract the boundary areas. The Sobel operator is composed of a horizontal Sobel operator and a vertical Sobel operator as shown in Fig. 8. The horizontal Sobel operator intensifies the horizontal edges and the vertical Sobel operator intensifies the vertical edges. All of the boundaries can be extracted by applying both operators to the target image. The pixels in the boundary areas have a high gray level, and the pixels outside the boundary areas have a low gray level using the Sobel operation. Boundary areas can be classified by the gray level differences of the pixels. Fig. 9 shows an image with intensified boundary areas by applying the Sobel operators.

-1	-2	-1
0	0	0
1	2	1

(a)

-1	0	1
-2	0	2
-1	0	1

(b)

Fig. 8. (a) Horizontal Sobel operator, (b) Vertical Sobel operator

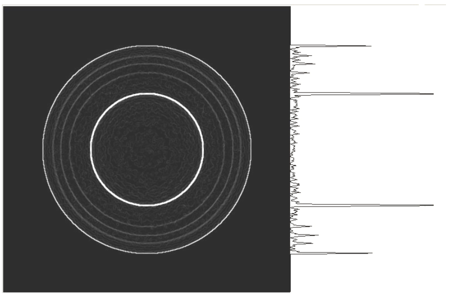

Fig. 9. Edge enhanced image by the Sobel operators

4.3 The Kernel Diameter and the Coating Thickness

We can confirm that the gray level of the boundary areas is much larger than that of the other areas in the profile for the edge enhanced image. Boundary areas can be classified on the basis of a proper threshold in the profile. Fig. 9 shows the intensified boundary areas in the profile. The position of a boundary is established for the center of each boundary area. The distances between the boundary positions and the center of a TRISO-coated fuel particle image are the radii of the kernel or the coating layers. The center of the image is calculated by equation (2) as the center of the weight [16] for the TRISO-coated fuel particle image.

$$x_a = \frac{m_{10}}{m_{01}}, \quad y_a = \frac{m_{01}}{m_{01}} \tag{2}$$

where

x_a : central x-coordinate of an object image,

y_a : central y-coordinate of an object image,

$m_{pq} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x^p y^p f(x, y)\,dxdy$, p, q = 0, 1, 2, , , .

The radius r_n of each layer can be calculated by equation (3) by using the measured distances, d_1~d_5, for the reconstructed image.

$$r_n = kd_n, \ n=1, 2, 3, 4, 5 \tag{3}$$

where

k : calibration coefficient,

$r_1 \sim r_5$: radius of the kernel, buffer PyC, I-PyC, SiC and O-PyC layer

$d_1 \sim d_5$: measured distance for the radius of the kernel, buffer, I-PyC, SiC and O-PyC.

The radii of the kernel and the coating layers were circularly by rotating them 360 degrees with a step of 5 degrees. Fig. 10 shows the measured radii of the kernel and the coating layers. The kernel diameter and the coating thickness were computed by the radii. As a result of the simulation, the mean value, standard deviation and error rate were measured as shown in Table 2. The standard deviation ranged from 1.4 to 2.3 µm. The measurement error ranged from -0.6 to +0.5 µm. The error rate ranged from -0.8 to +1.4 %.

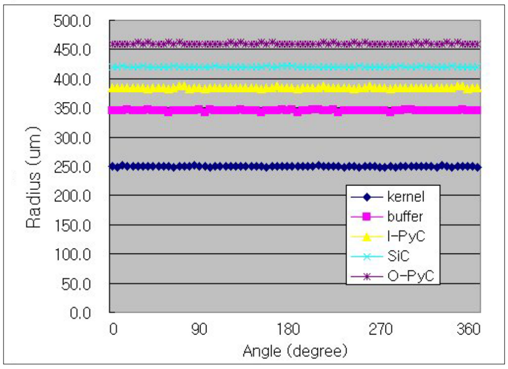

Fig. 10. Radii of the kernel and the coating layers

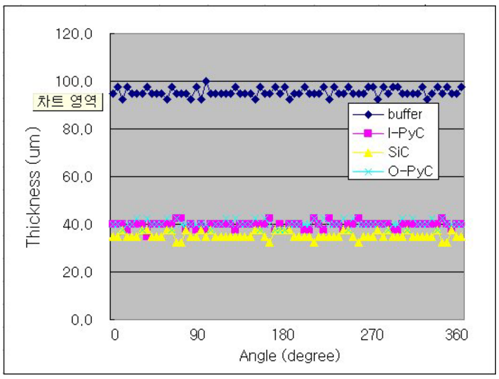

Fig. 11. Measured coating thickness

Table 2. Automatic measurement of the kernel diameter and the coating thickness

	Mean	Standard Deviation	Error	
Unit	µm	µm	µm	%
kernel diameter	499.4	2.3	-0.6	-0.1
buffer thickness	95.5	1.7	+0.5	+0.6
I-PyC thickness	39.7	1.4	-0.3	-0.8
SiC radius	35.5	1.5	+0.5	+1.4
O-PyC thickness	40.1	1.6	+0.1	+0.4

The coating thickness measurement may be improved by the developed automatic measurement algorithm when compared with the manual method for an X-ray CT with an error rate of 2.3% [14] or for X-ray radiography with an error rate of 6% [13].

5. Conclusions

The digital image processing algorithm was proposed to automatically the thickness of the coating layers in a TRISO-coated fuel particle. The FBP algorithm was applied to reconstruct the CT image using the virtual X-ray radiographic images for a simulated TRISO-coated fuel particle. The automatic measurement algorithm was developed to measure the coating thickness for the reconstructed image with noises. The boundary lines were automatically detected, then the coating thickness was circularly using the algorithm. As a result of the simulation, the standard deviation ranged from 1.4 to 2.3 µm, the measurement error ranged from -0.6 to +0.5 µm, and the error rate was less than 1.4%. The coating thickness may be measured more accurately by the developed automatic measurement algorithm when compared to the manual method.

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References

[1] Ji Yeon Park, Weon Ju Kim, Young Woo Lee and Jong Hwa Chang, “Development of TRISO coating process for HTGR fuel,” KAERI/AR-652/2002, 2002.

[2] Kazuhiro Sawa, Shuichi Suzuki and Shusaku Shiozawa, “Safety Criteria and Quality Control of HTTR fuel,” Nuclear Engineering and Design 208, pp. 305-313, 2001.

[3] Guenter Lohnert, “Topical issue on “Japan's HTTR”,” Nuclear Engineering and Design, 233, pp. 1-3, 2004.

[4] Masuro Ogawa and Tetsuo Nishihara, “Present status of energy in Japan and HTTR project,” Nuclear Engineering and Design, 233, pp. 5-10, 2004.

[5] Kazuhiro Sawa and Shohei Ueta, “Research and Development on HTGR fuel in the HTTR project,” Nuclear Engineering and Design 233, pp. 163-172, 2004.

[6] Xioming FU, Masashi TAKAHASHI, Shouhei UETA and Kazuhiro SAWA, “Comparison of HTGR Fuel Design, Manufacture and Quality Control Methods between Japan and China,” JAERI-Tech, 2002-049, 2002.

[7] Chunhe Tang, etc, “Research and Development of Fuel Element for Chinese 10MW High Temperature Gas-cooled Reactor, Journal of Nuclear Science and Technology,” Vol. 37, No. 9, pp. 802-806, September 2000.

[8] Chunhe Tang, etc., “Design and manufacture of the fuel element for the 10 MW high temperature gas-cooled reactor,” Nuclear Engineering and Design 218, pp. 91-102, 2002.

[9] John Hunn, “Coated Particle Fuel Characterization Lab for the Advanced Gas Reactor Fuel Development and Qualification Program,” ANS/GLOBAL 2003. 11.

[10] R. L. Hockey, etc., “Advances in Automated QA/QC for TRISO Fuel Particle Production,” Proceedings of ICAPP 2004, June 2004.

[11] S. W. Wilkins, T. E. Gureyev, D. Gao, A. Pogany and A. W. Stevenson, “Phase-contrast imaging using polychromatic hard X-rays,” Letters to Nature, 1995.

[12] Jiang Hsieh, “Computed Tomography,” SPIE Press, 2003.

[13] W.K. Kim, Y.W. Lee, J.Y. Park, and S.W. Ra, “Simulation of an X-ray Radiography for the Coating Thickness Measurement in the TRISO-coated Fuel Particle,” Proceedings of the KNS Autumn Meeting, to be published, 2005.

[14] W.K. Kim, Y.W. Lee, J.Y. Park, and S.W. Ra, “Simulation of the Coating Thickness Measurement in the TRISO-coated Fuel Particle Image Reconstruction by the Filtered Backprojection,” Proceedings of KIPS Autumn Conference, 2005 (to be published).

[15] Rafael C. Gonzalez and Richard E. Wods, “Digital Image Processing,” Addison Wesley, pp. 189-201, 1992.

[16] Rafael C. Gonzalez and Richard E. Wods, “Digital Image Processing,” Addison Wesley, pp. 514-518, 1992.

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