Non-destructive Evaluation of Nuclear Grade IG-110 Graphite Using Constant Potential X-Ray

R. Himawan, Sutrasno, S.B. Santoso

Center for Isotope and Radiation Application – National Nuclear Energy Agency (BATAN) Jl. Lebak Bulus Raya No. 49 Pasar Jum'at, 7002, Jakarta Selatan, Indonesia

E-mail: roziqh@batan.go.id

Abstract. The main structures of the High Temperature Gas-cooled Reactor’s core are made of graphite material. High temperature and the high flux of neutron exposure in the HTGR reactor affects the integrity of graphite material. In order to ensure the integrity of the graphite materials, in-service non-destructive inspection is needed. Commonly, prior to the operation, the radiography technique is conducted to evaluate the graphite material. The aim of this study is to develop a non-destructive inspection method in order to evaluate the quality of graphite materials. Five specimens made from nuclear grade graphite IG-110 produced by Toyo Tanso, Co. Ltd has been radiographically tested using X-ray constant potential machine to evaluate the graphite material. The parameter of the energy and intensity of X-ray has also been used in this computed radiography technique with a white type of phosphor imaging plate. A scanning machine of HD CR 35 NDT with 50 µm laser size and a 300 rpm scan rate equipped with a 16-bit system has been used to result in the digital image of the graphites. The results show that the increase of energy and intensity of the radiation to some extent produces better image contrast. The radiograph of the specimens also shows that there is no defect in the material. According to these results, it could be concluded that the digital radiography technique is appropriate for evaluating graphite material.

1. Introduction

The High-Temperature Gas-cooled Reactor is a graphite-moderated and gas-cooled (mainly, helium gas is used) reactor with a maximum core-outlet coolant temperature above 500 °C. There are two types of HTGR, that are pebble bed reactor and prismatic reactor. These two reactors have a different core design. Pebble bed reactor’s core has a cavity where the fuels are put in, while in the prismatic reactor’s core, the fuel bundle is a part of the core structure. Figure 1 shows a schematic of the pebble bed and prismatic reactor core[1], [2]. The reactor internal structures of the HTGR are mainly made up of graphite components. The graphite material is ceramic, therefor the ductility of graphite is significantly less than the ductility of metals.

The individual parts of graphite components in the core structure should meet the design’s principles and requirements to ensure safe operation and shutdown. Therefore, the core structure and its components should have sufficient strength to ensure the integrity and reliability of any conditions, even a severe earthquake[2]. It means, the core component, especially for graphite components, the presence of defects is not allowed. Since the graphite is a brittle material, even a small defect could induce a catastrophic failure. To ensure that the graphite components are defect-free, non-destructive testing should be conducted during the construction of the reactor.
Intensive studies have been conducted to develop a non-destructive testing method to detect a defect in graphite material, such as radiography testing, laser ultrasonic and magnetic adaptive method\cite{3}–\cite{5}. Radiography technique has a benefit or advantages over some of the other NDT methods in that the radiography provides a permanent reference for the internal soundness of the object that is radiographed. The sensitivity of x-rays is nominally 2\% of the thickness of the material\cite{6}. Besides that, according to the development of an X-ray device, that is constant potential X-ray, which the X-ray could be emitted with constant potential and low potential, the use of X-ray for characterizing material becomes wider, not limited for hard material but also soft material\cite{7}–\cite{9}. The development of an X-ray device also conducted for in-situ monitoring\cite{10}.

The developments in characterizing graphite material using X-rays have attained a significant achievement. S. Nickerson, et.al. developed a methodology to characterize a porosity of ceramics material using an X-ray CT image\cite{11}. In his study, a random microstructure has been quantifying using such parameters, successfully. J. Sumita et.al. develop an evaluation method of material properties and properties change induced by high neutron dose irradiation using X-ray tomography\cite{3}. A high-energy X-ray tomography technique was used to characterize the graphite morphology\cite{12}. However, an evaluation of graphite material using constant potential has not been conducted, yet. Therefore, the objective of this study is to examine the performance of constant potential in the evaluation of graphite material. The constant potential X-ray machine used in this study was “Isovolt”.

The developments in characterizing graphite material using X-rays have attained a significant achievement. S. Nickerson, et.al. developed a methodology to characterize a porosity of ceramics material using an X-ray CT image\cite{11}. In his study, a random microstructure has been quantifying using such parameters, successfully. J. Sumita et.al. develop an evaluation method of material properties and properties change induced by high neutron dose irradiation using X-ray tomography\cite{3}. A high-energy X-ray tomography technique was used to characterize the graphite morphology\cite{12}. However, an evaluation of graphite material using constant potential has not been conducted, yet. Therefore, the objective of this study is to examine the performance of constant potential in the evaluation of graphite material. The constant potential X-ray machine used in this study was “Iso volt”.

The specimens used in this study were made from nuclear grade graphite IG-110 produced by Toyo Tanso, Co. Ltd. The mechanical properties of IG-110 graphite are shown in Table 1 while the geometry and photograph of the specimen are shown in Figure 1. The constant potential with the brand of Iso volt was used in this study. The advantages of the use of constant potential are, the X-ray emitted continuously from the anode and the potential could be regulated with a small voltage step. The image of exposure results was captured using Imaging Plate and processed digitally. To obtain the best image quality, many shots were taken by varying exposure time, electric current, and voltage. While the source to film distance was set up remain constant. To examine the effect of material thickness, two-position of exposure was taken, which is 12.5 mm thickness direction and 62.5 mm thickness direction. Since the images are in digital ones, therefore, the image quality is quantified by the grey value.

The geometrical arrangement for detecting discontinuities of the IG-110 graphite specimen using an x-ray constant potential machine is shown in figure 3, and the source to object distance for all testing is
about 700 mm. To avoid the backscattering effect during the testing, 3 mm of the lead sheet placed on the bottom side. Meanwhile, a sheet of 0.125 mm Cu is positioned between the x-ray source and the test object to reduce the scattered radiation. A white type of imaging plate (IP) is then placed at the backside of the graphite to record the penetrated radiation. To evaluate the sensitivity of the radiograph, a wire duplex is positioned on the specimen of graphite to evaluate and measure a spatial resolution.

Table 1. Mechanical properties of graphite IG-110[13]

| Material properties                  | Value     |
|--------------------------------------|-----------|
| Density [Mg/m³]                      | 1.78      |
| Tensile strength (MPa)               | 25.3      |
| Compressive strength (MPa)           | 76.8      |
| Modulus of elasticity (GPa)          | 8.3       |
| Poisson’s ratio                      | 0.14      |
| S, value for tensile (MPa)           | 19.4      |
| S, value for compression (MPa)       | 61.4      |

Figure 2. Geometry and photograph of the specimen
3. Results and discussion

The result of the radiographic test was a latent image of a graphite specimen in the imaging plate. The imaging plate is then scanned into a digital image by a scanning machine of HD CR 35 NDT with 50 \( \mu \)m laser size and 300 rpm scan rate equipped with a 16-bit system of greyscale. Then, the common helpful software is implemented to the radiograph to evaluate and measure the defect of the specimen.

Figure 4 shows the images of 12 mm thick graphites exposed by is volt X-ray machine in various exposure times of the 30s, 40s, 50s, 60s, and 70s, respectively. The machine was set up at constant 60 kV and 1.0 mA. It is seen that the grey value of radiograph is higher by exposure time increase, starting from the grey value of 16.000 for 30 second time exposure (fig4.a) to 40.000 for 70 second time exposure (fig 4.e), and it also causes more contrast image. The image of duplex wires is more clearly displayed.
Figure 5 shows the images of 12 mm thick graphites in various voltages from 60 kV, 62 kV, 65 kV, 67 kV and 70 kV, respectively. The machine was set up at a constant current tube of 1.0 mA and given exposure time 60 seconds. It is clearly shown that the grey value of radiograph is higher by increasing the energy of radiation (kV), starting from the grey value of 30.000 for 60 kV (fig5.a) to 65.000 for 70 kV (fig 5.e). The image contrast increases from the kilovoltage of 60 kV to 67 kV (80 % of saturated) and the image is not clearly seen at 70 kV due to saturated grey value.

Figure 6 shows the images of 12 mm thick graphite in various current tubes from 1.0 mA, 1.3 mA, 1.5 mA, 1.7 mA and 2.0 mA, respectively. The machine was set up at a constant voltage of 60 kV and given exposure time 60 seconds. It is clearly shown that the grey value of radiograph is higher by increasing the intensity of radiation or milliamperage, starting from the grey value of 30.000 for 1.0 mA (fig6.a) to 65.000 (saturated) for 1.7 mA (fig 6.d). The image reaches the maximum contrast at the current tube of 1.5 mA (70 % of saturated grey value) as seen in fig 6.c.

Figure 7 shows the images of 62 mm thick graphites in various voltages from 60 kV, 62 kV, 70 kV, 75 kV and 80 kV, respectively. The machine was set up at a constant current tube of 1.0 mA and given exposure time 60 seconds. It is clearly shown that the grey value of radiograph is higher by increasing the energy of radiation (kV), starting from grey value of 20.000 for 70 kV (fig7.a) to 52.000 for 80 kV (fig7.c), and the maximum image contrast is obtained at a given 80 kV or approximately 80 % saturated grey value as displayed at the fig 7.c.

![Figure 5. Image result at constant electric current (1.0 mA) and exposure time (60 s) (electric voltage : (a) 60 kV, (b) 62 kV, (c) 65 kV, (d) 67 kV, and (e) 70 kV )](image-url)
4. Conclusion

Evaluation of nuclear grade graphite IG-110 using constant potential X-ray machine, Isovolt, has been conducted. The objective of this study is to examine the performance of constant potential in the evaluation of graphite material. According to the evaluation results it could be concluded that the Isovolt X-ray machine is effective for evaluating mechanical components made of IG-110 graphite. X-ray radiography evaluation depends on exposure time, electric voltage and electric current. Among these three parameters, electric voltage and current play an important role in providing a good image.
Acknowledgments

This work has been carried out as a key technology development study for the Experimental Power Reactor project. Financially supported by the Ministry of Research and Technology and Higher Education (Kemenristekdikti) through the INSINAS FLAGSHIP BATAN program, the fiscal year 2019 is acknowledged.

References

[1] M. Ishihara, J. Sumita, T. Shibata, T. Iyoku, and T. Oku, “Principle design and data of graphite components,” Nuclear Engineering and Design, vol. 233, no. 1–3, pp. 251–260, 2004.

[2] Z. Zhang, J. Liu, S. He, Z. Zhang, and S. Yu, “Structural design of ceramic internals of HTR-10,” Nuclear Engineering and Design, vol. 218, no. 1–3, pp. 123–136, 2002.

[3] J. Sumita et al., “Development of evaluation method with X-ray tomography for material property of IG-430 graphite for VHTR/HTGR,” Nuclear Engineering and Design, vol. 271, pp. 314–317, 2014.

[4] J. B. Spicer, L. R. Olasov, F. W. Zeng, K. Han, N. C. Gallego, and C. I. Contescu, “Laser ultrasonic assessment of the effects of porosity and microcracking on the elastic moduli of nuclear graphites,” Journal of Nuclear Materials, vol. 471, pp. 80–91, 2016.

[5] G. Vértésy, T. Uchimoto, T. Takagi, I. Tomáš, and H. Kage, “Nondestructive characterization of flake graphite cast iron by magnetic adaptive testing,” NDT and E International, vol. 74, pp. 8–14, 2015.

[6] S. K. Dwivedi, M. Vishwakarma, and P. A. Soni, “Advances and Researches on Non Destructive Testing: A Review,” Materials Today: Proceedings, vol. 5, no. 2, pp. 3690–3698, 2018.

[7] Z. Gong and Y. Yang, “The application of synchrotron X-ray techniques to the study of rechargeable batteries,” Journal of Energy Chemistry, vol. 27, no. 6, pp. 1566–1583, 2018.

[8] V. Lacivita et al., “Study of X-Ray irradiation applied to fresh dairy cheese,” Lwt, vol. 103, no. September 2018, pp. 186–191, 2019.

[9] A. C. G. Fonseca et al., “Precise determination of soil structure parameters in a X-ray and γ-ray CT combination methodology,” Progress in Nuclear Energy, vol. 114, no. January, pp. 138–144, 2019.

[10] M. Kudrna Prašek et al., “A compact and flexible induction furnace for in situ X-ray microradiography and computed microtomography at Elettra: design, characterization and first tests,” Journal of Synchrotron Radiation, vol. 25, no. 4, pp. 1172–1181, 2018.

[11] S. Nickerson, Y. Shu, D. Zhong, C. Könke, and A. Tandia, “Permeability of porous ceramics by X-ray CT image analysis,” Acta Materialia, vol. 172, pp. 121–130, 2019.

[12] C. Chuang, D. Singh, P. Kenesey, J. Almer, J. Hryn, and R. Huff, “Application of X-ray computed tomography for the characterization of graphite morphology in compact-graphite iron,” Materials Characterization, vol. 141, pp. 442–449, 2018.

[13] T. Shibata, J. Sumita, T. Tada, S. Hanawa, K. Sawa, and T. Iyoku, “Non-destructive evaluation methods for degradation of IG-110 and IG-430 graphite,” Journal of Nuclear Materials, vol. 381, no. 1–2, pp. 165–170, 2008.