Preliminary Application of CT Technology in Non-destructive Testing of Nuclear Fuel Elements

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Abstract. With the emergence of various novel fuel elements, traditional X-ray test technologies refer to national standards that have gradually been unable to meet the non-destructive testing (NDT) requirements for these novel fuel elements. As a new NDT technology, industrial computed tomography (CT) has great potential for NDT of nuclear fuel elements. In this paper, through a personalized transformation of self-developed X-ray equipment, we carried out CT scanning imaging experiments up to more than 400 kV on pellet-shell gap in rod-shaped fuel elements, a high-density annular component, and a tungsten-based workpiece. Not only that, after three-dimensional reconstruction and image analysis, it was found that sub-millimeter internal void defects could be detected. Furthermore, size measurements were carried out through image analysis which achieved a relative error of 5%. A conservative conclusion can be drawn from this research: industrial CT, including but not limited to micro-CT, high-energy X-ray CT, etc., has an optimistic future in testing internal defects and measuring internal dimensions of novel fuel elements.

Keywords: Nuclear fuel element · NDT · CT system · Measure dimensions

1 Introduction

Computed tomography technology can obtain tomography images of tested objects by calculating the attenuation information of the X-ray. It is capable of displaying the internal structure of the tested objects in an intuitive manner in the form of two-dimensional or three-dimensional images without destroying the tested objects. CT is featured with the fast speed of scanning, high resolution of image, and efficient utilization rate of radiation. Currently, X-ray CT technology has been comprehensively applied in various fields, including aerospace, aviation, military, and national defense, providing an important NDT method for the development of spaceflight rockets and spacecraft, aero-engines, and weapon system inspection.

Research institutes and universities all over the world have adopted CT technology to perform researches on nuclear fuels and nuclear materials. Argonne National Laboratory developed an XRD-CT NDT apparatus in 2017. Argonne Lab performed material

analysis and morphology observation of uranium molybdenum granular nuclear fuel. XRD-CT technology is of great significance in the preparation of nuclear fuels [1]. Purdue University and Los Alamos National Laboratory completed the experimental study of synchronous X-ray CT for the first time in 2020. They could compute the porosity and phase volume of U10Zr after neutron irradiation [2]. Argonne National Laboratory and Los Alamos National Laboratory applied near-field high-energy X-ray diffraction microscope (NF-HEDM) and μ-CT technology to non-destructively characterize the relationship between microstructure and fuel performance of sintered UO_2 in 2017 [3–5]. Germany Aachen University applied the combination of μ-CT and FIB-SEM technology to study the 3D inter-space network transportation properties of materials of the highly radioactive disposal experimental site in 2016 [6].

To meet the needs of scientific research and production, improve the testing efficiency and enhance the professional technical capability, the NDT center has performed the transformation research from X-ray Digital Radiography system (DR) to CT device. The original DR system has been transformed into a CT imaging system by hardware addition and software development, reaching a spatial resolution of 41 p/mm and a density resolution of 1%. Based on the confirmed resolution and sensitivity of the CT system, the imaging experiments of the gap in rod element, an annular components, and a tungsten-based sample are conducted. Meanwhile, artifacts generation and elimination measures of CT images are preliminarily discussed.

2 DR and CT Systems

2.1 Overview of DR Imaging System

DR imaging equipment (HS-XY-450, Dandong Huari Company) is capable of realizing a long-thin type of welding DR imaging. The device has consisted of an X-ray source, an X-ray digital imaging detector plate, a mechanical motion rack, and a necessary software system. The X-rays source emits X-rays, the detector plate receives signals in real-time, and the software system determines the automatic testing program after driving the mechanical rack to position the workpiece ROI as Fig. 1 shown. Influenced by the particularity of customization, the original DR system suffered from a poor testing range, inadequate testing efficiency, insufficient resolution, and weak testing capability. To improve the testing efficiency, increase the testing range, and enhance the testing technology capability, the research work on system transformation is implemented.

2.2 CT Transformation

The transformed system is deemed as a spiral scanning CT device, which is mainly composed of subsystems, including of X-ray source, detector system, mechanical system, high-precision motion control system, image data collection and transmission system, image processing system, radiation safety protection system. Through CT transformation, and reserving the original function capabilities, the new apparatus can realize DR two-dimensional imaging, CT tomography imaging, and CT three-dimensional imaging.

A new high voltage generator (450 kV) and auxiliary cables in the X-ray source were replaced for a stronger penetration ability. After replacement, the maximum voltage of
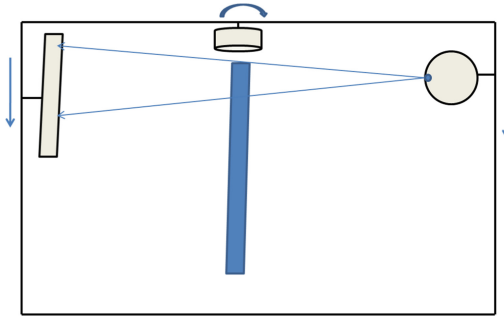
Fig. 1. Structure diagram of main components in the DR system

a high-voltage generator can reach 450 kV and the maximum power can reach 1,500 W. By adding a high precision turntable on a removable countertop at the vertically below cantilever, the samples could achieve 360-degree rotation and adjust the imaging magnification. New moving functions can be realized through the coordinated controlling of the motion control system. Figure 2 shows the pictures of the newly-added precision turntable and the high voltage generator.
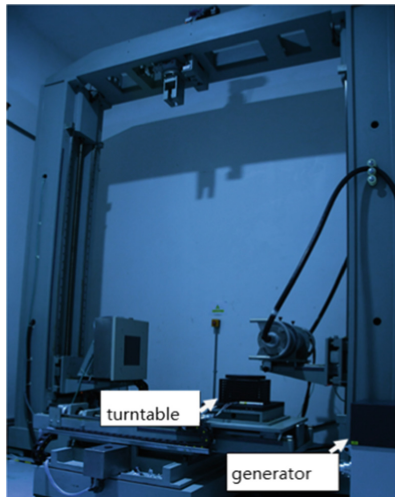

Fig. 2. Precision turntable and high voltage generator for ct imaging

The main technical indicators of the turntable include: a bearing capacity of 100 kg, maximum torque of 179 N*m, positioning accuracy of $\pm 30''$, the flatness of 5 µm, and axial deflection of 8 microns. There is no need to change the original multiple motion axes of the detector and X-ray source tube in the mechanical motion system.

The newly added turntable uses a three-claw chunk to install and fix various workpiece. When conducting CT scanning, the claws shall be fixed on the workpiece. Meanwhile, the turntable shall be disassembled quickly to ensure that the transformation has

no influence on the original function of DR. The newly added turntable is equipped with an independent electrical controlling card, which can be operated through the controlling software of the system. Other multi-axis's motion still adopts the original electrical controlling system. To realize the application needs of the CT system, the transformation system is equipped with original system controlling software, CT scanning controlling software, image reconstruction software, and image processing software. CT scanning controlling software is capable of realizing different working modes, including circular track scanning, spiral scanning, comprehensive view field scanning, and bias scanning. The image reconstruction software is capable of correcting the scanned data in real-time and repairing the image deviation caused by mechanical systems and geometric errors. Image processing software is capable of realizing CT data visualization and analysis, applying functions of data measurement, image processing, data output, animation, and other necessary features.

3   CT Imaging Experiments

3.1   CT Imaging and Artifacts

During the process of CT data collection, the initial X-ray passes through the object and occurs the attenuation after the X-ray source emitting a certain energy ray. As being absorbed by the object, partial rays come from transmission rays, and other partial rays come from scattering rays. Through the receiving by the detector plate, both transmission rays and scattering rays form a ray image, and finally impact the digital image processing and displaying system. The process is prone to be influenced by various factors, resulting in data deviation from the expected value, which seriously influences the image reconstruction results.

Various artifacts from detector outputting information cause an influence on the reconstruction results, seriously polluting the attenuation information of X-rays. Artifact on CT images is caused by equipment or sample and does not belong to the image of the scanned object, which shows that different shapes in the image will affect the accuracy of diagnosis. Generally, there are commonly two kinds of artifacts, which are artifacts caused by samples and artifacts caused by equipment. The causes of artifacts are complex and the typical artifacts include geometric artifacts, hardening artifacts, scattering artifacts, motion artifacts, and metal artifacts, which are shown in Fig. 3.
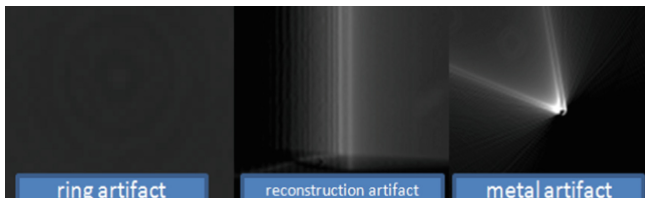

Fig. 3. Various artifacts during CT imaging

The removal of artifacts is mainly through various hardware corrections or software algorithms compensation. Based on generally suppressing most artifacts and stable

operation this equipment, we optimized the CT imaging system parameters. Finally, the spatial resolution of CT imaging system can reach 4 LP/mm, the density resolution can reach 1%, and the sensitivity is higher than 0.4 mm. The imaging of the line pair card and round hole card of the CT imaging system is shown in Fig. 4, where the resolution and sensitivity can be clearly observed. Based on this, the CT imaging research of some fuel simulators are implemented.
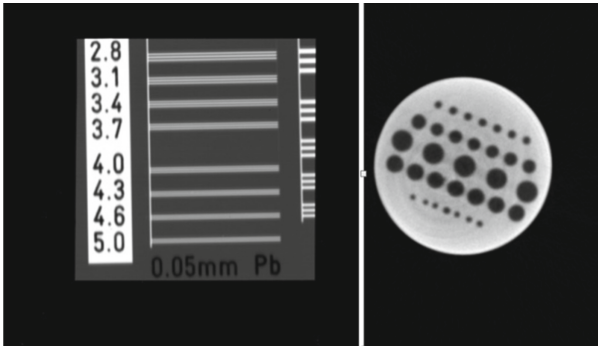

Fig. 4. Imaging of line pair test and round hole card CT

3.2   CT Imaging of Typical Work Piece

During the ray testing of the gap between shells and pellets in fuel rods, the X-ray energy selected shall be capable of penetrating the thickest place of 360° rotation of the workpiece. To obtain a high image resolution, scanning imaging is usually implemented in the range of small focus ($\leq$0.3 mm) and large focal length (1300 mm). This is because to combine the reduced size of the light source and enlarged geometric projection, a higher spatial resolution can be obtained. However, reducing the light source means reducing the luminous flux and prolonging the exposure time. To obtain the maximum testing efficiency, the core issue lies in the balance between the light source diameter and the luminous flux. The imaging of the pellet-shell gap in a simulation fuel rod are shown in Fig. 5. The gap within a certain range of different simulators can be effectively measured. In addition, it can be clearly seen that the internal assembly size is less than 0.1 mm, but it is unavailable to confirm the size obtained from the destructive test. The size exceeds the spatial resolution of the transformation system. This imaging experiment can qualitatively judge that there is a gap between pellets and the shell with a size less than 100 μm.

In the CT imaging of high-density annular components, the X-ray energy will not capable of penetrating completely until it rises to 430 kV. The reconstruction and analysis process is similar to that of fuel rod simulators. The CT images of the annular workpiece are shown in Fig. 6. Three views show the slice projection in three directions respectively. It can be observed obviously that the position with poor X-ray attenuation shows black. The X-ray intensity becomes weak after the absorption of solid substances.
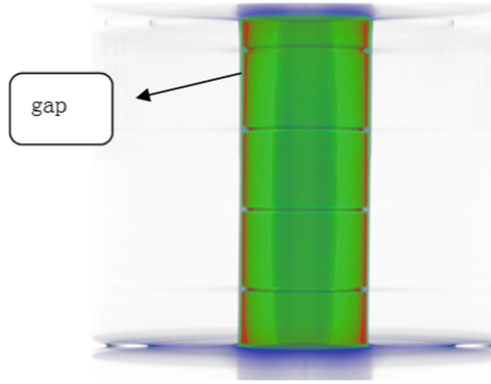
Fig. 5. CT imaging of pellet-shell gap

There are certain ray artifacts in the peripheral area of the components, and there are also reconstruction artifacts brought by the equipment or sample in the inner hole area. After selecting various imaging parameters, the ring structure can be observed in the three-dimensional image. After analyzing and measuring the image, the error between the measured size from images and the actual verification tool is about $\pm(3–5)\%$.
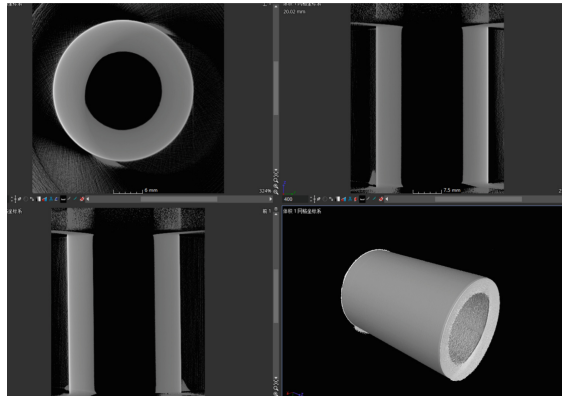

Fig. 6. CT imaging of a high density annular component

Influenced by the complex internal structure of additive manufacturing, it is difficult to be directly tested by the traditional ray or ultrasonic testing methods. Therefore, three-dimensional imaging technology represented by X-ray CT has strong application potential in nondestructive testing or online monitoring. Regarding the research on CT imaging of a triangular prism tungsten workpiece manufactured by 3-D printing, the sample size was 28 mm, the height was 100 mm, and there were 6 holes with a diameter of 2 mm and one hole with a diameter of 0.1 mm on a certain end face. When performing CT imaging for this sample, the ray energy is capable of completely penetrating only when it rises up to 445 kV. The specific experimental conditions are as follows: voltage

445 kV, current 1.2 mA, small focus 0.3 mm, exposure 0.1 s, image merging number 3, focal length 1,400 mm. Through Fig. 7, we can learn that circular holes with regular sizes are distributed on the triangular prism, but there are some non-eliminative artifacts in the triangular boundary region. Through the resolution calculation after physical calibration, the blind hole diameter is about 2.1 mm, the length is 96.5 mm, and the blind hole section length is 3.5 mm. Influenced by the decrease of sensitivity under high voltage, the seventh through-hole with a diameter of 0.1 mm (not shown in the image, but exists in the real object) is unavailable to be identified.
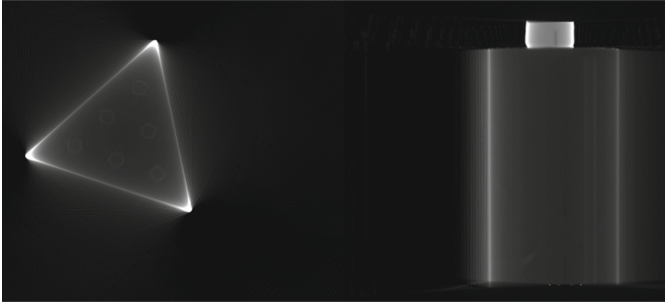

Fig. 7. Scanning reconstruction of triangular prism model

3.3 Key Factor Analysis of CT Imaging

The main factors influencing the data collection during the experiment include that dead pixels of the X-ray detector will cause the point to be unresponsive to X-rays (the dead pixels will only be displayed in the scanning stage), thus making it impossible for the pixel to collect projection data. Invalid data caused by mechanical error, program running time difference, air ambient temperature, and humidity would also bring negative effects. Furthermore, from the imaging process, we can find the installation and motion accuracy of the scanning mechanism, projection collection density, reconstruction algorithm accuracy, and the experiment factors which include exposure parameters, quantum noise, ray beam hardening, scattered ray influence, tester dynamic response, dark field noise influencing CT imaging quality.

The complex artifacts problem was caused by equipment, involving all aspects, including the data collection system, the high-voltage system, and the reconstruction process. There are several situations that will result in fringe artifacts, including the distortion of filter window, unstable rotation of scanning frame, and contamination of x-ray window. A poor detector channel will cause a clear ring artifact, and the dead pixel will also cause the same artifacts. If the temperature of the detector is too high or too low, the nonlinear response from the detector and the different performance of the integral amplifier, there will be the fuzzy ring artifacts. Data collection system: the components are also capable of generating artifacts. The development of CT imaging technology is closely connected with the development of ray sources, high-resolution X-ray detectors and various artifacts elimination algorithms. On the one hand, based

on the traditional absorption of single energy spectrum X-ray CT imaging, different substances may correspond to similar or identical CT values, resulting in the incapability to effectively distinguish target information through CT images. On the other hand, the spatial resolution is limited by the focus size of the X-ray source, the size of the detector pixel unit, the size of the measured objects, and the object image magnification ratio. There is a direct method to develop and improve the spatial resolution, including directly reducing the size of radiation source or detector pixel, and directly obtaining the resolved projection data through the magnification ratio of the object image. Besides, there is an indirect method to develop and improve spatial resolution. For instance, the current nano-CT or μ-CT imaging produces the focal depth fine beam to form an enlarged projection image on the detector through the X-ray lens.

4   Conclusions

This paper implements CT system transformation from DR imaging equipment. Through the overall planning of the X-ray source, X-ray detector, mechanical controlling, projection data collection, image reconstruction, and three-dimensional display, our team realizes the integrated operation interface, which not only improves the work efficiency, simplifies the operation process, and stabilizes the system, but also provides a more convenient and efficient inspection imaging for the nondestructive testing of nuclear fuels and nuclear materials. Through the necessary CT imaging technology conditioned experiment, the paper explores the suitable CT three-dimensional imaging parameters for the specific workpiece. The newly transformed apparatus is capable of realizing a spatial resolution of 41 p/mm and a density resolution of 1%. Through three processes of CT scanning, data reconstruction and image analysis, the volumetric defects within the sensitivity range (0.4 mm) and the dimension measurement (3–5)% error can be identified. Through analyzing and discussing the key factors in the imaging process, the paper proposes the core issues and development goals of developing high-quality CT imaging technology, providing a reference for related research in the future.

References

1. Palancher, H.: 2D and 3DX-ray Difffraction and Imaging of Nuclear Fuels (2017)
2. Thomas, J., Bengoa, A.F., Nori, S.T., et al.: The application of synchrotron micro-computed tomography to characterize the three-dimensional microstructure in irradiated nuclear fuel. J. Nucl. Mater. **537**, 152161 (2020)
3. Pokharel, R., Brown, D.W., Clausen, B., et al.: Non-destructive characterization of UO2 nuclear fuels. Microsc. Today **25**(6), 42–47 (2017)
4. Jailin, C., Bouterf, A., Poncelet, M., et al.: In situ μ-CT scan mechanical tests: Fast 4D mechanical identification. Exp. Mechan. **57**(8) (2017)
5. Jin, S.C., Hsieh, C.J., Chen, J.C., et al.: Development of limited-angle iterative reconstruction algorithms with context encoder-based sinogram completion for micro-CT applications. Sensors **18**(12) (2018)
6. Yu, W., Jie, P., Lwa, B., et al.: Characterization of typical 3D pore networks of Jiulaodong formation shale using nano transmission X-ray microscopy. Fuel **170**, 84–91 (2016)