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Development of a Fast X-ray 3D Imaging System for Defect Inspection of Cylindrical Lithium-Ion Batteries

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1. Introduction

Due to the growth of the electric vehicle market, the secondary battery market has likewise expanded substantially. Various internal defects in secondary batteries increase the risk of fires in electric vehicles, making inspection necessary during production [1]. In particular, given the nature of these batteries, X-ray inspection equipment is widely used for internal inspection after assembly. To reliably visualize internal structures without risking misdetection, 3D imaging is essential. However, using conventional methods to obtain 3D images can take over 30 minutes per battery, primarily because the existing system design does not allow for a larger X-ray focal spot. A smaller focal spot requires lower power output [2], which in turn slows down the inspection process. To solve this problem, in this paper, we adopt an optical magnification technique instead of a purely geometric one, thereby decoupling the X-ray focal spot size from spatial resolution. Consequently, we employ a high-power X-ray tube with a larger focal spot to acquire 3D images more quickly.

2. Methods and Results

2.1 Design of Fast X-ray 3D Imaging System

2.1.1 Object – Cylindrical 21700 Battery

The test object is a 21700 cylindrical battery whose external case is made of stainless steel. The internal electrodes are in a jelly-roll configuration, where the cathode consists of NMC 622 attached to an aluminum strip, and the anode consists of graphite attached to a copper strip. Using a Zeiss Xradia 520 X-ray Microscopy system, we conducted experiments to determine the optimal tube voltage for the battery. As a result, it was found to be in the range of 100–120 kVp.

2.1.2 Decoupling X-ray focal spot size from spatial resolution

In conventional 3D X-ray imaging systems that employ geometric magnification, a micro-focus X-ray tube with a small focal spot is typically used to achieve high resolution. However, its low output power hinders fast inspection speeds. In this study, we adopted a scintillator-based approach that decouples the X-ray focal spot size from the spatial resolution, enabling high-resolution imaging even with a relatively large focal spot. Accordingly, we can use a high-power X-ray tube with a larger focal spot to shorten the acquisition time for 2D projection images. Specifically, instead of using a conventional micro-focus X-ray tube at around 10 W output, we employed a high-power X-ray tube of about 400 W output. This greatly increases the X-ray flux, allowing for the rapid acquisition of low-noise 2D projection images.

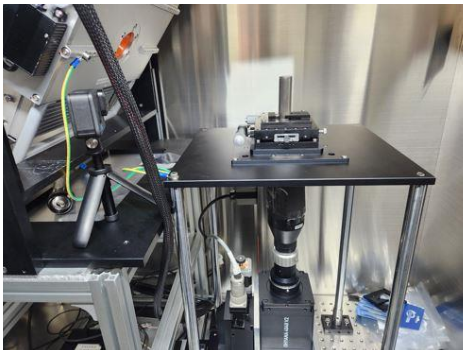

Fig. 1. The developed high-speed X-ray 3D imaging system

2.2 Spatial Resolution Measurement

We evaluated the system's spatial resolution by measuring the MTF [3]. Using a 10 mm-thick tungsten block, an edge spread function (ESF) was obtained from the line profile of the edge region; subsequently, the line spread function (LSF) was derived via differentiation. A 2D Fourier transform of the LSF then yielded the MTF. The measured MTF results are shown below.

Table I: Spatial Resolution according to Focal Spot Size

kVp / mA	Focal Spot Size (um)	Spatial Resolution (um)
100 / 0.5	50	44.59
140 / 0.5	70	47.95
120 / 1	120	49.77
120 / 3	360	50.10

2.3 3D imaging of a 21700 Clindrical Battery

The geometry used for image acquisition is illustrated as follows. [Geometry diagram and example of a 2D projection image]

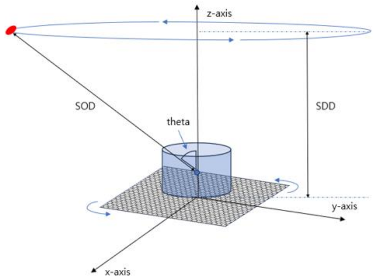

Fig. 2. Geometry Diagram of 2D Projection Acquisition

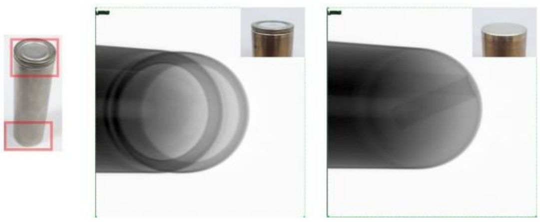

Fig. 3. 2D Projection Images of a 21700 Cylindrical Battery

The 2D projection acquisition conditions are as follows.

Table II: 2D Image Acquisition Parameters

Scintillator	CsI 150 um	kVp / mA	120 / 3
Magnification	0.7x	Filter	Cu 0.5mm
Eff. Pixel Size	26 um (2x2bin)	Exposure time	1 s

After collecting 800 two-dimensional images, we reconstructed a 3D volume using FBP (Filtered Back Projection) within the CERA Xplorer software.

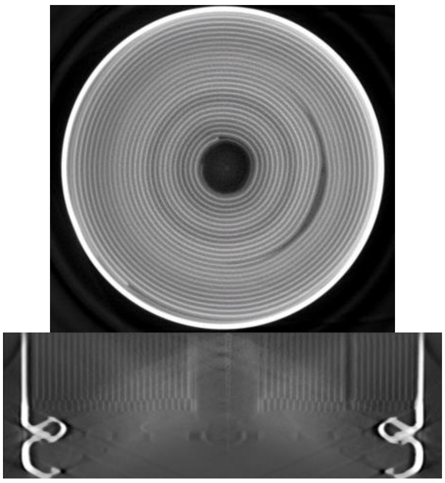

Fig. 4. Cross-sections of the internal jelly roll and the central yz-plane of a 21700 cylindrical battery, acquired using the developed X-ray system

3. Conclusions

For high-speed inspection of cylindrical lithium-ion batteries, we have designed and developed a 3D X-ray imaging system that utilizes a high-power X-ray tube. Even with a focal spot size of about 400 µm, the system maintained a spatial resolution of approximately 50 µm, which is sufficient for internal 3D imaging of secondary batteries. By further upgrading to an X-ray tube with higher output, using a scintillator with higher light yield, an optical lens with a larger numerical aperture (NA), and a camera with higher quantum efficiency, it should be possible to reduce the scan time even further.

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