High-voltage micro-CT system

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CT Lab HV

Abstract

This article explores the capabilities of X-ray Computed Tomography (CT) as a non-destructive 3D imaging tool for inspecting dense and complex materials. While not yet as widely adopted as Optical Microscopy (OM) and Scanning Electron Microscopy (SEM), X-ray CT is gaining recognition for its ability to provide detailed volumetric data non-destructively.

The CT Lab HV, developed by Rigaku, features a 225 kV X-ray source, a high-precision rotation stage, and a large detection area, enabling a broad variety of high-resolution imaging applications. Application examples, including additively manufactured superalloys and lithium-ion battery protection boards, highlight its effectiveness in defect detection, structural analysis, and product simulation. As demand for advanced imaging grows, the CT Lab HV offers an innovative solution for industry and research, enhancing the adoption of X-ray CT in critical applications.

1. Introduction

1.1. X-ray computed tomography

X-ray Computed Tomography (CT) is a non-destructive 3D imaging technique that reveals the internal structure of objects with minimal or no sample preparation. The flexibility and capability of X-ray CT make it invaluable across a wide range of applications and materials, from lightweight biological specimens to high-density items like electronics, batteries, and 3D-printed metals. X-ray CT is used for tasks such as product inspection and failure analysis, identifying defects like pores, cracks, and voids, as well as anomalies including misalignment, delamination, and leakage. With adequate resolution, X-ray CT links the actual product to its virtual model, creating precise 3D replicas for measurement and simulation.

1.2. X-ray CT fundamentals and application development

Currently, CT has not yet been as widely adopted as traditional Optical Microscopy (OM) and Scanning Electron Microscopy (SEM). However, the distinct advantage of lab-scale CT—offering 3D non-destructive imaging and excellent compatibility with these traditional tools—is increasingly being recognized in industry and academia. As public awareness of its potential grows, so does interest in integrating CT into production and research applications.

Two factors must be considered to address key demands and guide the development of CT technology: the fundamental physics of X-ray imaging and the sample criteria associated with emerging applications.

The foundation of conventional X-ray CT imaging lies in absorption contrast, which arises from variations in the X-ray absorption rates of different structural features within the scanned sample. The Beer-Lambert Law governs this relationship between material properties and X-ray absorption:

$$I_{measured} = I_{incident}\, e^{-\mu t} \tag{1}$$

$I_{incident}$ represents the X-ray intensity before passing through the material, $I_{measured}$ is the remaining X-ray

Fig. 1. CT Battery samples of various sizes.

intensity reaching the detector after absorption. t indicates the thickness of the material, while μ is the attenuation coefficient related to the material property. The value of μ for regular X-ray CT conditions can be further expressed as being proportional to several factors as follows [(1)]:

$$\mu \propto \frac{\rho Z^4}{E^{3.5}} \tag{2}$$

ρ represents density, Z is the atomic number, and E is the X-ray photon energy used for imaging.

To summarize the implication of the relationship between the sample and X-ray contrast, X-ray absorption is greater for a material that is thicker (higher t), has a higher density (ρ), and/or is composed predominantly of elements with higher atomic numbers (Z). In those cases, higher X-ray photon energies (E) are required to penetrate through the material and generate sufficient contrast in the transmitted projection image.

The rising demand for CT technology is being shaped by emerging technological trends in product development, driven by evolving market needs. Key examples include lithium-ion batteries, largely from the electric vehicle (EV) industry; circuit assemblies in the electronics and semiconductor sectors; and metal additive manufacturing products, which are increasingly utilized in aerospace and other manufacturing industries.

Typical samples generated from these industries can generally be high density and high mass. For example, lithium-ion battery samples often feature protective shells or packaging made from dense materials. Additionally, batteries are often found in pack configurations or integrated into assemblies for use in electric vehicles, drones, and smart devices. Figure 1 illustrates examples of lithium-ion battery samples in various sizes and formats, ranging from small coin and cylindrical cells to larger prismatic cells. Similarly, circuit assemblies and metal additive manufacturing samples also include dense and high-mass materials.

Since X-ray CT image quality is governed by the Beer–Lambert Law and samples from these technologies often contain high-density components with greater mass, there is an increasing demand for systems capable of handling such samples. Specifically, the ideal CT system for imaging these types of samples requires X-ray sources with higher photon energy to effectively handle their larger size and density.

2. CT Lab HV

To address the demand for imaging high-density and large samples, Rigaku has developed the CT Lab HV system. This X-ray CT system features an X-ray source offering a maximum tube voltage of 225 kV and a maximum power of 300 W. The X-ray source is paired with a spacious sample stage and high-precision direct-drive motor rotation stage with exceptional load capacity. Data are captured using a large 434 × 434 mm flat-panel detector. This setup allows for imaging samples up to 600 mm in diameter, 1200 mm in height, and weighing up to 50 kg.

The CT Lab HV system provides an impressive imaging field of view (FOV) range from 4 mm to 350 mm and a minimum voxel size of 1.5 µm. With a minimum X-ray source focus size of just 3 µm and variable source-to-object distance (SOD) and

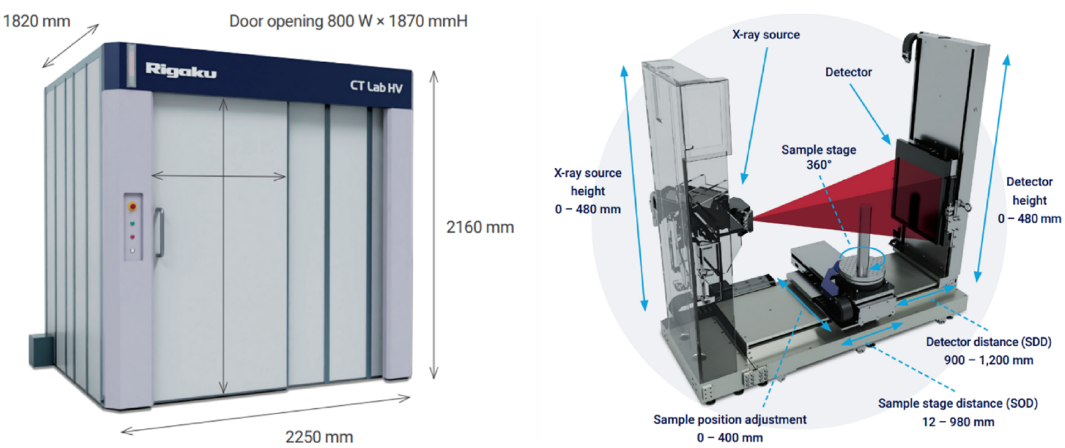

Fig. 2. (Left) Dimensions of the CT Lab HV main unit. (Right) Source-sample-detector configuration.

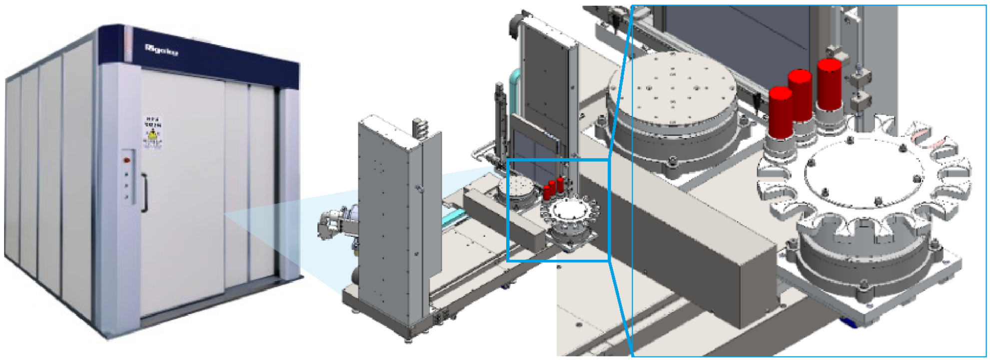

Fig. 3. Example of the automatic sample changer implementation.

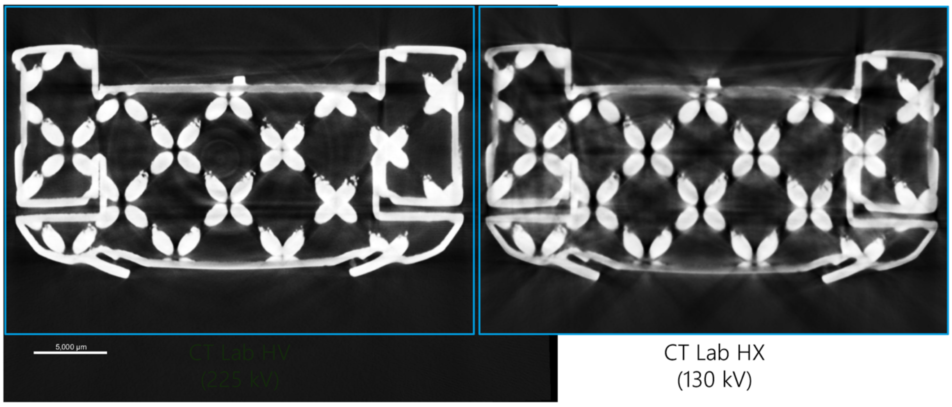

Fig. 4. (Left) Scan with CT Lab HV. (Right) Scan with CT Lab HX on an Inconel® Superalloy car model with the average dimension of 8 cm in length, 4 cm in width, and 3 cm in height.

source-to-detector distance (SDD), the system achieves 3 μm spatial resolution, determined by resolved line pairs in a resolution phantom. Figure 2 illustrates the device dimensions, sample stage configuration, and detector setup.

The spacious housing of the CT Lab HV also supports the integration of an automatic sample changer, as shown in Fig. 3. Additionally, it offers customizable configurations to accommodate unique designs tailored to various automation systems or experimental environments.

The high voltage capability of the CT Lab HV is critical for producing high-quality scans with minimal artifacts. As clearly shown in Fig. 4, there is a significant difference between the scan results obtained at the maximum tube voltage of the CT Lab HV (225 kV) and the CT Lab HX (130 kV). Scans performed at lower voltage exhibit more noticeable beam-hardening artifacts and less defined contrast compared to the scan performed at higher voltage. The increased tube voltage of the CT Lab HV allows for superior imaging of dense materials with enhanced clarity. Furthermore, for certain applications, the CT Lab HV system achieves a comparable signal-to-noise ratio to the CT Lab HX, but with a shorter exposure time.

3. Application Examples

3.1. 3D Printed superalloy

In this application example, the CT Lab HV was used to inspect the internal structure of a superalloy (Inconel®) car sample produced via powder bed fusion by Nissin Manufacturing Co. Ltd. Imaging high-density, heavy materials like the Inconel® superalloy used in this 3D-printed car sample requires higher X-ray energy to minimize beam hardening artifacts. As a result, the sample was scanned using 200 kV, 70 μA. Figure 5 shows the scanned sample exterior, as well as a section of the internal structure revealed through transparency.

Data collected at 200 kV provides excellent grayscale contrast, enabling segmentation through simple histogram thresholding. After segmenting the sample's solid structure, the grid-like structure was visualized, and the volume thickness was analyzed using Dragonfly 3D World. Figure 6 shows the volume thickness analysis result in both 3D and 2D views.

To demonstrate the outstanding compatibility between CT scan and product property simulation, a surface mesh of the 3D-printed car sample was created for load simulation using VGStudio MAX. A force of 150 kN was uniformly applied to the roof section of the superalloy car sample, simulating downward compression. The resulting distribution of maximum principal stress is displayed in Fig. 7 in both 3D and 2D views. In the visualization, red areas represent

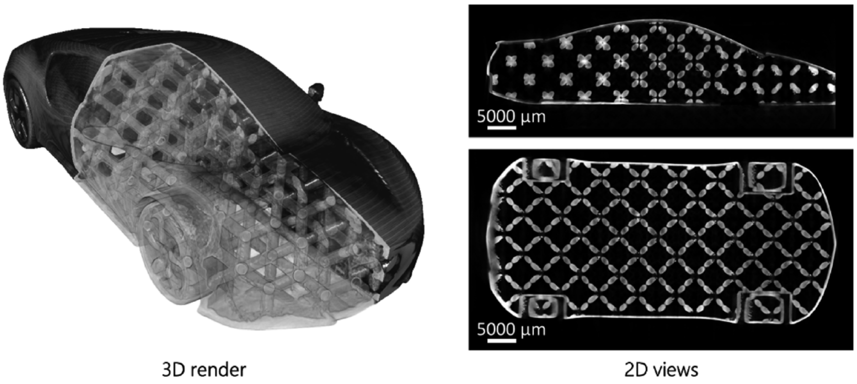

Fig. 5. 3D render of the superalloy sample and 2D cross-section views.

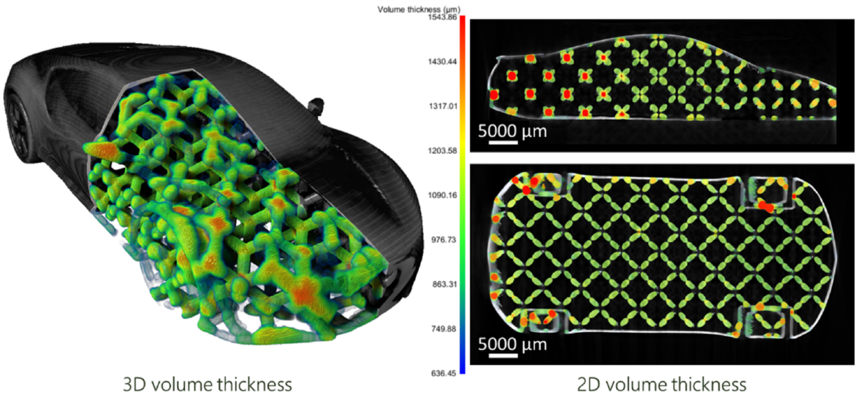

Fig. 6. The volume thickness of the superalloy car is demonstrated in 3D and 2D perspectives.

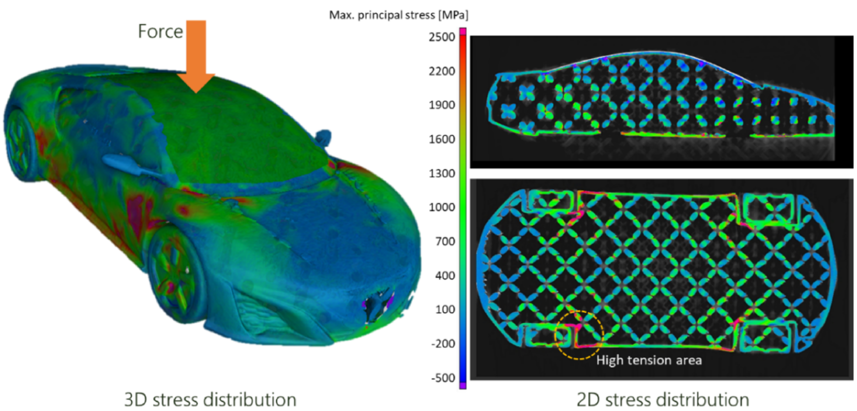

Fig. 7. The load simulation result shows the principal stress distribution throughout the scanned product structure.

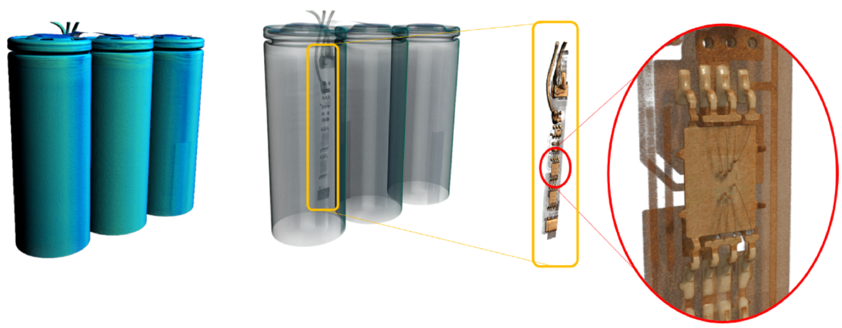

Fig. 8. 3D view of the battery pack (left). Battery pack protection board (center). One of the two MOSFET transistors (right).

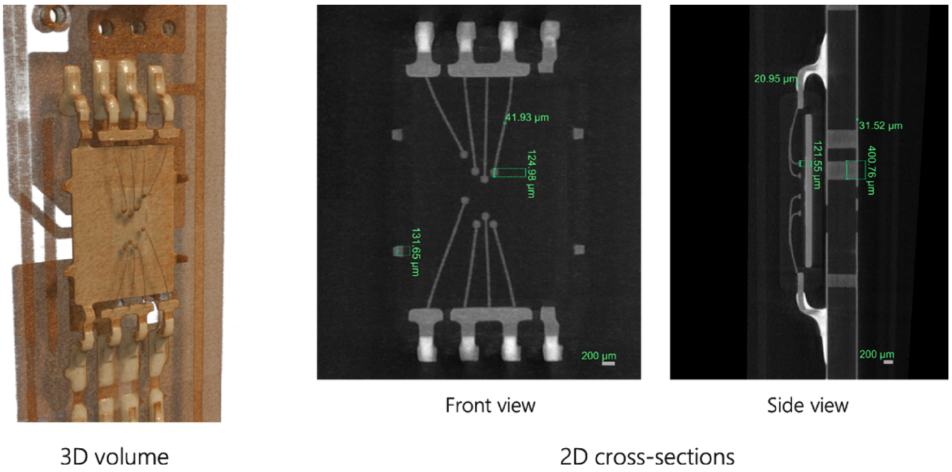

Fig. 9. 3D and 2D views of the MOSFET with measurements labeled.

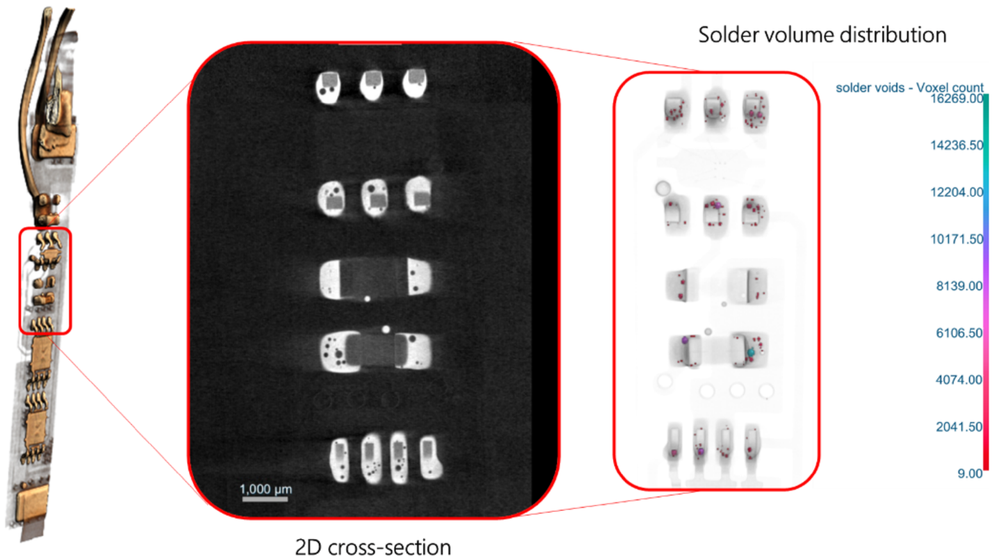

Fig. 10. 2D and 3D views of solder void distribution, with voids depicted in colors corresponding to increasing volume from red to pink, magenta, blue, and green.

regions of high tensile stress, while blue areas represent higher compression stress. If the stress in high-stress areas exceeds the material's modulus, permanent deformation may potentially lead to damage or fractures in the car sample. Figure 7 shows the simulation results, highlighting areas of concern with high principal stresses.

3.2. Battery protection board

In this application example, a lithium-ion battery pack was scanned using the CT Lab HV. The analysis focused on the MOSFET transistor wiring and solder joint connections within the small protection board on the battery pack. These protection boards are essential for safeguarding against short-circuits, overcharging, and over-discharging. Figure 8 shows a 3D view of the battery pack and protection board, with an enhanced view of one of the two MOSFET transistors.

Figure 9 displays a 3D view and 2D cross-sections of the MOSFET at 90° angles to each other. The wires and wire connections are clearly visible, with dimensions of approximately 40 µm and 125 µm, respectively, in the front view cross-section. The side views reveal additional measurements for a thin layer of solder and the board, with even smaller thicknesses of around 21 µm and 32 µm, respectively.

Segmentation was performed for solder joints in MOSFETs and capacitors to label voids. The volume of solder voids was quantified based on the number of encompassing voxels, with results color-coded according to size. Figure 10 displays 2D and 3D views of solder voids in adjacent components of the protection board. Smaller voids are shown in red, transitioning to pink, magenta, blue, and green as their volume increases.

4. Conclusions

The CT Lab HV represents an important step forward in the effort to meet the growing needs for non-destructive imaging for both industry and academics.

By combining a high-power 225 kV X-ray source, clear spatial resolution, and a larger sample stage, the CT Lab HV is designed to fulfill the demands of emerging applications such as batteries, electronics, and metal additive manufacturing.

The examples presented in this article highlight the system's ability to generate detailed 3D data for diverse sample types. From analyzing additively manufactured superalloy structures to inspecting critical components in lithium-ion battery protection boards, the CT Lab HV demonstrates versatility and reliability in producing high-quality results.

As X-ray CT continues to gain broader recognition as a powerful structure characterization tool, the CT Lab HV contributes to advancing its adoption by offering enhanced capabilities tailored to modern research and industrial challenges. By addressing key imaging demands with precision, the CT Lab HV provides a robust platform for researchers and engineers to further explore and refine their work.

References

(1) H. Hall: *Reviews of Modern Physics* **8** (1936), 358–397.