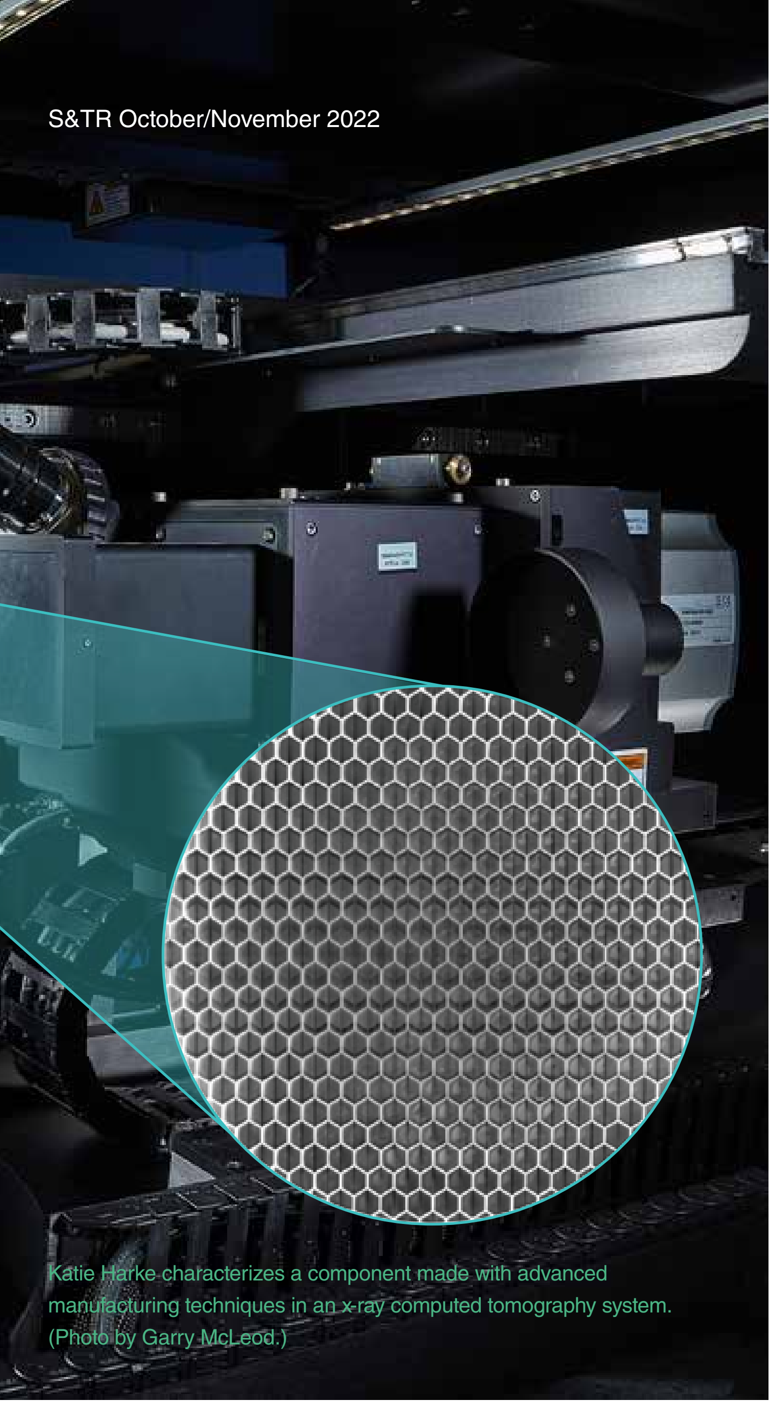
FROM PLASMA TO DIGITAL TWINS

MICROMETERS matter when aberrations smaller than the width of a hair can jeopardize an entire system. Whether working with semiconductors or optics, research teams from all disciplines at Livermore recognize that stringent standards of precision ensure operability of mission-critical equipment. Only after extensive testing can any component be qualified for its function. However, nearly all components require a thorough quality control process that keeps them intact and functional—no dissection allowed—from microscale objects replete with intricate details to additively manufactured parts built micrometers at a time.

At Livermore, this challenge goes to the Nondestructive Evaluation (NDE) group. “Put simply, our job is to look inside things. We check for irregularities and make sure physical components will function as intended,” says NDE group leader Joe Tringe. The group has an array of techniques at its disposal for inspecting objects’ interiors without disturbing them: computed tomography (CT), optical laser interferometry, and ultrasound, for example, can be used alone or in combination to gauge whether a component’s physical and material properties fall within allowed tolerances.

Laser Precision

Metrology—the study of measurement—offers data-backed confidence for performance of the Laboratory’s specialized components. Despite the breadth of diagnostic tools available to NDE scientists, data out is only as good as data in. This reality led Harry Martz, director of Livermore’s Nondestructive



Katie Harke characterizes a component made with advanced manufacturing techniques in an x-ray computed tomography system. (Photo by Garry McLeod.)

The Berkeley Lab Laser Accelerator (BELLA) Center supported work to perform x-ray tomography of high-Z components. Optics in the foreground channel electron and laser beams that are fired toward a sample staged at the far side of the setup.

Characterization Institute (NCI), in search of even higher-precision methods. NCI identifies requisite NDE processes for Livermore's diverse programs and coordinates with outside research institutions when additional development is needed. As part of a project funded by the Laboratory Directed Research and Development (LDRD) Program, Martz drew talent from Lawrence Berkeley National Laboratory as well as the United Kingdom–based Rutherford Appleton Laboratory and Manufacturing Technology Centre to focus on a class of notoriously camera-shy objects: x-ray resistant materials. The group addressed limitations of x-ray computed tomography (XCT)—used to digitally reconstruct objects in 3D from serial radiographs—when imaging high atomic number (high-Z) components. "We're trying to achieve higher spatial resolution and minimize uncertainty when imaging these materials to streamline the qualification and design cycle of additively manufactured components," says Martz.

Robust, high-Z materials such as the superalloy Inconel (used in rocket engines and heat exchangers) impede incident x rays, distorting radiographs. To ensure x rays fully penetrate Inconel components during evaluation, scientists must crank up x-ray energy to more than 1 megaelectronvolt (nearly 10 times higher than a standard chest x ray). Unfortunately, such powerful beams typically require large focal spot sizes. The result is a less precise probe, meaning minute imperfections in critical, additively manufactured components that could trigger mechanical failure—precisely the flaws that must be identified—could therefore evade detection.

Martz's team sought to produce high-energy x rays while maintaining minimal beam spot size to improve components' digital reconstructions. Martz explains, "Physics models have generally assumed a monoenergetic x-ray source when, in reality, lab-based x rays are polyenergetic, with energy distributed above and below the desired value. We need as close to a monoenergetic source as possible so subsequent image reconstruction excludes artifacts that deviate from ground truth." The team saw promise in the nascent method of laser–plasma acceleration (LPA) under development at the Berkeley Lab Laser Accelerator (BELLA) Center. Adapting BELLA's hardware for their experimental needs, the researchers set out to generate narrow-band x rays and perform CT with the method for the first time.

In the world of accelerator physics, LPA is the next big thing in a small package. A short, intense pulse of laser light is fired and split into two beams, the first of which is focused into a volume of gas to create a plasma. High electric field gradients then accelerate the plasma's electrons to ultrarelativistic velocities at a rate that is far more efficient than traditional linear accelerators. Meanwhile, the second beam is rerouted to collide with the produced electron beam to create energetic x rays through a phenomenon called inverse Compton scattering (ICS). X rays generated through ICS are used to produce radiographs.

The team probed a small, additively manufactured Inconel object using LPA-driven ICS, hoping to achieve more than 200 times greater spatial resolution than with conventional XCT. The setup's tunable, quasi-monoenergetic x-ray spectrum would reduce energy spread, providing more precise images of the stubborn material than ever before. "Unfortunately, research isn't always successful the first time around," says Martz. The group successfully acquired CT data, although neither the x-ray beam nor the CT resolution was as precise as they hoped. But Martz remains optimistic. "The work we did at BELLA was a worthwhile risk. Even without the crisp images we strove for, simply obtaining CT data with this new process is an achievement in its own right, and what we learned prepares us for the next attempt." Their project indicates promising evaluative capabilities by demonstrating the feasibility of a new NDE resource.

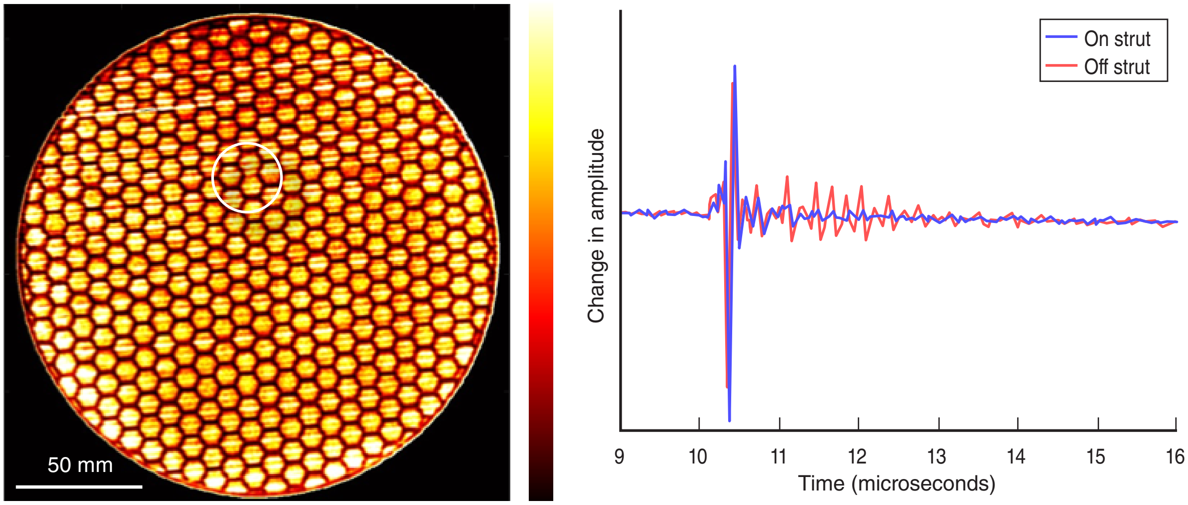
Putting It All Together

While Martz's group works to expand XCT capabilities, Tringe leads another LDRD project exploring NDE methods effective in other situations. "Ultrasound, while not well suited for many 3D imaging problems, is attuned to slight density changes and perceives cracks, voids, and layer thicknesses like no other method," says Tringe. "We wanted to combine the strengths of multiple modalities—XCT, ultrasound, neutron imaging, and so on—to provide the best quantitative data possible for critical components."

Tringe's team of NDE specialists and university collaborators tackled integration of data from multiple modalities into composite images, a task more complex than merely overlaying multiple images. Each modality is uniquely suited to detecting particular features and compositions, and each supports a different spatial resolution. "We have to decide which part of an image represents true physical boundary features—the dark side? the light side? somewhere else along the gradient?—and do so algorithmically for thousands of images. With XCT, we consider where within the object we're looking as well as the spot size, energy spectrum, and x-ray source scattering. For ultrasound, the determination can depend on material thickness and porosity."

Metrology is inextricably tied to uncertainty, but knowing the exact level of precision in one's methods can prove challenging. "In evaluating additively manufactured parts," says Tringe, "scientists require precise quantitative information from CT. They often are searching for subtle deviations in geometrically complex structures, not conspicuous changes in image contrast like in medical scans." The team determined how to quantify the uncertainty associated with multimodal measurement, comparing obtained readings to "exemplar" objects with verified dimensions to isolate the factors responsible for certain measurement errors.

The research group also transformed multimodal data into true-to-life "digital twins," ultra-precise computed replicas of a component's structural and material properties. Using digital twins, scientists can simulate properties including heat transfer and physical deformation to ascertain a component's performance and longevity. "A good digital twin is better than a snapshot in time," says Martz,

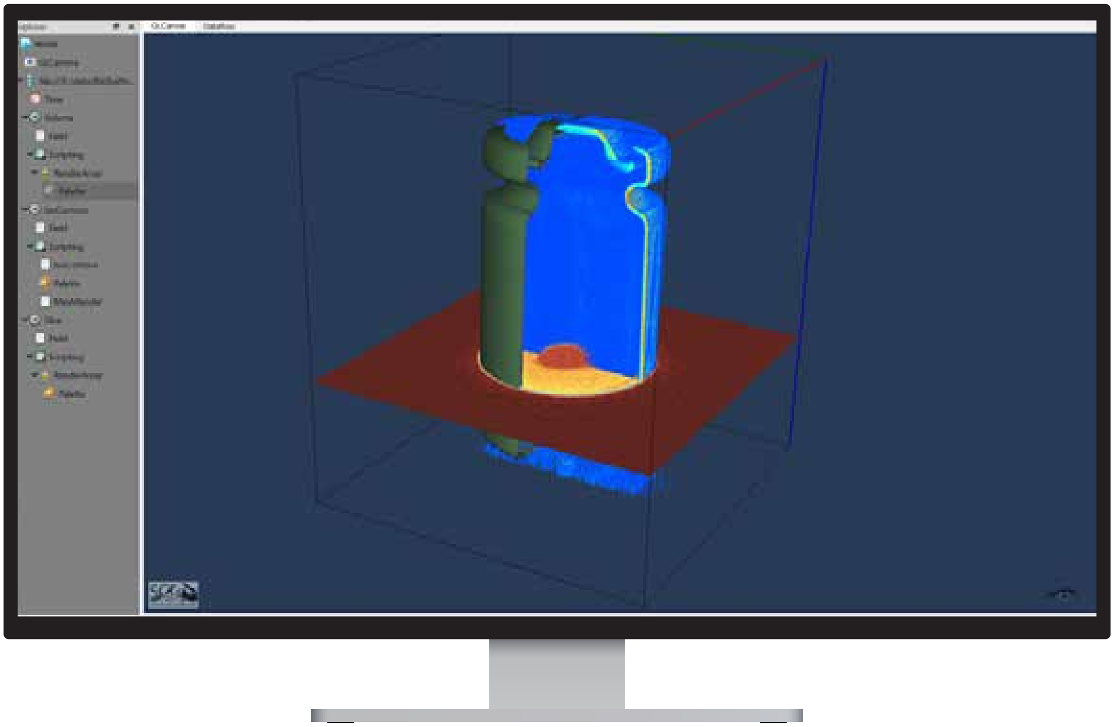


Ultrasound can detect faults in repetitive structures where other nondestructive evaluation methods may fall short. (left) Echoes in a planar ultrasound C scan (represented as brightness) denote cavities in an additively manufactured titanium honeycomb, revealing a missing strut (circled). (right) A time-dependent ultrasound A scan measurement confirms the missing strut, indicated by incongruous waveforms.

who served as an adviser on the project. “For example, each time an airplane lands, rubber is stripped off the outer layer of its tire. With a digital twin, we can predict how friction and stress will impact the tire’s performance both in its current state and after repeated landings to determine when it might need replacement.”

Computational Foundations

Under Tringe’s leadership, the LDRD team developed a library of algorithms to combine data from XCT, ultrasound, and neutron imaging methods and visualize 3D component reconstructions. Using the numerical technique of forward projection to estimate unseen features, preliminary reconstructions were iteratively refined and rebuilt through a machine-learning model that adjusted geometry and reduced modality-specific artifacts. The team first tested their method on exemplars to further tune the computing process before applying it to additively manufactured components. The resulting model is more than the sum of its parts, reflecting the most confident readings obtained from each modality individually.



Developed by researchers from the University of Utah and Lawrence Livermore, OpenViSUS software allows users to organize, analyze, visualize, and interact with multimodal 3D data as indicated in this image integrating x-ray and neutron scans of a battery, where different colors reflect different material densities.

Equipped with a trove of data describing structure and composition, the researchers transformed statistics into a comprehensible, user-friendly form. Collaborating with the University of Utah, they built OpenViSUS, open-source software to organize, analyze, and visualize massive data sets—an improvement over existing third-party software that can buckle under processing requirements. Integrated with Livermore Tomography Tools, researchers can run OpenViSUS directly on a laptop to explore and interact with multimodal reconstructions of objects in 3D.

Optimum 3D visualization, however, is found in virtual reality (VR). “Unlike a computer screen, VR completely immerses you in a space,” says Tringe. Reconstructions of highly complex components such as truss structures contain hundreds of thousands of features. Computers can statistically sample slices of an object to check for defects, but defects just outside the sampled slice could be missed. “While we often defer to machines and statistics for consistency,” he says, “we still need a person in the loop to interact intuitively with the data. We could deploy multiple machine-learning algorithms that direct VR wearers to potential problem areas demanding inspection while fully immersed in the 3D structure.” Although VR is developing, the NDE team now has a valuable supply of data and exemplars for future use.

Through innovation and collaboration, Livermore continues to cultivate its strengths in NDE, computing, and additive manufacturing to ensure the safety and operability of national security infrastructure. The cutting-edge CT technique tested by Martz’s research team provides “meaningful NDE capability transfer to meet our program needs,” says Martz. Tringe reflects, “I’m proud of how this large team with diverse backgrounds cooperated on such a complex project, all while dispersed due to pandemic complications. Innovation in these critical processes allows Livermore to fulfill its stewardship duties to an ever-increasing standard of excellence.”

–Elliot Jaffe

Key Words: Additive manufacturing, computed tomography (CT), digital twin, high-z material, laser–plasma accelerator (LPA), multimodal reconstruction, nondestructive evaluation (NDE), OpenViSUS, qualification, surveillance, virtual reality (VR), x rays.

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