Nondestructive examination of complex additive manufactured components using neutrons is a valuable technique for imaging and measuring residual stress.

Why neutrons?

Neutron techniques might be less familiar than x-ray methods to materials scientists and engineers, but are similar in many ways. For example, x-ray and neutron diffraction both use Bragg’s Law to describe scattering from single crystals, powders, and polycrystalline solids. However, one important difference is that neutrons are much more penetrating than x-rays in most materials. X-ray scattering occurs within a few microns (with lab sources) to a few millimeters (using high-energy synchrotron radiation) of the surface, whereas neutrons often penetrate several centimeters. Therefore, neutrons serve as a nondestructive probe of the bulk microstructure in engineering solids. Another difference is that x-ray scattering inten-
Neutron computed tomography (nCT) reconstructs a 3-D image of the contrast due to attenuation of neutrons inside an object by transforming multiple 2-D radiographs of the object as it is rotated around its axis. Neutron CT was performed at HFIR’s CG-1D cold neutron imaging prototype facility on Inconel 718 turbine blades fabricated by additive manufacturing using direct laser metal sintering (DLMS) at Morris Technologies (Cincinnati, Ohio). Neutron radiographs are generated using a LiF/ZnS scintillator that converts neutrons into light, which is subsequently detected by a CCD camera. Spatial resolution at the sample position is approximately 75 μm. The radiograph and nCT data in Fig. 3 indicate a relatively low neutron attenuation through the blade itself, and higher attenuation at the base of the object. The dark/low transmission region is likely due to the increased thickness at the blade base. Some internal air/sample interfaces show an interesting texture that could affect airflow through the turbine. After reconstruction, the volume rendering provides a 3-D visualization of the object (Fig. 3 center). Quantitative analysis is often based on transverse slices obtained from the reconstructed piece (Fig. 3 right).

ORNL is developing a world-class neutron imaging instrument called VENUS (Versatile nEutron imagiNg instrument at Sns), which will use the SNS in a unique way to measure and characterize large-scale and complex systems. VENUS will offer the opportunity to advance scientific research in a broad range of areas such as energy, materials, additive manufacturing, transportation, engineering, plant physiology, biology, and archeology. It will have unprecedented spatial resolution (~10 μm), providing 3-D visualization of surface texture and porosity. The unique capabilities are derived from the intrinsic SNS time-of-flight (TOF) properties, which allow probing the wavelength-discrete neutron attenuation. Energy-selective and Bragg edge-imaging properties will provide enhanced contrast mechanisms, material identification, and the opportunity to map strain inside samples.

Neutron residual-strain measurements

In addition to tomodraphy, neutron diffraction can be used to nondestructively measure residual strain in a material and determine residual stresses. Strain is determined through Bragg’s Law by measuring distances between crystallographic planes of the strained sample and a reference. Figure 4 illustrates how the sample interior is mapped. The nominal gauge volume is fixed in space on a goniometer and defined by the intersection of projections of incident and receiving slits. The sample is moved (x, y, and z, and rotation) relative to the gauge volume and mapped. While diffraction outside the gauge volume occurs along the
beam path, it is not recorded because these neutrons are blocked by the receiving slits. The direction of the measured strain component is given by the scattering vector, which bisects the incident and diffracted beams and is perpendicular to the diffracting planes.

**Characterization of EBF³ samples**

NASA Langley Research Center (Hampton, Va.) has been working on large-scale metal additive manufacturing for the past ten years. The electron beam freeform fabrication process (EBF³) uses a high-power electron beam with wire feedstock to fabricate large structural aerospace components. These components often exceed a meter in length and require many kilograms of deposited material. The incremental nature of the additive process combined with the large scale of EBF³ fabricated components results in high levels of distortion and/or residual stress. Understanding how these residual stresses evolve is critical in developing effective mitigation strategies.

Two applications of primary interest for the EBF³ platform are terrestrial-based manufacturing of aerospace structures and remote, space-based fabrication of hardware. For the former, knowledge of residual stress accumulation helps develop fixturing, path planning, and intermediate heat treatment strategies minimize throughput time and out-of-tolerance distortion. For the latter, knowledge of the residual stresses helps predict final bulk properties, as heat treatment may not be available for structures fabricated extraterrestrially.

NASA recently initiated neutron diffraction measurements on EBF³-deposited aluminum samples using the Vulcan Engineering diffractometer at SNS. Initial measurements evaluated the impact of an intermediate thermal anneal treatment on residual stress. The stress relief heat treatment shifted the residual stresses from the substrate into the deposited material. This is important for the EBF³ process where the substrate plate is usually incorporated into the final part and often accounts for the bulk of out-of-plane distortion. These data were used to develop basic models using commercially available finite element modeling software. Additional trials at SNS scheduled for early 2013 will help validate the early models and provide a predictive capability to minimize residual stress and distortion in large-scale additive structures.

**Characterization of DLMS turbine blades**

Experiments were also conducted on the VULCAN beam line to determine if residual strains could be measured in complex components with internal structure, which is also of interest elsewhere⁹. A series of turbine blades were fabricated from Inconel 718 using DLMS technology. The blades have a wall thickness down to 1 mm and curved internal cooling passages (see Fig. 3). Three blades were analyzed at VULCAN together with a strain-free reference powder (Fig. 5). Slits on both the incident and diffracted beams give a gauge volume of $2 \times 2 \times 2$ mm, $^{2}$ Two detector banks (not shown) are located to the left and right of the samples allowing for simultaneous collection of two orthogonal strain components.

![Fig. 4 — Schematic of neutron diffraction set up viewed from above shows nominal gauge volume (dark square) as defined by the slits\(\textsuperscript{7} \).](image)

![Fig. 5 — Precision alignment of the turbine blades and powder sample (top) in the VULCAN beam line (bottom).](image)
conditions, respectively. Each square and diamond in Fig. 6 is nominally 1 and 4 mm², respectively.

In the as-built blade, strains parallel to the long axis of the blade are more compressive on the convex surface than the concave surface, which may be related to sequencing in the DLMS build process. In general, residual strains in the as-built sample become more tensile (or less compressive) as the dovetail base is approached. At the base, residual strains return to being more compressive. After a proprietary stress relief process, residual strains become very compressive and much more uniform throughout the lower portion of the blade, suggesting that the blade will be less likely to distort during service. The combination of neutron tomography and residual strain measurement is a critical approach for examining complicated components that can be built using additive manufacturing.

HFIR residual stress mapping

Preliminary experiments are underway at the HFIR’s NRSF2 beamline (HB-2B, Fig. 7) to map stress distributions in complex parts produced by additive manufacturing. Whereas the VULCAN beamline allows for simultaneous acquisition of strains from multiple crystallographic planes, HB-2B selects a single diffraction peak as the strain sensor. Peak data are recorded for a series of sample locations and orientations to produce a residual stress map throughout the structure. Diffraction peak shifts are a measure of changes in atom-to-atom spacing, and may be related to tensile or compressive strains in the sample. Peak intensity changes may indicate preferred orientation, or changes in sample composition, and peak width may be related to crystallite size, dislocation density, and other microstructural features. The facility is being used to measure residual stress in simple prismatic shapes fabricated using various AM techniques to gain a fundamental understanding of process parameters on stress evolution. This information will be used to verify process models and stress mitigation strategies currently under development.

Summary

The use of neutrons to characterize additive manufactured components is a unique, valuable technique for imaging and measuring residual stress. Neutron and x-ray techniques can be used in a complementary fashion, providing information about the bulk and surface of a component, respectively. Neutrons are useful to characterize complex components, such as those fabricated using additive manufacturing techniques. In this article, the penetrating power of neutrons facilitated unique characterization of aircraft parts fabricated using additive manufacturing, imaging internal structures and passageways and mapping residual strains in a complex turbine blade. Future projects combining these techniques will be required to fully use the potential of additive manufacturing.

Research sponsored by the U.S. DOE, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle LLC. Research conducted at ORNL’s High Flux Isotope Reactor and Spallation Neutron Source was sponsored by the Scientific User Facilities Div., Office of Basic Energy Sciences, Department of Energy.

References


For more information: Thomas Watkins, Ph.D., Group Leader & Senior Research Staff, Scattering and Thermophysics Group, MS&T Div., ORNL, tel: 865/387-6472; email: watkinstr@ornl.gov; http://www.ornl.gov/sci/physical_sciences_directorate/mst/dtp/watkins.shtml.

Choosing a hardness tester just got a whole lot easier.